The Macroeconomic Consequences of Infrastructure Investment

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Abstract

Can greater investment in infrastructure raise U.S. long-run output? Are infrastructure projects a good short-run stimulus to the economy? This paper uses insights from the macroeconomics literature to address these questions. I begin by analyzing the effects of government investment in both a stylized neoclassical model and a medium-scale New Keynesian model, highlighting the economic mechanisms that govern the strength of the short-run and long-run impacts. The analysis confirms earlier findings that the implementation delays inherent in infrastructure projects reduce short-run multipliers in most cases. In contrast, long-run multipliers can be sizable when government capital is productive. Moreover, these multipliers are greater if the economy starts from a point below the socially optimal amount of public capital. Turning to empirical estimation, I use the theoretical model to explain the econometric challenges to estimating the elasticity of output to public infrastructure. Using both artificial data generated by simulations of the model and extensions of existing empirical work, I demonstrate how both general equilibrium effects and optimal choice of public capital are likely to impart upward biases to output elasticity estimates. Finally, I review and extend some empirical estimates of the short-run effects, focusing on infrastructure spending in the ARRA.

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1 Introduction

Public capital can play an important role in increasing long-run output and standards of living. Because of nonrivalry in consumption and/or non-excludability in use, the private sector will tend to underprovide key types of productive capital. Hence, there is a role for government to raise social welfare by providing public capital, even when it must tax private resources to finance it. Economic history is replete with examples of public capital, and infrastructure in particular, that had significant impacts on long-run GDP and/or welfare. For example, Gordon (2017) highlights the contributions of publicly provided sanitation, clean water, and electrical infrastructure to both the rise in life expectancy and increase in productivity in the U.S. during the first part of the 20th Century. In the post-WWII period, the U.S. interstate highway program has been linked to significant increases in productivity and output (e.g. Aschauer (1989), Fernald (1999), Leff Yaffe (2020)).

More recently, government infrastructure spending has also figured prominently in policy discussions regarding short-run stimulus. Government infrastructure spending is viewed by many policymakers as having advantages over government consumption spending for stimulating the economy during a recession. In a traditional Keynesian model, both productive and wasteful government spending stimulate the economy in the short run through standard income and multiplier effects and help push output back to potential output. Government investment spending such as infrastructure spending, however, has the additional advantage that it can change the path of potential output. In particular, if a short-run increase in government spending also raises the stock of productive public capital or long-run total factor productivity (TFP), then government spending provides two benefits: Keynesian demand stimulus in the short run and neoclassical supply stimulus in the long run. These lasting effects are particularly welcome since typically stimulus packages must be financed with an increase in distortionary taxes after the recession is over. If output remains higher because of the long-run effects of more public capital, then the tax base expands and the necessary increases in tax rates are less.

In this paper, I examine the macroeconomic theory and empirical evidence on the benefits of infrastructure spending, both in the long run and the short run. Much of the theory and the empirical work suggests that even when there are substantial long-run benefits of infrastructure investment, the short-run benefits are probably lower than for non-productive government spending. In the last few years, the macroeconomic theory literature has discovered that realistic features of infrastructure investment, such as the importance of time to build and sector-specific demand effects, can work to reduce the short-run aggregate stimulus effects, even when the long-run supply-side benefits are present. Moreover, much of the existing macroeconomic empirical evidence is consistent with the predictions of these theories. I conclude that infrastructure investment may not be the most powerful short-run stimulus.

On the other hand, theory and empirical estimates suggests that public capital and infrastructure spending in particular have had significant positive effects on long-run output and productivity. Whether current levels of infrastructure spending are above or below the optimal level depends on estimates of the production function output elasticity to public capital, as well as considerations of distortionary taxation and heterogeneity in the returns to different types of infrastructure.

The paper proceeds as follows. Section 2 uses insights from both neoclassical and New Keynesian models to study the effects of government investment. The first few subsections present and calibrate both a stylized neoclassical model and a medium-scale New Keynesian model with lump-sum taxation. These sections discuss the economic mechanisms and intuition for how government investment can affect the macroeconomy. Section 2.4 simulates the models and compares the effects of increases in government consumption versus government investment and presents short-run multipliers. It shows that government investment and consumption have similar effects on output in the New Keynesian model, in contrast to the neoclassical model in which government investment has weaker short-run effects. Section 2.5 amends both models to include realistic time-to-spend and time-to-build delays. The simulations from these versions of the model show that these delays dramatically reduce the short-run multipliers, so much so in the New Keynesian model that government investment offers no stimulus for the first few years.

Section 2.6 delves further into the multipliers at longer horizons. Both the neoclassical model and the New Keynesian model produce significantly higher multipliers at longer horizons. The size of these multipliers depends crucially on three key features: (i) the productivity of public capital in the aggregate production function; (ii) whether the increase in public capital moves the economy towards the social optimum or away from it; (iii) and how the public capital is financed.

Section 2.7 summarizes some of the models from the literature that analyzes the effects of government capital, and infrastructure in particular. Several of these models highlight other important features for the short-run effects of government investment, including the behavior of monetary policy.

Section 3 then moves on to the empirical evidence on the long-run effects of public investment in the U.S. After a brief overview of the empirical literature studying the elasticity of output to public capital, I use the stylized neoclassical model of Section 2.1 to demonstrate the types of biases that can arise in estimation the output elasticity to public capital and discuss ways to reduce the bias.

Section 4 surveys the empirical estimates of the short-run effects of government investment spending. Much of the focus is on the ARRA studies, and in particular on the infrastructure part of the ARRA. I offer new estimates of the effects of the ARRA on employment in highway construction.

Section 5 asks the question "is the U.S. underinvesting in public capital?" The analysis compares past and current levels of government capital to the optimal levels implied by the stylized neoclassical model to shed light on this question. Section 6 summarizes some of the key results that emerge from the paper and concludes.

2 Government Investment in Dynamic Macroeconomic Models

This section analyzes the short-run and long-run effects of government investment and public capital in both a stylized neoclassical model as well as a medium scale New Keynesian model. The neoclassical model forms the underlying basis of the New Keynesian model, so the economic mechanisms of the neoclassical model continue to be key drivers of short-run results in New Keynesian models unless they are specifically shut down. The neoclassical mechanisms are the drivers of the long-run benefits of public capital since the New Keynesian elements affect the economy only in the short run.

I use simulations of the models to illustrate several important insights from the recent literature studying the short-run effects of government investment. The first two are from the Leeper, Walker, and Yang (2010) analysis of government investment in an estimated medium-scale neoclassical model. First, if government investment is productive, then the negative wealth effect of increased taxation is muted by the positive wealth effect of future productive public capital. As a result, in the short run output may respond less to an increase in government investment than to government consumption. Second, government investment in public capital, and particularly infrastructure, typically involves implementation delays and these delays severely mute the short run multiplier. The third insight is from Boehm (2019) who notes that the long service life of private capital leads to a very high intertemporal elasticity of substitution in investment demand. Because investment rates are typically small relative to the capital stock, agents are very willing to intertemporally substitute investment, much more so than for consumption. The fourth insight is about the importance of the initial level of public capital relative to the socially optimal level. Long-run multipliers are higher if the economy is starting below the optimal level of public capital.

The models I study in this section treat all public capital the same, and do not incorporate features that are unique to infrastructure. However, the basic mechanisms at work in the models apply to any type of public capital that appears in the production function. In Section 2.7, I discuss some of the models that specifically incorporate the benefits of transportation infrastructure.

2.1 A Stylized Neoclassical Model

Most of the macroeconomic analysis of government investment builds on the pioneering work of Baxter and King (1993), who were the first to analyze both the short-run and long-run effects of government investment in a fully dynamic general equilibrium neoclassical macroeconomic model.[1] In the typical neoclassical model, government purchases have direct impacts on the economy in several ways. Let G_t^C denote government consumption goods purchases in period t and let G_t^I denote government investment goods purchases. The sum of government purchases has a direct impact through the economy-wide resource constraint:

$$C_t + I_t + G_t^C + G_t^I \leq Y_t \tag{1}$$

1. Baxter and King's (1993) model considers only effects on steady-state levels, not on growth rates. Other strands of the literature have studied the growth consequences of public capital in endogenous growth models. See for example the important papers by Glomm and Ravikumar (1994, 1997)

C_t is private consumption, I_t is private investment, and Y_t is output. This resource constraint is key to the wealth effects that drive the labor and output response in neoclassical and benchmark sticky price New Keynesian models. A government that purchases goods and services extracts resources from the economy. Financing through current or future lump sum taxes adds no additional effects, so the resource constraint captures the key impacts. If there is no direct effect of government spending on the production possibilities of the economy, a rise in government purchases leaves the private sector with fewer resources. Households respond by lowering their own consumption and leisure and raising their labor supply. Employment rises not because the demand for labor has risen (since government spending does not directly affect the aggregate marginal product of labor) but because labor supply has risen. The rise in labor supply induced by the wealth effect is the key mechanism by which an increase in government purchases raises output in the neoclassical model and the benchmark New Keynesian sticky price model. In fact, as Broer et al. (2020) show, the benchmark New Keynesian model achieves higher multipliers than the neoclassical model by adding an additional negative wealth effect that stems from countercyclical markups and profits.

While government consumption and government investment enter symmetrically in the resource constraint in equation 1, they play different roles in the rest of the economic structure. Most modelers assume that government consumption enters household utility, but in a separable way, so that it has no impact on the marginal utility of consumption.[2] In this case, there is no additional impact of government consumption on the economy, other than raising household welfare.

To be concrete, suppose that a representative household maximizes lifetime utility U:

$$U = E_0 \sum_{t=0}^{\infty} \beta^t \left[\ln C_t - \nu \frac{N_t^{1+\phi}}{1+\phi} + \Gamma(G_t^C) \right] \tag{2}$$

2. Important recent exceptions include Ercolani and Valle e Azevedo (2014) and Sims and Wolff (2018). Both papers incorporate public capital and also allow government consumption to affect the marginal utility of private consumption. Gallen and Winston (2019) argue that government investment in transportation infrastructure can also affect utility because a higher stock of transportation infrastructure leads to time savings for the household by reducing time spent commuting to work and time spent traveling to shop.

β is the discount factor. This functional form is now widely used in macroeconomic models. Utility depends on the logarithm of consumption, C_t, and a CES function of hours worked, N_t. ϕ is the inverse of the Frisch elasticity of labor supply.

Government investment, on the other hand, can have direct effects on the production function. Baxter and King (1993) specify a stylized Cobb-Douglas aggregate production function:

$$Y_t = A_t K_{t-1}^{\alpha} N_t^{1-\alpha} \left(K_{t-1}^G\right)^{\theta_G} \tag{3}$$

A_t is the level of total factor productivity (TFP), K_t is the private capital stock at the end of period t, K_t^G is the public capital stock at the end of period t, and N_t is the quantity of labor. Typical analyses assume constant returns to private inputs, which is also assumed here. The size of θ_G, the exponent on public capital, plays an important role in the long-run impact of government investment, which can have consequences for its short-run impact as well. If θ_G is greater than zero, then in this calibration there are increasing returns to scale.

Note that virtually all of the short-run effect of government spending on output must operate through labor input for the following reason. Both private and public capital are relatively fixed in the short run, so if government spending does not affect TFP (A_t) in the short run, government spending can raise GDP in the short run only to the extent that it raises labor input.

Finally, government investment and public capital are linked since government investment this period adds to the public capital stock available at the beginning of next period:

$$K_t^G = G_t^I + (1-\delta_G)K_{t-1}^G. \tag{4}$$

δ_G is the depreciation rate on public capital. Since government investment is typically a small fraction of the steady state stock of public capital, it takes numerous periods of elevated government investment to raise the public capital stock a noticeable amount. The capital accumulation equation for private capital is similar:

$$K_t = I_t + (1-\delta)K_{t-1}, \tag{5}$$

where δ is the depreciation rate on private capital.

Equation 3 and 4 capture the distinguishing characteristics of government investment relative to government consumption. A dollar increase in government investment raises the stock of public capital through equation 4, which has multiple effects on the production function in equation 3. First, for given TFP, private capital, and labor, the higher public capital stock leads to higher output. Second, because the higher public capital stock raises the marginal products of both private capital and labor, it incentivizes firms to invest in more capital and hire more labor. In the neoclassical model, the only type of government spending that raises the demand for labor is government spending that directly raises TFP or public capital.

How the government spending is financed has first-order effects on the response of output and labor. The simplest assumption, and the one that gives the highest multipliers, is that the government uses lump sum taxes. The government budget constraint is given by:

$$G_t^C + G_t^I = T_t \tag{6}$$

where T_t is lump sum taxes. In the representative household, perfect financial markets, and rational expectations case, the timing of the lump sum taxes has no effect: deficit spending with later increases in lump sum taxes is equivalent to balanced budget lump sum taxes. In this case, the social planner solution is equivalent to the decentralized competitive equilibrium. In the more realistic case that the government must raise distortionary taxes, the timing of those taxes matter and the positive effects of government spending on output can be severely muted.

In this benchmark economy, the social planner chooses sequences C_t, N_t, I_t, Y_t, and K_t to maximize the lifetime utility of the representative household given in equation 2, subject to the economy-wide resource constraint in equation 1, the production function in equation 3, the capital accumulation equations in equations 4 and 5, as well as exogenous processes for the two types of government spending. In principle, the social planner can also choose the level of public capital to maximize social welfare. Since the simulations involve exogenously varying public investment, public capital is taken as exogenous for now. As I will show below in Section 2.6, the multiplier depends on where public capital starts relative to the optimal level.

The first order conditions and steady-state conditions for this model are presented in the appendix.

2.2 A Medium-Scale New Keynesian Model

Many policymakers have advocated infrastructure spending to jumpstart an economy during a downturn, so it is important also to consider the effects of public investment in a model that captures traditional Keynesian notions of slack resources and income multipliers in the short run. Therefore, I also construct and simulate a model that incorporates some key Keynesian mechanisms.

I do not use the benchmark New Keynesian model, which features sticky prices but flexible wages, because recent work on heterogeneous agent New Keynesian models has revealed that the sticky price assumption raises multipliers through a very implausible mechanism. Broer et al. (2020) demonstrate that labor supply rises more in response to demand shocks in a benchmark NK model than in a neoclassical model because of an additional negative wealth effect. In particular, sticky prices lead to countercyclical markups and countercyclical profits, causing households to raise their labor supply in response to the additional negative wealth effect. Adding noncompetitive labor markets and sticky wages causes labor to be demand-determined so this implausible mechanism is shut down or at least muted even when the model also includes sticky prices.

The model I use expands on the influential Galí, López-Salido, and Vallés (2007) study of the response of consumption and output to government consumption spending in a NK model. Their model includes capital adjustment costs, sticky prices, noncompetitive labor markets, rule-of-thumb consumers, monetary policy rules, and government debt feedback rules featuring lump-sum taxes.

I extend their model by (i) adding government investment spending and public capital; (ii) adding sticky wages (following Colciago's (2011) extension of Galí et al. (2007)); (iii) replacing private capital adjustment costs with investment adjustment costs; and (iv) allowing variable private capital utilization. These last two features are now widely used in medium-scale NK models.

To be specific, the NK model used here superimposes the following features on the simple stylized neoclassical model presented in the last section.

- **Adjustment costs on investment**. This feature appears in many medium-scale NK models, but it can also be added to a neoclassical model.[3] For the typical government spending process used in most simulated models, adjustment costs on investment severely mute the short-run crowding-out effect on private investment and raise multipliers, an effect that has been overlooked by much of the literature.

- **Variable utilization of capital**. This feature allows firms to vary their utilization of capital (at a cost), so that capital services are more cyclical than the capital stock. The result is more elastic output supply since it mutes the diminishing returns to labor and prevents real marginal cost from increasing much when output rises. There is ample evidence that capital utilization varies significantly over the business cycle (e.g. Shapiro (1993)). This feature is not uniquely NK since it can also be added to a neoclassical model. It is a way to capture the more elastic supply curves that might characterize an economy with slack resources.

- **Sticky prices and noncompetitive product markets**. This feature characterizes even the simplest textbook New Keynesian model. In the simplest version of the NK model, this assumption is the only deviation from the neoclassical model (along with the accompanying monetary policy rule). It is assumed that firms are monopolistically competitive and a face a Calvo-style (1983) adjustment cost on prices.

- **Sticky wages and noncompetitive labor markets**. Following Colciago (2011), I assume that households mark up wages over the marginal rate of substitution and that they face Calvo-type (1983) adjustment costs. Most medium-scale NK models include both sticky wages and sticky prices.

- **Rule-of-Thumb Consumers**. In order to generate larger Keynesian effects of temporary income on consumption, I adopt Galí et al.'s (2007) assumption that a certain fraction of consumers neither borrow nor save and simply consume all

3. See, for example, Leeper et al.'s (2010) study which I will discuss in more detail below. For various reasons, investment adjustment costs are generally favored over capital adjustment costs, though in many instances the two types of adjustment costs produce similar results.

of their current income. More recent heterogeneous agent models use more sophisticated modeling and call the behavior "hand to mouth" but the effects are similar in many instances. The other consumers are assumed to be fully optimizing, forward-looking, and owners of all of the capital in the economy.

- **Elastic Labor Supply.** This feature is based not on an addition to the neoclassical model but rather on the calibration of a particular parameter. As I will discuss in more detail below, in both the neoclassical model and the NK model, I will allow the Frisch elasticity and the Hicks elasticity of labor supply to be significantly greater than implied by the micro estimates. This assumption facilitates a higher elasticity of supply, roughly mimicking the situation of an economy with slack and leading to higher multipliers for government spending.

- **Monetary policy and fiscal policy rules**. The monetary and fiscal policy rules follow Galí et al. (2007). The monetary authority follows a Taylor rule that responds only to inflation. Lump-sum taxes respond to both the deviation of government debt and government spending from their steady-state values.

The appendix shows more details of this NK model.

2.3 Calibration of the Models

Even the simple neoclassical model presented earlier cannot be solved analytically unless the depreciation rate on capital is set at 100 percent, so we must analyze the models quantitatively.

Both the neoclassical and New Keynesian (NK) models are calibrated to be quarterly. The calibrated parameters with their descriptions is shown in table 1. Consider first the shared parameters. For utility in equation 2, the discount factor β is set to 0.99, which implies an annual real interest rate of 4 percent. ϕ is set to 0.25, which implies a relatively high Frisch intertemporal elasticity of labor supply of 4. This high value is set both to match Baxter and King's (1993) calibration in the neoclassical model and to generate a high elasticity of labor supply for the NK model.[4] As I will show, a lower value of the Frisch elasticity implies a lower value of the multiplier.

4. Baxter and King (1993) specify a utility function with the log of leisure rather than the direct hours term included above. Their calibration of the parameter on log leisure implies a Frisch elasticity of 4. See footnote 2 of Shimer (2009) for a demonstration.

In the production function equation 3, the capital share α is set to 0.36. I follow Baxter and King (1993) and Leeper et al. (2010) and set the parameter on public capital at $\theta_G = 0.05$. I will also consider higher values in the range produced by the meta-analysis by Bom and Ligthart (2014), who find a mean estimate of 0.08 in the short run and 0.12 in the long run. I set the depreciation rates to those implied by BEA data in 2018, calculated as the ratio of current cost depreciation of fixed assets to the stock of fixed assets at the end of the previous year.[5] The ratio yields an estimate of quarterly depreciation rates of $\delta_G = 0.01$ and $\delta = 0.015$.

For the medium-scale model, I set the investment adjustment cost parameter and the utilization cost parameters similar to the values estimated by Leeper et al. (2010). The steady-state wage and price gross markups are set to 1.2 and the Calvo probability of not being able to adjust prices or wages is set to 0.75, which corresponds to an average price and wage duration of one year. Following Galí et al. (2007), I assume a high fraction of rule-of-thumb consumers, 50 percent of the population. More details on the calibration of the medium-scale model are provided in the appendix.

In the simulations, the economy starts from an initial steady state in which total government spending is 17.5 percent of GDP, the value in 2019. Of that, government investment spending is 3.5 percent of GDP, similar to the actual ratio in 2019.

Government spending is driven by appropriations shocks. As in Leeper et al. (2010), I assume that appropriations, *AP*, follow a standard first-order autoregressive (AR(1)) process:

$$AP_t = \text{constant} + \rho \cdot AP_{t-1} + \epsilon_t \tag{7}$$

Like Leeper et al. (2010), I assume an AR(1) process for government spending with a serial correlation parameter 0.95, which involves a very persistent increase. Since multipliers are higher the more persistent the change in government spending, the multipliers I report below are higher than the ones that I would find for a less persistent increase in government spending.

The experiments are designed to compare the effects of government investment shocks to government consumption in both the stylized neoclassical model as well as the New Keynesian model and variations on those models. Most important, the exper-

5. The data are from the fixed asset tables at bea.gov.

iments highlight the significant dampening of multipliers when there are implementation delays.

2.4 Experiments with No Implementation Delays

In this section, I compare the effects of an increase in government investment to an increase in government consumption in both the neoclassical and the New Keynesian models. With no implementation delays, government spending is equal to appropriations, i.e.:

$$G_t^J = AP_t \text{ for } \quad J = C, I \tag{8}$$

Figure 1 compares the effect of an increase in government consumption to an increase in government investment in the stylized neoclassical model. For both experiments, the path of government spending is the same, with only the type varying across experiments, so the two lines lie on top of each other in the upper left graph. The rest of the graphs show the endogenous response of key variables to an unanticipated increase in government consumption or government investment that is autocorrelated. Government spending, output, consumption, private investment, and public capital are expressed in deviations from their own steady state values as a percent of steady-state output. Labor input and wages are percent deviations from their own steady state values. The real interest rate is annualized percentage points deviations from its own steady state.

Consider first an increase in government consumption, whose effects are depicted by the solid line. As discussed above, the direct effect is a negative wealth effect on consumption and leisure. The government is extracting resources from the economy, so consumption falls and labor supply rises. This rise in the labor supply boosts output, with an impact multiplier of 0.47. Private investment spending is crowded out. There is no change to public capital. All values eventually return to their original steady-state levels since the government spending increase is not permanent.

The effect of an increase in government investment is shown by the dashed line. In this case, the impact effect on labor, consumption, and output is somewhat less than for a government consumption increase. A muted negative wealth effect is key to this difference: the government is still extracting the same amount from current output, but it is now using it to build up wealth in the form of productive capital.

Private investment falls more during the first two years than in the government consumption case. The weaker wealth effect on labor means that output rises less in the short-run, so more private spending must be crowded out by the government spending. The same weaker wealth effect means that households do not reduce their consumption as much, so the brunt of the crowd-out falls on private investment. The differential short-run response of consumption and investment is a key theme in Boehm's (2019) analysis of the short-run multipliers on government consumption versus government investment. The long service life of private capital leads to a very high intertemporal elasticity of substitution in investment demand.[6]

As the public capital stock is built up, output remains high. Labor input remains high and private investment recovers since the higher level of public capital raises the marginal products of both labor and private capital. Not shown in the figure are the results when the exponent on public capital, θ_G, is 0.1 rather than 0.05. These effects are similar, though the muted wealth effect is a little more evident in the short-run and the positive stimulus is more evident in the intermediate run.

Table 2 shows the undiscounted cumulative multipliers for the first year, since this horizon is relevant for stimulus spending. Following Mountford and Uhlig (2009), these multipliers are the integral of the impulse response of output divided by the integral of the impulse response of appropriations up to four quarters.[7]

The top panel of Table 2 shows the short-run cumulative multipliers for this stylized neoclassical model ("baseline") as well as for two permutations. The first year multiplier for government consumption in the baseline neoclassical model is 0.5 and for government investment is 0.4. Thus, the short-run multiplier is lower for government investment in the baseline neoclassical model. The lower multiplier owes to the smaller negative wealth effect because households anticipate that their public capital will increase. I will discuss the last column later.

The second and third rows show multipliers for two variations on the stylized neoclassical model. The second row of the table shows that both the government consumption and investment multipliers fall dramatically when the Frisch elasticity is set to value equal to the micro estimates of 0.5 rather than the baseline calibration of 4. On the other hand, the third row shows that adding investment adjustment costs and

6. In Boehm's model there is even more crowding out because consumption goods and investment goods are produced in different sectors and there is imperfect labor mobility between sectors.

7. Because of the short horizon, discounting has only a small effect. In a later section that looks at longer horizon multipliers, I present both integral and discounted multipliers.

variable capital utilization to the baseline model raises the multiplier. The main effect comes from the investment adjustment cost, which hinders the crowding out effect on investment. In this version of the model, there is no difference in the first-year multipliers for government consumption and government investment.

Figure 2 shows the same experiments in the New Keynesian model. The solid lines show the effects of government consumption and the dashed lines show the effects of government investment. As discussed earlier, I included features and calibrated the model specifically to mimic slack in order to raise the short-run multiplier significantly.

The impact effect on output is almost 1.3 percent for an increase in government consumption. The combination of a high fraction of rule-of-thumb consumers with imperfect labor markets counteracts the negative wealth effect on the consumption of optimizing consumers and creates a rise in aggregate consumption, as first demonstrated by Galí et al. (2007). Private investment is not crowded out because of the adjustment costs on investment. Labor input rises robustly since it is demand-determined. The rise in labor earnings increases the consumption of the rule-of-thumb consumers.

Labor input rises by the same amount when the shock is to government investment, as shown by the dashed line. The wealth effect mechanisms in the neoclassical model that dampened the labor supply response to government investment shocks relative to government consumption in the short run are absent in this model. The other variables have a slightly more positive response to government investment than to government consumption. Output, consumption, and capital utilization all have slightly higher impact responses. As public capital is built up, private investment rises and real wages recover.

The bottom panel of Table 2 shows the first year multipliers for the New Keynesian model with $\theta_G = 0.05$. In the baseline NK model, the first-year multiplier for government consumption is 1.06 and for government investment is 1.12. The remaining rows show the multipliers for variations on the baseline NK model. Eliminating adjustment costs on investment and variable utilization significantly reduces both the government consumption and investment multipliers, so that they are even smaller than the baseline neoclassical model. I will summarize the mechanism since I have not included graphs for these alternative parameterizations. Without adjustment costs on investment, investment is significantly crowded out on impact, much more so than even the baseline neoclassical model. As a result, labor demand responds little on impact and only slowly rises thereafter. Real wages are approximately constant, so there is no increase in earnings to spur the consumption of the rule-of-thumb consumers. The multiplier ends up being less than in the neoclassical case because the NK model mutes the negative wealth effect on labor supply from the expected future taxes. The remaining rows show that using a lower Frisch elasticity or assuming no rule-of-thumb households also reduce the multiplier relative to the baseline case. All of the variations shown reduce the multiplier below unity.

There are three main findings from this analysis. First, in the neoclassical model the short-run government consumption multiplier is somewhat higher than the government investment multiplier. Second, in the New Keynesian model, government investment multipliers are slightly above government consumption multipliers. Third, both models are sensitive to the calibration of the Frisch labor supply elasticity and the presence of investment adjustment costs and variable capital utilization. The size of multipliers depends crucially on these features of the model.

2.5 Experiments with Time to Spend and Time to Build

Leeper et al. (2010) highlight two important limitations to the stimulus effects of government investment: implementation delays and future fiscal financing adjustments involving distortionary taxation. They estimate a more elaborate neoclassical model and consider the effects of these two additions. Each serves to diminish the multipliers. Since the negative effects of distortionary taxation are already well-known, I will focus on the more novel feature of implementation delays.

As Leeper et al. (2010) point out, typically there are delays between appropriations and actual outlays. In addition, many infrastructure projects do not become part of productive capital stock until the project is completed (e.g. a bridge). While routine maintenance of roads may involve delays of a year between appropriations and completion, new highways, roads and bridges can involve delays of four years.

The American Recovery and Reinvestment Act (ARRA) illustrates how difficult it is to fast-track infrastructure project investment. The ARRA stimulus package specifically targeted "shovel-ready" projects because of the urgency for immediate government spending. Even then, there were significant delays between the appropriations, the outlays and the actual use of the new infrastructure.

Figure 3 shows the cumulative spending as a percent of Federal Highway Administration appropriations in the ARRA. These data are aggregated from Leduc and Wilson's

(2017) state-level annual fiscal year data.[8] The ARRA was passed in February 2009, but by the end of June 2009 only 11 percent had been spent. By the end of June 2010, just over half had been spent. The cumulative spending did not approach 100 percent of appropriations until the end of June 2012. The mean (and median) duration of recessions in the U.S. postwar period is 11 months, so most infrastructure stimulus would not be spent by the end of the recession. On the other hand, the unemployment rate often remains elevated for several years after a recession; for example, the unemployment rate was still 8.2 percent in mid-2012. Thus, it is possible that delayed spending might still be useful as a stimulus in a severe recession.

I now illustrate Leeper et al.'s (2010) insight about implementation delays in the context of my models. I allow for both of Leeper et al. (2010) delays: a delay between appropriations and outlays, which I call *time to spend*, as well as a time-to-build delay. The time-to-spend delay is captured by lags between appropriations and government investment spending as follows:

(9)
$$G_t^I = \sum_{n=1}^{N} \omega_n AP_{t-n}$$

Note that because the summation begins at n=1, there is a one-quarter delay between the appropriation and the start of spending. When the appropriation is passed, households and firms have perfect foresight about the future path of government spending. Thus, these delays create "news" effects that can show up in behavior before government spending actually changes.

The time-to-spend feature is modeled in the following replacement equation to equation 4:

(4')
$$K_t^G = AP_{t-N} + (1-\delta)K_{t-1}^G$$

8. All but four states have fiscal years that end on June 30th. The remaining four states, which accounted for 18 percent of the appropriations, have fiscal years that end on September 30th. Since the data are not available at higher frequency, I follow Leduc and Wilson and simply aggregate across the states and show dates on the graph that are the ending quarters for the fiscal years of the majority of the states.

I set N = 6 quarters and assume that $\omega_n = 1/6$ for each $n = 1, ..., 6$ to roughly match the peak and cumulative spending of the ARRA on government grants.[9]

Figure 4 shows the impact of government investment both with and without time to spend and time to build in the NK model. The dashed line repeats the no-delay case shown in Figure 2. The dashed line with circles shows the responses when there are implementation delays. The impact of delays is dramatic. Rather than jumping 1.3 percent on impact, output now falls slightly for a quarter before rising to a peak of around 0.9 after almost two years. Rather than rising, private investment falls slightly during the first year because of the slower buildup of the public capital stock. Without the short-run increase in employment or real wages, rule-of-thumb households do not raise their consumption. As a result the negative wealth effect on the optimizing households dominates and pushes down aggregate consumption. Thus, the time-to-spend delay knocks out the initial positive response seen in the no-delay case and the time-to-build delay slows down the positive effects of the eventual rises in public capital.

The last column of table 2 shows the multipliers for the case of delays. Recall that all of the multipliers are calculated relative to the integral of the appropriations response, which is identical to the no-delay government investment response but different from government investment spending when there are time-to-spend delays. In all variations of the neoclassical models and the NK models, the delay reduces the multiplier, dramatically in most cases. With delays, the neoclassical model produces greater multipliers than the NK model, though they are all still below 0.4. The features that helped the NK model produce high multipliers in the case of no delays produces 0 or negative multipliers in the case of delays.

In short, in the presence of implementation lags multipliers fall to zero or even negative values.

2.6 More on Multipliers

This section covers three important additions to the discussion of multipliers from the last section. First, it presents the multipliers for longer horizons for the various models. Second, it discusses how multipliers depend crucially on the government investment-to-output ratio relative to the social optimum. Third, it adds a reminder of the importance of how public capital is financed.

9. BEA NIPA series show quarterly ARRA capital grants-in-aid to states peaking in in 2010Q3 and cumulative spending at 50 percent of the total.

Figure 5 shows the present discounted value cumulative multipliers for the first 20 quarters for government consumption, government investment when $\theta_G = 0.05$ (short dashed line) and when $\theta_G = 0.1$ (long dashed line). As before, the denominator is appropriations not spending. The top panel shows results for the neoclassical model. With no delays, the government investment multipliers are lower than the government consumption multipliers for the first ten quarters, but then exceed them by increasing amounts as time goes on. The government investment multiplier is lower in the short run when capital is more productive (e.g. θ_G is higher), since the negative wealth effect that raises labor supply is even more muted when that capital is more productive. With 6-quarter time-to-spend and time-to-build delays in government infrastructure investment, the output multiplier for government investment is less than the multipliers for the government consumption for longer. Thus, evaluated only by the short-run multiplier, government infrastructure investment is inferior to government consumption investment in its potential to stimulate the economy.

The New Keynesian model results are reversed relative to the neoclassical model in the short run for the case in which there are no delays. Government investment multipliers are higher and more productive public capital leads to higher multipliers. However, delays work against the NK mechanisms and make the multipliers on government investment much lower than for government consumption for the first several years.

Table 3 shows the long-run multipliers for each of the cases. Here is where government investment spending has its great advantages. Consider only the top half of the table for now. While the present value long-run multiplier for government consumption ranges from 0.4 in the neoclassical model to 0.9 in the New Keynesian model, it ranges from 1.3 to almost 2 when $\theta_G = 0.05$ and from 2 to almost 3 when $\theta_G = 0.1$. Time-to-spend and time-to-build delays do not have much effect on the long-run multipliers. Discounting has noticeable effects, as illustrated in the last columns showing undiscounted integral multipliers. In those cases, the government investment multiplier is higher and the neoclassical multiplier is not as far below the New Keynesian multiplier.

All of the multipliers I have shown, however, are based on raising government investment spending relative to a steady state with the government investment-to-output ratio of 3.5 percent, which was calibrated to the value for the U.S. in 2019. Leeper et al. (2010) calibrated their values similarly. It turns out that the multiplier depends significantly on whether the steady state value of the government investment to GDP ratio is above or below the socially optimal value of public investment.[10]

The expression for the optimal steady-state ratio of government capital and investment to GDP in the neoclassical model are:[11]

$$\frac{K_G}{Y} = \frac{1}{\beta^{-1} - 1 + \delta_G} \cdot \theta_G \tag{10}$$

$$\frac{G^I}{Y} = \frac{\delta_G}{\beta^{-1} - 1 + \delta_G} \cdot \theta_G \tag{11}$$

Recall that K_G is public capital, G^I is government investment, Y is output, β is the discount rate of the representative household, δ_G is the depreciation rate on public capital, and θ_G is the exponent on public capital in the aggregate production function. The economic intuition is straightforward: the higher is the intrinsic productivity of public capital, the greater should be the ratio of public capital to output and hence the higher the steady-state ratio of public investment to output to maintain that level. Using the calibration from the stylized model, the fraction multiplying θ_G in the capital ratio equation is equal to 49 (if output is measured quarterly) or 12.5 (if output is annualized), and in the investment ratio equation is 0.49. If $\theta_G = 0.05$, as in the baseline calibration of the model, the optimal public investment to output ratio is 2.5 percent; if $\theta_G = 0.1$, it is 5 percent. Thus, the simulations of the previous sections are all based on starting from a point at which the steady-state government investment-to-GDP ratio is above the social optimum if $\theta_G = 0.05$ but below the social optimum if $\theta_G = 0.1$.

The bottom half of table 3 illustrates the impact on the multipliers if the simulations are re-run starting from a steady state in which the government investment to GDP ratio is much lower, 1.5 percent rather than the 3.5 percent of the top half of the table. Consider first the simulations for $\theta_G = 0.05$. The present discounted value multipliers in the bottom half of the panel are 60 to 80 percent greater, depending on the model. For example, with no delays the NK multiplier is 1.8 when the economy starts out at the higher government investment to output ratio, but 3.2 when it starts out at the lower ratio. The undiscounted multipliers are 90 to 110 percent higher.

10. I am indebted to Chris House for suggesting I explore this possibility.
11. See the appendix for the derivation of these equations.

The changes are even more dramatic when $\theta_G = 0.1$. The optimal ratio of government investment to GDP is 5 percent, so the starting point of the economy at 1.5 percent is very far below the optimum. In this case, present discounted value multipliers and undiscounted multipliers roughly double.

In sum, these results illustrate the importance of considering where the economy starts relative to the socially optimal amount of public capital in evaluating multipliers. In the long run, multipliers will be substantially higher if the economy starts from a steady state in which the government investment ratio to GDP is below the social optimum. In the short run, the effects are smaller and can be flipped if there is a wealth effect on labor supply.

Finally, it is important to remember that all of the simulations are based on the assumption of non-distortionary lump sum taxes to pay off the government debt. This assumption was made in part to capture short-run multipliers relevant for stimulus programs that are financed by deficits in the short run. Adding more realistic distortionary taxation at longer horizons, however, dramatically lowers the multipliers. For example, Leeper et al. (2010) show that in the baseline no-delay case with $\theta_G = 0.05$ of their model, the present-value cumulative multiplier for government investment is 0.39 when taxes are distortionary but 0.93 when they assume counterfactually that taxes are lump sum.

2.7 Comparison to the Literature

This section overviews some of the results from models in the literature. I first discuss reasons for any differences relative to the results of my simulations. I then briefly discuss the rich models from the transportation and trade literatures that incorporate more of the details of transportation infrastructure. Finally, I discuss the importance of monetary accommodation and the zero lower bound on interest rates for the size of short-run multipliers.

Table 4 summarizes multipliers from four neoclassical analyses of the effects of government spending. Baxter and King's (1993) long-run multipliers illustrate the amplifying effects of permanent increases in government spending and higher productivity of capital on multipliers. Leeper et al.'s (2010) multipliers illustrate the dampening effect of distortionary taxation and lower Frisch elasticities on multipliers. Nevertheless, the result that the long-run multiplier for government investment is greater than for government consumption in a neoclassical model is robust to these details.

The third panel of table 4 shows details of the work of Ercolani and Valle e Azevedo (2014), who estimate a medium scale model that has many features similar to a New Keynesian model (such as price and wage markups) but no nominal rigidities. Their paper is unique in its estimation (rather than calibration) of θ_G. They estimate a value of $\theta_G = 0.09$, though they favor results from an alternative model in which they set θ_G to be 0, implying that public capital is unproductive.

The final panel of table 4 shows details of recent work by Gallen and Winston (2019), which represents an important step forward in the way it incorporates features unique to transportation infrastructure into a dynamic macroeconomic model. They include time-to-build delays, short-run disruptions of construction to the utilization of existing infrastructure, and the beneficial effects of improved transportation infrastructure on household time savings. Their model implies that infrastructure spending is not a good short-run stimulus, even when the long-run benefits are very positive.

Not shown in the table are the important models from the geography of trade literature, which takes transportation costs and spatial features seriously in modeling the potential benefits of transportation infrastructure. The quantitative analyses in these models directly model and measure the extent to which transportation infrastructure reduces trade costs between two points, opens access to markets, and allows for a variety of spillovers, agglomeration effects, and congestion effects. This literature, which is also known as "Quantitative Spatial Economics," has been surveyed recently by Redding and Turner (2015) and Redding and Rossi-Hansberg (2017). Recent contributions include those by Donalson and Hornbeck (2016), who revisit Fogel's (1964) classic analyses of the contributions of railroads to U.S. economic growth; Donalson (2018), who studies the impact of railroads in India during the Raj; and Allen and Arkolakis (2019), who develop a new geographic framework and use it to study the welfare effects of improving each segment of the U.S. highway system.

Table 5 summarizes several analyses from the New Keynesian literature. Many of these studies were conducted in response to the financial crisis and the stimulus programs adopted in response. I now highlight a key result from this literature that was not part of my experiments: the importance of monetary accommodation.

In New Keynesian models, the degree of monetary accommodation has important effects on short-run multipliers. As the Coenen et al. (2012) experiments show, the instantaneous multiplier for a 2-year government investment stimulus is 0.9 for a standard Taylor rule but 1.6 if the stimulus is accompanied by monetary accommodation. When monetary policy is accommodative, the central bank does not raise nominal interest rates to combat inflation. As a result, real interest rates decrease.

The result that government spending multipliers are higher when monetary policy is accommodative is closely linked to the effects of government spending at the zero lower bound (ZLB) of interest rates. When interest rates are at their zero lower bound, the monetary authority cannot lower nominal interest rates. However, carefully timed fiscal spending stimulus that lasts no longer than the zero lower bound period can generate higher expected future inflation. These expectations lower the *ex ante* real interest rate and spur economic activity during the ZLB period. It is this mechanism, identified by Woodford (2011), and others, that can lead to high government spending multipliers at the ZLB.

This same mechanism leads to an unusual additional result, first highlighted by Eggertsson (2011). A negative supply shock, which in normal times would result in a fall in output, is predicted to *stimulate* output during a ZLB period. The negative supply shock generates higher expected inflation, which lowers the real interest rate and spurs demand.

Bouakez, Guillard, and Roulleau-Pasdeloup (2017, 2019) demonstrate that this mechanism can lead to a further reversal of NK results when the economy is at the ZLB. Recall from the earlier simulations that introducing time-to-build delays in public capital drastically lowered the short-run multiplier on government investment spending in the New Keynesian model during normal times. They show, however, that when the economy is at the ZLB, longer time-to-build delays lead to *higher* short-run multipliers. Time-to-build delays prevent increases in the public capital stock (which are a positive supply shock) from occurring during the ZLB period, which helps counter any deflationary pressures. Their impact multipliers are 1.8 for government investment with no time-to-build delay, and 4 for government investment when there is a four-year time-to-build delay.

The possible expansionary effects of negative supply shocks at the ZLB are not just a side show with respect to implications for optimal fiscal policy. The same mechanism also predicts that raising distortionary income taxes (a negative supply shock) at the ZLB is expansionary, as Eggertsson (2011), Woodford (2011), and Drautzburg and Uhlig (2015) demonstrate in both simple calibrated NK models and estimated medium scale NK models. Thus, if ZLB effects generate higher government investment multipliers when there are time-to-build delays, they raise them even more if the spending is financed by increases in current distortionary taxation rather than by deficits. This uncomfortable prediction is probably not understood by many who believe that spending multipliers are higher at the ZLB.

Some recent work has questioned this ZLB mechanism, however. First, Dupor and Li (2015) do not find evidence of the generated inflation effect and Bachmann et al. (2015) do not find an impact of individual consumer inflation expectations on their spending propensities in the Michigan Survey of Consumers. Second, evidence contradicts the prediction that negative supply shocks are expansionary at the ZLB. For example, Wieland (2019) tests this prediction by studying the impacts of the earthquake and tsunami as well as the effect of oil price shocks in Japan, a country which has been at the ZLB for decades. He finds that these negative supply shocks were contractionary, contradicting the prediction of NK theory.

That said, there is some empirical support for higher multipliers being higher during ZLB periods. In Ramey and Zubairy (2018) we estimate multipliers around 1.4 at the ZLB in historical data if we exclude periods of WWII rationing. Miyamoto, Wataru and Sergeyev (2018) apply Ramey and Zubairy's methods to Japan and find higher multipliers at the ZLB, around 1.5 on impact. Further, as discussed below, Boehm (2019) finds some evidence for higher multipliers for government investment spending at the ZLB. Thus, whatever the mechanism, multipliers may be higher at the ZLB.

3 Empirical Evidence on the Long-Run Effects of Public Capital and Infrastructure

This section begins by reviewing some of the leading estimates of the elasticity of output to public capital, with a focus on the long run. It then uses the stylized neoclassical model to illustrate the two leading methodological challenges: (i) the distinction between production function elasticities and general equlibrium steady-state elasticities and (ii) the endogeneity of public capital. I illustrate the econometric problems by estimating the effects of public capital on artificial data generated by a simple extension of the model in Section 2.1. Finally, I discuss a promising way to address the challenges and present some initial estimates that emerge.

3.1 An Overview of Existing Estimates

There is a long literature that seeks to measure the returns to infrastructure investment. An early example is Fogel's (1964) pioneering analysis of the contributions of railroads to U.S. economic development. Several decades later, Aschauer (1988, 1989) famous hypothesis that the productivity slowdown in industrialized countries was caused by reductions in infrastructure investment led to renewed research in this area. He estimated an aggregate production function and found an elasticity of output to public capital of 0.39 in U.S. data. Munnell's (1990) extension of his work found similar results, with elasticities between 0.31 and 0.39. Bom and Ligthart's (2014) excellent literature review discusses the variety of estimates of the production function elasticity of output to public capital and conducts an insightful meta-analysis. Their meta-analysis settles on a mean production function elasticity of output to public capital of 0.08 in the short run and 0.12 in the long-run. They find that the elasticity is higher for public capital installed by local or regional governments and for core infrastructure. The mean estimate of the output elasticity for these latter types of public capital is 0.19 in the long-run.

Cubas (forthcoming) estimates the production function elasticity of output to public capital using information from the national income and product accounts combined with marginal product relationships. He finds an estimate of 0.09 for the U.S. Ercolani and Valle e Azevedo (2014) are perhaps the only researchers to estimate the production function elasticity of output to public capital in a medium-scale dynamic general equilibrium macroeconomics model. They find that when they incorporate both public capital and allow government consumption to be a substitute or complement to private consumption, the estimate of the production function elasticity to public capital is 0.09. Owing to significant uncertainty surrounding that estimate and other indications of model fit, however, their preferred specification is one in which the elasticity is constrained to 0.

The empirical macroeconomics literature tends to focus on estimates of output *multipliers*. Much of the recent macroeconomics literature has focused on short-run effects of general government spending, but several papers also provide estimates for long-run multipliers on government investment spending. For example, Ilzetzki et al. (2013) use structural vector autoregressions on a panel of countries to study the effects of government spending in a wide range of circumstances. They use standard Cholesky decompositions to identify shocks and when they focus on government investment they find multipliers for public investment that ranged between 0.4 in the short-run to 1.6 in the long run.

Some of the most convincing evidence of the productivity of public capital has used regional or industry variation in the U.S. to estimate the output effects of road construction in the U.S. It is important to note that these estimates give only relative effects because aggregate effects are typically taken out by constant terms or time-fixed effects. Fernald (1999) exploits the differences in benefits of the U.S. interstate highway system across industries. He specifically models transportation services as an input into the production function, taking into account the complementarity between vehicles owned by the industries and roads and the difference uses across industries. He finds that industries that rely more heavily on transportation experienced greater increases in productivity than other industries as a result of the building of the U.S. interstate highway system. Using additional identifying assumptions, he translates his relative estimates into a production function elasticity of output to roads of 0.35, an estimate similar to Aschauer's (1989) estimate. However, he argues that the effects are not large enough to be the principal explanation of the productivity slowdown.

Leff Yaffe (2020) uses state panel data and narrative evidence to estimate the output effects of the building of the U.S. interstate highway system, accounting for anticipation effects and crowding-in of state and local spending on roads. His multiplier estimates are significantly affected by the estimated "crowd-in" of state highway spending. In particular, an infusion of funds to a state (instrumented using Bartik-style instruments) typically led to additional road building to connect to the interstate highway system. When he includes the additional state and local spending in the government spending measure, Leff Yaffe's long-run relative multiplier estimate is 1.8.

Leduc and Wilson (2013) estimate the effects of Federal highway grants to states during more recent times using annual state-level data starting in the 1990s. They report various long-run (i.e. 10 year) multipliers. Their favored ones are just under 2.

The estimates are mixed for emerging economies. Cubas (forthcoming) studies the contribution of public capital across countries using a growth accounting framework that specifically incorporates its non-rival features. He finds some contribution of public capital to explaining cross-country income differences, but the magnitude depends on the degree of congestion of public capital. Henry and Gardner (2019) survey the evidence across numerous countries and conclude that in only a minority do infrastructure projects, such as paved roads and electricity, clear the required hurdles. On the other hand, Izquierdo et al. (2019) use a variety of identification methods and samples and find that the multiplier on public investment is very high in countries that start with low levels of public capital.

3.2 Production Function vs. General Equilibrium Output Elasticities

Earlier sections illustrated the importance of the production function elasticity of output to public capital for the effects of government investment. In this section and the next, I highlight two major challenges associated with estimating this key production function parameter. The first is associated with the difference between the production function elasticity and the steady-state general equilibrium elasticity. The second is the problem of the endogeneity of public capital spending. I illustrate the challenges by comparing the approaches used in three leading sets of papers: (1) Aschauer (1989) and Munnell's (1990) static production function estimates; (2) Pereira and Frutos's (1999) and Pereira's (2000) structural vector autoregression (SVAR) estimates; and (3) Bouakez et al. (2017) TFP and cointegrating relation estimates.

Aschauer (1989) and Munnell (1990) and much of the literature that followed estimated their production elasticities using log levels of contemporaneous variables. They regressed the logarithm of aggregate output on the logarithms of contemporaneous values of labor, private capital, and public capital, or transformed the equation to regress productivity measures on public capital. Thus, temporarily leaving aside the endogeneity issues that I will discuss in the next section, they were estimating the production function elasticity, θ_G from the production function in equation 3 from Section 2.1. In log form, that equation becomes:

$$ln(Y_t) = ln(A_t) + \alpha \cdot ln(K_{t-1}) + (1-\alpha) \cdot ln(N_t) + \theta_G \cdot ln(K^G_{t-1}) \tag{12}$$

θ_G is the partial derivative of the log of output with respect to the log of public capital. To estimate the partial derivative, the regression must control for the contemporanous values of the private inputs.[12]

12. See Bom and Ligthart (2014) for a more detailed discussion.

Let us now compare their method and results to the analysis by Pereira and Frutos (1999), denoted "PF" in the following exposition, who used structural vector autoregression (SVAR) to estimate the output elasticity to public capital.[13] PF noted several possible problems with the estimation method of Aschauer and Munnell, including issues of possible spurious regression (e.g. because the macroeconomic variables are nonstationary), omission of dynamic feedbacks, and possible simultaneous equation bias. They sought to address all three of these issues by using a structural vector autoregression (SVAR) to estimate the elasticity of output to public capital. First, they tested and found unit roots in the logs of output, labor, and the two capital stocks. They could find no evidence of cointegration, so they estimated their system in first differences to avoid spurious regression. Second, their use of the SVAR allowed complete dynamics. Third, they allowed for reverse causality from output and the other variables to public capital and identified exogenous movements in public capital as the innovation to public capital not explained by lagged values of the other endogenous variables, i.e., they used a Cholesky decomposition to identify the exogenous shock.

Pereira and Frutos (1999) fully recognized that they were estimating a different elasticity from the one estimated by Aschauer and Munnell. PF's headline number is a long-run elasticity of private output to public capital of 0.63.[14] This elasticity of output to public capital estimated by PF is not, however, the production function elasticity θ_G. The production function elasticity of output to public capital, θ_G, is the elasticity of output to an increase in public capital, holding TFP, labor, and capital constant. There is another elasticity of output to public capital, however, that includes the endogenous response of the private inputs to public capital in general equilibrium. The increase in public capital raises the marginal products of private inputs, which leads to incentives to accumulate more private capital. It is this elasticity that PF estimate. PF's impulse response function estimates show that private capital also rises permanently. (Employment bounces around in the short run, but then returns to a level slightly above its

13. Bom and Ligthart (2014) briefly survey the SVAR studies, but exclude them from their meta-analysis of output elasticity estimates. As I will demonstrate shortly, this was the correct decision given their focus on production function estimates. See Bom and Ligthart (2014) footnote 15 for a list of papers that use SVAR methods.

14. To obtain this number, PF first estimate the impulse responses of all the endogenous variables, including public capital, to their identified exogenous shock to public capital. They then calculate the long-run elasticity (shown in their Table 6) as the ratio of the impulse response of log output at 5 to 10 years to the impulse response of log public capital at 5 to 10 years, since both impulse responses have stabilized at their new levels by that time. Those impulse responses are shown in their Figure 1.

former value.) Because private capital is allowed to respond, PF's elasticity is not the production function elasticity.

The relationship between the production function elasticity and the steady-state output elasticity can be derived from the neoclassical model presented in Section 2.1.[15] In particular, the steady-state output elasticity to government capital, $\epsilon^{SS}_{YK_G}$, is:

$$\epsilon^{SS}_{YK_G} = \frac{1}{1+\Omega} \cdot \left[\Omega + \frac{1}{1-\alpha} \cdot \theta_G\right], \quad \text{where } \Omega = \frac{1}{1+\phi} \cdot \frac{\delta_G \cdot K_G}{C}. \tag{13}$$

$1/(1+\phi)$ is the Hicks elasticity of labor supply, δ_G is the depreciation rate on public capital, and K_G/C is the ratio of public capital to consumption.

If we use the calibration of the baseline neoclassical model from Section 2.1, the relationship is given by:

$$\epsilon^{SS}_{YK_G} = 0.043 + 1.49 \cdot \theta_G. \tag{14}$$

The constant term is positive because, even when public capital is not productive (i.e. $\theta_G = 0$), labor supply increases and consumption falls relative to output because of the negative wealth effects. Thus, the steady-state elasticity of output to steady-state public capital is always greater than the elasticity of output to public capital in the production function. Most of this difference is due to the negative wealth effect raising labor supply and part is due to the induced investment in private capital, which grows as θ_G rises.

We can use this relationship to calculate what PF's estimated elasticity would imply for the value of θ_G. Their long-run elasticity of 0.63 which allows private inputs to respond is the general equilibrium steady-state elasticity. Equation 14 implies that θ_G is 0.39, exactly equal to Aschauer's estimate! Thus, Aschauer's (1989) production function output elasticity maps exactly to Pereira and Frutos (1999) long-run general equilibrium elasticity of output. According to the stylized model, the latter estimate should be larger because private inputs are also responding.

15. This expression incorporates the assumption that the social planner also raises government consumption to maintain a constant steady state government consumption-to-output ratio.

3.3 The Econometric Problem of Endogenous Capital

The endogeneity of public capital is a potentially serious problem, recognized by many researchers. Aschauer (1989) used OLS for his main estimates, but attempted to deal with possible reverse causality by using lagged endogenous variables as instruments. Using lagged endogenous variables as instruments was a common practice in the late 1980s, but is now known to require implausible exclusion restrictions in most macroeconomic applications.

The simultaneity problem occurs because larger and more wealthy economies invest in more public capital. In fact, since a benevolent social planner should choose a level of public capital that maximizes the discounted utility of the representative household, it should respond to technological progress by increasing the amount of public capital.

We can make this point concrete by using what I have called a “DSGE Monte Carlo” (Ramey (2016)). The idea is to simulate artificial data from a DSGE model for which we know the "true" parameters, and then apply an estimation method to the artificial data to see if it can recover the true parameters.

To be specific, I generalize the calibrated neoclassical model to allow the social planner to choose the optimal level of public capital, based on maximizing the discounted utility of the representative household.[16] I use the baseline calibration with $\theta_G = 0.05$. I then allow technology, A in equation 3, to vary. Because an increase in A raises the marginal product of public capital, a social planner will respond by raising public capital. Since I am interested in long-run effects, I calculate how steady-state values of the key variables change with changes in technology.

I estimate a regression similar to the one used by Bouakez et al. (2017). In particular, rather than regressing output itself on the inputs, they use Fernald’s (2014) measure of TFP as the dependent variable. Fernald makes very general assumptions and carefully measures TFP at the industry level using factor shares and then aggregates them to get aggregate TFP. He also adjusts it for cyclical utilization. In the context of the simple aggregate production function in my model, Fernald’s measure is defined as follows:

16. Note that the social planner problem is not concave, since I assume constant returns in the private inputs, so existence and uniqueness are not guaranteed. See Glomm and Ravikumar (1994, 1997) for a thorough analysis of model in which the government chooses the public capital optimally. My explorations with the simple model suggest that there exists a unique maximum of the social planner problem, as long as θ_G is not too large.

$$ln(TFP) = ln(Y_t) - \alpha ln(K_t) - (1-\alpha) ln(N_t) \tag{15}$$

Log TFP is defined as log output less share-weighted log private capital and labor.[17] This definition and the production function from equation 3 above implies the following relationship between Fernald's measure of TFP and public capital:

$$ln(TFP) = ln(A_t) + \theta_G \cdot ln(K_t^G) \tag{16}$$

Thus, Fernald's (2014) TFP measure consists of both true level of technology, ln(A), and the effects of public capital.

Suppose we regress Fernald's log TFP measure on the log of public capital. Since true technology is not observed, it shows up in the error term of the regression, i.e., the ε_t in

$$ln(TFP) = \theta_G \cdot ln(K_t^G) + \varepsilon_t \tag{17}$$

Bouakez et al. (2017) estimate the regression as a cointegrating equation.[18] I will describe more details of their procedure below.

In the artificial data I generate from my model, I calculate the measure of TFP as the log of output minus the share-weighted logs of private capital and labor, just as Fernald does. I set the weights equal to the actual shares from the model. I then regress the log of TFP measure on the log of public capital using the artificial data generated by the model. Recall that I am focusing only on steady-state equilibrium values.

This regression produces an estimate of θ_G equal to 0.64, which is severely biased upward relative to the true value of 0.05. The reason for the upward bias is intuitive. When there is an increase in technology, A, the marginal product of all inputs increases. As a result, private agents increase private capital and the social planner increases pub-

17. Fernald (1999) performs the calculation in growth rates, as is standard for Solow residuals. However, these can be integrated to obtain log levels.

18. As surveyed by Bom and Ligthart (2014), several researchers have estimated cointegrating equations, but the applications were for other countries or panel data across sectors.

lic capital. Thus, the error term ε_t in equation 17 is positively correlated with public capital.

One could in principle solve the problem by using instrumental variables, but it is difficult to find instruments for public capital in aggregate data. Bouakez et al. (2017), however, employ a method that reduces the upward bias significantly. Although they do not discuss endogeneity issues, their method goes far to reduce this type of bias. I now describe their method.

In a short discussion section at the end of their quantitative model paper, Bouakez et al. (2017) review the literature on the productivity of public capital and then present some independent evidence using U.S. aggregate data. They use Fernald's (2014) TFP measure to avoid estimating a complete production function. They then add "it is still important to account for the additional factors that may affect TFP in the long run" (Bouakez et al. (2017), p. 75), but do not explain why it is important. The DSGE Monte Carlo analysis I developed above provides the perfect motivation: any changes in measured TFP (apart from public capital) are likely to lead the government to change public capital endogenously. Thus, in order to reduce the bias in the regression in equation 17, one should control for as many sources of TFP as possible in order to remove them from the error term, ε. Bouakez et al. (2017) construct measures of the stock of research and development spending and the stock of human capital. Their finding of cointegration between the log level of Fernald's TFP, log public capital, log R&D stock and log human capital is strong evidence that they have identified the key drivers of TFP.

Pereira and Frutos (1999) estimated their model in first-differences because they could not find cointegration. Bouakez et al. (2017) analysis shows that more key variables needed to be included. By estimating the cointegration equation, Bouakez et al. (2017) are picking up the long-run, presumably steady-state, relationships because the estimates are driven by the stochastic trends.[19] Bouakez et al.'s main estimates, shown in their Table 2, imply a production function elasticity of output to public capital of 0.065.

We can shed light on the extent to which Bouakez et al.'s procedure reduces the upward bias in actual data. In particular, we can re-estimate their equation, omitting

19. See King et al. (1987) for a discussion of the role of stochastic trends in long-run growth. The 1987 NBER working paper version is much more complete than the 1991 AER version.

the other determinants of TFP (i.e. the R&D stock and human capital stock), and see how the estimated coefficient on log public capital changes.

Using their replication files, I estimate their equation on their data, but omit their controls for TFP. The result is an estimate of the coefficient on the log of public capital of 0.33, in contrast to their estimate of 0.065. My estimate is much higher and is closer to the original estimates of Aschauer and Munnell. The difference between these two estimates is perfectly explained by the type of bias I just demonstrated in my DSGE Monte Carlo. Bouakez et al.'s controls for other factors affecting TFP go far to reduce the bias.

Using these variables as controls, however, may lead Bouakez et al.'s estimates to be *downward biased*. Government investment is likely a key driver of both the R&D stock and human capital, i.e. public capital affects A in the stylized model, so it is not appropriate to simply include these two variables as controls. Thus, their estimate is very likely a lower bound on the value of θ_G.

These exercises have illustrated the difficulties in estimating the production function output elasticity to public capital. Obtaining unbiased estimates is difficult because almost everything is endogenous.

4 Empirical Evidence on the Short-Run Effects of Government Investment in Public Capital

During the Great Recession, government infrastructure spending received much attention because of its possible role in stimulating the economy. The American Recovery and Reinvestment Act (ARRA), enacted in early 2009 in the depths of the Great Recession, used both transfers and government purchases to try to stimulate the economy. Infrastructure spending was an important component of the purchases. The stimulus package specifically targeted "shovel-ready" projects because of the urgency for immediate government spending. As shown earlier in Figure 3, the delays in spending were nevertheless substantial.

As I discussed in Section 2.5, the theoretical evidence suggests that, dollar for dollar spent, government investment spending has lower short-run stimulus effects than government consumption. The next sections review the empirical evidence.

4.1 Aggregate Evidence

Pereira and Frutos (1999), reviewed in detail in the discussion of long-run estimates in Section 3, also studied the short-run effects. They found negative short-run effects of infrastructure spending on employment in all of their specifications. This fact, coupled with the recognition of the delays in investment, led them to recommend against using public investment for short-run stimulus. They argued that it could actually be counterproductive.

As discussed earlier, Ilzetzki et al. (2013) used structural vector autoregressions on a panel of countries to study the effects of government spending in a wide range of circumstances. When they focused on government investment they found multipliers for public investment around 0.4 in the short-run.

The work of Boehm (2019), which I discussed in the last section for its quantitative model predictions, tests those predictions using a panel of OECD countries. Recall that his key economic insight is that government investment should have a lower short-run multiplier than government consumption because the elasticity of intertemporal substitution for investment is much higher than for consumption. This feature means that government investment spending crowds out much more private investment spending than government consumption spending crowds out private consumption. He tests this prediction of his model using a panel of OECD countries from 2003 to 2016. He identifies exogenous shocks to government consumption and investment using a Choleski identification, controlling for forecasts to avoid anticipation effects. He estimates multipliers near zero for government investment and around 0.8 for government consumption. He also finds evidence supporting the mechanisms he highlights in his theory. In particular, he finds that a government consumption shock does not crowd out private consumption, but a government investment shocks significantly crowds out private investment. Consistent with this evidence, he also finds little change in the real interest rate in the consumption goods sector after a consumption shock, but a significant increase in the real interest rate in the investment goods sector.

Boehm also offers some final evidence that provides some support to the models predicting higher multipliers at the zero lower bound. When he estimates his model separately over zero lower bound periods and normal periods, he finds evidence of a slightly higher multiplier for government investment than government consumption during zero lower bound periods. Recall that Bouakez et al. (2017, 2019) showed that at the ZLB, the NK model predicted a flipping of the ranking of multipliers, with government investment multipliers higher at the ZLB. Boehm's point estimates qualitatively support this prediction. The standard errors of the estimates are higher, though, so the estimates are not statistically different from each other.[20]

4.2 Cross-State Evidence

Many of the recent studies have estimated the effects of infrastructure by exploiting variation across states. This is especially true of the studies of the effects of the ARRA. These studies can estimate only relative effects because they exploit subnational data; that is, they answer the question "how much more employment or output occurs in State A when it receives $1 more in spending than the average state?" Thus, the estimates do not provide direct evidence on aggregate effects because, by construction, they net out financing effects and they do not measure the net effects of positive spillovers versus business-stealing effects. Moreover, most do not account for induced state and local spending, so the multiplier estimate may undercount the total government spending required to produce the result. Nevertheless, they provide valuable insight into the underlying mechanisms.

The state employment data is typically much better than gross state product data. As a result, most studies focus on employment effects rather than gross state product effects. This focus is reasonable for short-run studies that are interested in the stimulus effects of government investment.

Leduc and Wilson (2013) estimate the effects of Federal highway grants to states during using annual state-level panel data from 1993 to 2010. Their long-run multipliers were discussed in a previous section. As noted by Ramey (2018), however, their short-run estimated effects do not suggest much stimulus effect. Their Figure 4 shows the effects of state highway spending on state total employment. The impulse response shows little effect on impact or at year 1, but then a significantly negative effect on state employment at years 2 through 5. Thus, their results suggest that highway spending is counterproductive as a short-run stimulus. These results echo those found by Pereira and Frutos (1999) in aggregate data. Gallen and Winston (2019) provide a possible explanation for the short-run negative effects on total employment: highway construction can be very disruptive to the local economy.

20. In the smaller ZLB sample, the government investment multiplier estimate is 1.2 with a standard error of 0.66 for the first four quarters and 0.95 with a standard error of 0.72 for the first eight quarters.

Studies that focused all or in part on the infrastructure elements of the ARRA include Wilson (2012), Chodorow-Reich, Gabriel and Woolston (2012), Leduc and Wilson (2017), Dupor (2017), and Garin (2019). Chodorow-Reich (2019) synthesizes and standardizes the various studies of the ARRA for all types of spending and finds very similar employment multiplier estimates once they are standardized to calculate multipliers the same way. He finds that all of the leading instruments, whether they be Medicaid formulae, Department of Transportation factors, or a mixture of many factors, produce similar results. In particular, he estimates that two job-years were created for each $100,000 spent. As I point out in Ramey (2019), however, these estimates are based on unweighted data and do not take into account crowd-in of state and local spending. Once I make those adjustments, I find that each $100,000 spent led to 0.8 job-years created. These estimates are based on weak instruments, though, since the literature's instruments that are so strong for the ARRA grants are unfortunately weak for spending including additional state and local spending.

Leduc and Wilson (2017) used cross-state variation in ARRA appropriations for highways to study flypaper effects, i.e., whether federal grants for highway construction crowd in or crowd out state and local spending on highways and roads. They found significant crowd in, with each dollar in federal aid resulting in a total of $2.30 in state highway spending. The focus of their paper was the response of state and local spending and how that interacted with rent seeking, but in the appendix they showed regressions of the change in employment in the highway, street and bridge construction industry on the instrumented appropriations. They were able to find a significant positive results in only one case of several. The failure to find positive results echoes my point that the earlier Leduc and Wilson (2013) analysis of highway spending before the ARRA did not find positive effects on total employment in the short run.

As Garin (2019) argues, a positive effect of highway spending on *construction* employment is a necessary condition for any further effects, such as local spillovers and Keynesian multipliers. Therefore, I examine in more detail the impacts of the ARRA highway grants on employment in highway, street and bridge construction, which I will call "highway construction" for short. I use Leduc and Wilson's (2017) data and a similar specification, which they describe in the text associated with Table B1. In particular, the regressions, which use cross-state variation for identification, estimate the effect of ARRA highway apportionments per capita in 2009 on the variables of interest in the succeeding years. I use the baseline sample of 48 states of Leduc and Wilson, and instrument for apportionments with their two road factors. I include their political variables as controls, though I lag them in my local projection specification so that all right-hand side variables are dated 2009 or earlier. I include the change in per capital employment in highway construction between 2007 and 2008 as an additional control for pretrends. I estimate the impulse response in each year using a series of local projection regressions in which the left-hand side variable is the change in the variable of interest from 2008 and year h, where h ranges from 2009 to 2013.

Figure 6 shows the impulse responses for the specification just described. The upper left graph accurately estimates that all of the ARRA obligations occurred in 2009. The upper right graph shows that the outlays occurred mostly in 2009 and 2010. The lower left graph supports the main result of Leduc and Wilson (2017), which is that total highway spending rose by more than the outlays. My new result is the impulse response for highway construction employment, shown in the lower right graph. According to the estimated impulse response function, highway employment barely responds in 2009 and 2010, but then falls significantly after that. These effects are clearly contrary to the intended effects of the ARRA.

Dupor (2017) in "So, Why Didn't the 2009 Recovery Act Improve the Nation's Highways and Bridges" argues that the ARRA did not improve the highways and bridges because the federal grants completely crowded out state and local spending. Thus, Dupor argues for the opposite result of Leduc and Wilson (2017), who find significant crowding in. Dupor notes that the difference might be due to his addition of the logarithm of state population as a control. He does not, however, make clear the econometric motivation for adding this control.

To determine how the results change when log population is included as a control, I add Dupor's log population control in the model I used to estimate the impulse responses shown in Figure 6. The results when the population control is included are shown in Figure 7. The top two graphs are similar to those from the previous specification, but the bottom left graph showing the impact on total highway spending is very different. In contrast to the analogous graph in Panel A, there is no change in total highway spending in Panel B. This result suggests complete crowd out. The highway construction employment effects, however, are similar, with virtually no change in 2009 and 2010 but a significant negative effect in 2011 through 2013. The results obtained by adding Dupor's control variable no longer imply that increases in highway spending lower highway construction employment, but they imply that no change in highway spending lowers highway construction employment.

Neither of the implied stories by Leduc and Wilson (2017) or Dupor (2017) is encouraging for highway grants as a stimulus. In the Leduc and Wilson results, total highway spending rises significantly as a result of the federal grants, but it results in a decrease in employment in highway construction. In the Dupor results, federal grants are ineffective in raising total highway spending, and still highway construction employment falls.

One possible explanation for the puzzling decline in highway construction employment might be a problem with the instruments. However, Chodorow-Reich (2019) tested the overidentifying assumptions using those instruments along with other leading ones from the literature and could not reject the overidentifying assumptions. Thus, this explanation seems less likely.

Garin (2019) finds slightly more positive results. He uses a database on almost 3,000 counties and ARRA spending on highways to estimate the direct effects on overall construction (not just highways) employment, as well as total employment. The biggest effect he finds is in total construction employment in 2010, with six jobs created per $1 million. He finds that each dollar of stimulus spent in a county led construction payrolls to increase by 30 cents over the next five years, an increase that is consistent with the labor share in the construction industry. However, when he tests for general equilibrium effects on local employment and payroll, he estimates effects that are close to zero. He finds no evidence of a local multiplier effect.

In sum, there is scant empirical evidence that infrastructure investment, or public investment in general, has a short-run stimulus effect. There are more papers that find negative effects on employment than positive effects on employment. The ARRA results are particularly negative, since the ARRA spending occurred at a time when interest rates were at the zero lower bound and the unemployment rate was 9 to 10 percent. Despite the slack in the economy and the accommodative monetary policy, the effects on construction employment were either small positive or negative.

5 Is the U.S. Underinvesting in Public Capital?

Numerous commentators have argued that the U.S. is underinvesting in public capital, and particularly in infrastructure. In this section, I shed light on this question with data on trends and insights from the models presented earlier.

Figure 8 shows government capital as a percent of GDP from 1929 to 2018. The data are current-cost net stock data on government capital and nominal GDP from the BEA. The figure shows long-run trends for all government capital, nondefense government capital, and transportation capital relative to GDP. All show significant swings over time. The total government capital ratio hit peaks in the 1940s and the mid-1970s. Both the nondefense and transportation government capital ratios hit peaks in the 1930s, the mid-1970s, and in the early 2010s. The ratios have fallen only slight since the early 2010s. Thus, current levels of public capital are comparable to those of some of the past high points.

Of course, this comparability does not mean that the level is optimal or that the allocation of government capital across types is optimal. We can shed light on this question by returning to the extension of the neoclassical model that allows the social planner to choose the optimal steady-state public capital, discussed in Section 2.6. For reference, I repeat the equations for the optimal level of government capital and investment:

$$\frac{K_G}{Y} = \frac{1}{\beta^{-1} - 1 + \delta_G} \cdot \theta_G\,, \qquad \frac{G^I}{Y} = \frac{\delta_G}{\beta^{-1} - 1 + \delta_G} \cdot \theta_G$$

where K_G is public capital, G^I is government investment, Y is output, β is the discount rate of the representative household, δ_G is the depreciation rate on public capital, and θ_G is the exponent on public capital in the aggregate production function. Recall from Section 2.6 that the calibration of the stylized model, converted to an annual basis to match the BEA data, implies that the fraction multiplying θ_G in the capital ratio equation is equal to 12.5 and in the investment ratio equation is 0.49.

With these formulas, we can compare the current state of public capital investment in the U.S. to the optimal ratios implied by the stylized model. Table 6 shows the ratios of government capital and investment to GDP 2018 using BEA data, along with the model-implied optimal ratios for three values of θ_G: the simulation baseline calibration of 0.05, Bouakez et al. (2017) estimate of 0.065, and the upper bound of Bom and Ligthart's (2014) range of 0.12.

The first two rows of table 6 show the ratios for the U.S. in 2018, for both total government capital and nondefense government capital. Excluding defense capital, government capital is currently 64 percent of GDP and government investment in nondefense capital is 2.6 percent of GDP.

The next three rows of table 6 show the model-implied optimal ratios. If θ_G is equal to 0.05, then the socially optimal government capital-output ratio is 63 percent and the socially optimal government investment-output ratio is 2.5 percent. These model-implied ratios match the BEA data almost exactly. However, if the true θ_G is higher, then the socially optimal ratios are higher. For example, $\theta_G = 0.065$ implies a socially optimal capital ratio of 81 percent and $\theta_G = 0.12$ implies a socially optimal capital ratio of 150 percent. Thus, viewed through the lens of this simple model, the current U.S. levels of government investment are socially optimal only if θ_G is as low as 0.05. If θ_G is higher, then the U.S. is underinvesting in public capital.

Clearly, the value of θ_G is crucial to the calculation. Obtaining more definitive estimates of this parameter is important for assessing whether U.S. levels of government investment are too low.

Other assumptions of the model affect the optimal ratio calculation as well. The stylized model makes strong assumptions about elasticities of substitution between factors of production and returns to scale, both of which can affect the calculation. The model also incorporates the unrealistic assumption that public capital is homogeneous. If public capital is heterogeneous, then marginal products are not proportional to average products. For example, even if the overall level of transportation infrastructure is near the optimum, it may be misallocated: the current amount of transportation infrastructure might be too high in Detroit but too low in Seattle.

The stylized neoclassical model also assumes no distortions in the economy. The need to finance government spending with distortionary taxes might reduce the implied optimal government investment rate since a unit of government capital would cost more than a unit of output because of the depressing effect of distortionary taxes on output. On the other hand, the New Keynesian-style product market and labor market distortions might lead to second-best results implying higher public capital.

In sum, the current range of plausible estimates of θ_G is too wide and the model used in this paper is too stylized to give a definite answer to the question of whether the U.S. is underinvesting in public capital. Nevertheless, the simple calculation offers a starting point for thinking about the issue in more general models and serves as an impetus to more research aimed at narrowing the range of plausible estimates of θ_G.

6 Summary and Conclusions

This paper has studied both the short-run and long-run macroeconomic effects of government investment. The theoretical analysis has considered both neoclassical and New Keynesian models. The empirical analysis has surveyed estimates at the aggregate and regional levels, illustrated the econometric challenges, and extended some existing empirical work. The following points summarize some of the key findings.

First, even when government investment has significant long-run effects, the short-run stimulus multipliers are less than those from government consumption in most situations. The two key reasons are (i) the effects of time-to-build delays and (ii) the propensity of government investment to crowd out private spending more than government consumption does. These results are supported by quantitative models, empirical panel studies across OECD countries, time series analysis in the U.S., and cross-state studies. The effects of time-to-spend and time-to-build delays, which appear to be inherent in infrastructure projects, work against the standard New Keynesian mechanisms and lower short-run multipliers.

Second, the long-run multipliers on government investment depend critically on both the production function elasticity of output to public capital and on where the economy begins relative to the socially optimal level of public capital. Higher production function elasticity raises multipliers and starting far below the socially optimal level of public capital also raises multipliers.

Second, my review and small extension of the empirical literature on the long-run estimates suggests that the aggregate production function elasticity of output to public capital is probably between 0.065 and 0.12, similar to the range found by Bom and Ligthart's (2014) meta-analysis. However, this elasticity is very stylized and does not take into account possible differences in the marginal products of different types of government capital. Some studies find higher estimates for core infrastructure, while others do not.

Third, there is both theoretical support and some empirical support for the short-run multiplier on government investment being higher when interest rates are constrained by the zero lower bound (ZLB). The theoretical mechanisms that lead to this effect, however, also imply that at the zero lower financing government spending with distortionary income taxation rather than deficits leads to higher multipliers, a result contrary to most economists' priors.

Fourth, cross-section and panel evidence on U.S. states or counties that focuses on bridge, highway, and road infrastructure spending suggests that the spending leads to either no change or a decline in employment in the first several years, even during ZLB periods. There is no obvious explanation for these puzzling results, though the disruptive effects of construction on existing infrastructure might play a role.

In sum, the macroeconomic approach to government investment provides strong support for the long-run benefits of infrastructure spending. However, the same approach raises questions about the suitability of investment in infrastructure and other public capital as a short-run stimulus.

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Appendix

The following provides the first-order conditions and steady state conditions for the models presented in Section 2.

Stylized Neoclassical Model

The social planner chooses sequences $\{C_t\}, \{N_t\}, \{I_t\}, \{Y_t\}$, and$\{K_t\}$ to maximize the lifetime utility of the representative household given in equation 2, subject to the economy-wide resource constraint in equation 1, the production function in 3, the capital accumulation equations in 4 and 5, as well as exogenous processes for the two types of government spending. The first-order conditions for the perfect foresight solution are:

(A-1) $$\frac{(1-\alpha)Y_t}{C_t} = \nu N_t^{\phi}$$ Marginal Rate of Substitution Condition

(A-2) $$\frac{C_{t+1}}{C_t} = \beta[\alpha \frac{Y_{t+1}}{K_t} + 1 - \delta]$$ Consumption Euler Equation

If the social planner chooses government capital optimally, then we also have the first-order condition for that choice:

$$\frac{C_{t+1}}{C_t} = \beta[\theta_G \frac{Y_{t+1}}{K_t^G} + 1 - \delta_G]$$

The steady-state conditions are:

(A-3) $$\frac{K}{Y} = \frac{\alpha}{\beta^{-1} - 1 + \delta}$$

(A-4) $$\frac{C}{Y} = 1 - \delta \cdot \frac{K}{Y} - \delta_G \cdot \frac{K^G}{Y} - \frac{G^C}{Y}$$

(A-5) $$N^{1+\phi} = \frac{1-\alpha}{\nu C/Y}$$

$$I = \delta \cdot K \tag{A-6}$$

$$G^I = \delta_G \cdot K^G \tag{A-7}$$

$$Y = AK^{\alpha} N^{1-\alpha} (K^G)^{\theta^G} \tag{A-8}$$

If the social planner chooses public capital optimally, then in steady state,

$$\frac{K^G}{Y} = \frac{\theta_G}{\beta^{-1} - 1 + \delta_G}$$

New Keynesian Model

I construct the model by modifying Galí et al. (2007) to add government capital and sticky wages (using Colciago's (2011) assumptions). I also add variable capital utilization and replace capital adjustment costs with investment adjustment costs following Christiano et al. (2005) and Schmitt-Grohé and Uribe (2005). My model shares many similarities with Sims and Wolff's (2018) model extended with rule-of-thumb households.

Here I will highlight a few key details and refer readers for now to Galí et al. (2007) for more details concerning the parts of the model that overlap. The full model equations will be made available in an online appendix.

Households

The general specification of households closely follows Galí et al. (2007). There are two types of households, optimizing households and rule-of-thumb households. Both have the same utility function, identical to the one used for the neoclassical model, equation 2. Optimizing households maximize their lifetime utility subject to an intertemporal budget constraint. Sources of income include labor earnings, returns on the holding of government bonds, rental income from capital, and dividends. Uses of income are consumption, investment in physical capital, lump-sum taxes and purchases of government bonds. Optimizing households own all of the capital in the economy and receive all profits. They also make decisions on the utilization of capital. Rule-of-thumb households consume their entire income each period, with their income consisting of labor earnings less lump-sum taxes.

Labor market

Both types of households supply j types of labor, which firms use to create aggregate labor input through a CES aggregator. The elasticity of substitution between the different types of labor in this CES aggregator is ε_w. A fictitious labor union sets wages to maximize the weighted utility across the two types of households. The union can only reoptimize the wages with probability $1-\theta_w$ and takes this into account when it is allowed to adjust the wage for type j labor. Because wages are marked up over the marginal rate of substitution, households are willing to supply whatever labor is demanded. The labor supply of both types of households is always equal.

Investment adjustment costs and capital utilization

The capital accumulation equation from the baseline neoclassical model is modified as follow.

$$K_t = (1-\delta(u_t))K_{t-1} + I_t\left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right]$$

where depreciation depends on utilization as follows

$$\delta(u_t) = \delta_0 + \delta_1(u_t - 1) + \delta_2(u_t - 1)^2$$

and investment adjustment costs are

$$S\left(\frac{I_t}{I_{t-1}}\right) = \frac{\kappa}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2.$$

Prices, production, and resource constraints

The model follows Galí et al. (2007) regarding competitive final goods firms and monopolistically competitive intermediate goods firms, who mark up price over marginal cost and face price adjustment costs. The elasticity of substitution parameter for the CES aggregator of intermediate goods to final goods is given by ε_p. The probability that a firm can adjust prices is $1 - \theta_p$.

The aggregate production function is modified in three ways relative to my neoclassical model:

$$s_t \cdot Y_t = A_t \, (u_t \cdot K_{t-1})^{\alpha} \, \left(N_t^d\right)^{1-\alpha} \left(K_{t-1}^G\right)^{\theta_G}$$

In this version, output depends on capital services, which is the product of the utilization rate u and the stock of capital. Wage stickiness leads to inefficient use of the types of labor (outside of steady state), so there is a wedge between the amount of labor supplied, N_t, and the effective amount of labor available for production, N_t^d:

$$N_t = \tilde{s}_t N_t^d, \text{ where } \tilde{s}_t \geq 1.$$

Similarly, the distortions caused by price stickiness imply a wedge (outside of steady state) between the amount of spending (Y = C + I + G) and the amount produced , so $s_t \geq 1$.

Monetary policy and fiscal policy

The specification of the Taylor rule and the behavior of lump-sum taxes follows Galí et al. (2007). According to notes by Martín Uribe, Galí et al. (2007) implicitly assume that the deviation of lump-sum taxes from steady state is always equal for both types of households.

Table 1. Baseline Calibration of the Models

Parameter	Value	Description
Parameters in both models		
β	0.99	Subjective discount factor
ν	1	Weight on disutility of labor
ϕ	0.25	Inverse of the Frisch elasticity of labor supply
α	0.36	Exponent on private capital in production function
θ_G	0.05	Exponent on government capital in production function
δ	0.015	Depreciation rate of private capital
δ_G	0.01	Depreciation rate of public capital
gy	0.175	Steady-state share of total govt spending to GDP
giy	0.035	Steady-state share of govt investment to GDP
ρ_G	0.95	Autoregressive coefficient on appropriations process
Additional parameters of the New Keynesian model		
κ	5.2	Investment adjustment cost parameter
δ_1	0.025	Parameter on linear term of capital utilization cost
δ_2	0.05	Parameter on quadratic term of capital utilization cost
μ_P	1.2	Steady-state price markup
μ_W	1.2	Steady-state wage markup
θ_P	0.75	Calvo parameter on price adjustment
θ_W	0.75	Calvo parameter on wage adjustment
ε_P	6	Elasticity of substitution between types of goods
ε_W	6	Elasticity of substitution between types of labor
γ	0.5	Share of rule-of-thumb consumers
ψ_b	0.33	Debt feedback coefficient in fiscal rule
ψ_g	0.1	Spending feedback coefficient in fiscal rule
ψ_π	1.5	Monetary policy response to inflation

Table 2. Short-Run Multipliers from Simulated Models

Model Version (θ_G = 0.05)	Govt consumption AR(1)	Govt investment AR(1)	Govt investment delays
Neoclassical Model			
Baseline	0.47	0.40	0.37
Frisch elasticity = 0.5	0.14	0.13	0.13
Invest. adj. cost, capital utiliz.	0.63	0.63	0.15
New Keynesian Model			
Baseline	1.06	1.12	0.08
No invest. adj. cost, no utiliz.	0.19	0.16	0.06
Frisch elasticity = 0.5	0.76	0.82	-0.20
No rule-of-thumb households	0.68	0.73	-0.05

Notes: These estimates are based on the calibrated models described in Section 2. The multipliers are equal to the ratio of the integrals of the impulse responses of output and appropriations.

Table 3. Long-Run Multipliers from Simulated Models

Model Version	Present Discounted Value		Undiscounted Integral	
	Neoclassical	New Keynesian	Neoclassical	New Keynesian
Govt consumption	0.44	0.89	0.43	0.90
	Initial Steady State: Govt Investment/GDP = 3.5%			
No delays				
Govt investment, $\theta_G = 0.05$	1.3	1.8	2.4	3.0
Govt investment, $\theta_G = 0.10$	2.2	2.8	4.3	5.0
6-qrt time to spend & build				
Govt investment, $\theta_G = 0.05$	1.3	1.7	2.4	2.9
Govt investment, $\theta_G = 0.10$	2.1	2.5	4.3	4.9
	Initial Steady-State: Govt Investment/GDP = 1.5%			
No delays				
Govt investment, $\theta_G = 0.05$	2.4	3.2	4.9	5.4
Govt investment, $\theta_G = 0.10$	4.4	5.4	9.3	9.8
6-qrt time to spend & build				
Govt investment, $\theta_G = 0.05$	2.3	2.9	4.9	5.3
Govt investment, $\theta_G = 0.10$	4.1	5.0	9.3	9.7

Notes: These estimates are based on the calibrated models described in Section 2. The multipliers are equal to the ratio of the integrals of the impulse responses of output and appropriations. PDV is present discounted value, integral is undiscounted. The top panel shows multipliers from simulations for which the steady-state government investment to GDP ratio is 3.5%, which matches the data. The bottom panel shows multipliers from simulations for which the steady-state ratio is 1.5%.

Table 4. Summary of Some Neoclassical Models from the Literature

Paper feature summary	Experiment	Govt investment multiplier
Baxter-King (1993)	Permanent increase in G	
Calibrated	Long-run multipliers	
Lump-sum taxation	$\theta_G = 0$	1.2
	$\theta_G = 0.05$	2.6
	$\theta_G = 0.40$	13.0
Leeper, Walker, Yang (2010)	AR(1) parameter 0.95	
Estimated	Short run, no delays	0.5
Investment adj. costs, utiliz.	Short run, 3 year delays	0.1 - 0.3
Distortionary tax response	Long run, across delay times	
Calibrated $\theta_G = 0.05$ or 0.10	$\theta_G = 0.05$	0.3 - 0.4
	$\theta_G = 0.1$	0.9 - 1.1
Ercolani-Valle e Azevedo (2014)	AR(1) parameter 0.94	
Estimated	Preferred estimate $\theta_G = 0$	
Features similar to medium NK	4-quarter	0.8
but no nominal rigidities	Long run	0.4
Distortionary tax, balanced budget	Unconstrained estim. $\theta_G = 0.09$	
Nonseparable utility in C and G	4-quarter	0.8
	Long run	3.6
Gallen and Winston (2019)	Multipliers calibrated to CEA	
Calibrated, transport infrastructure	Long run U.S.	1.5
Time-to-build	Long run Japan	0.9
Short-run disruption from construction		
Better transport saves household time		
$\theta_G = 0.038$		

Table 5. Summary of Some New Keynesian Models from the Literature

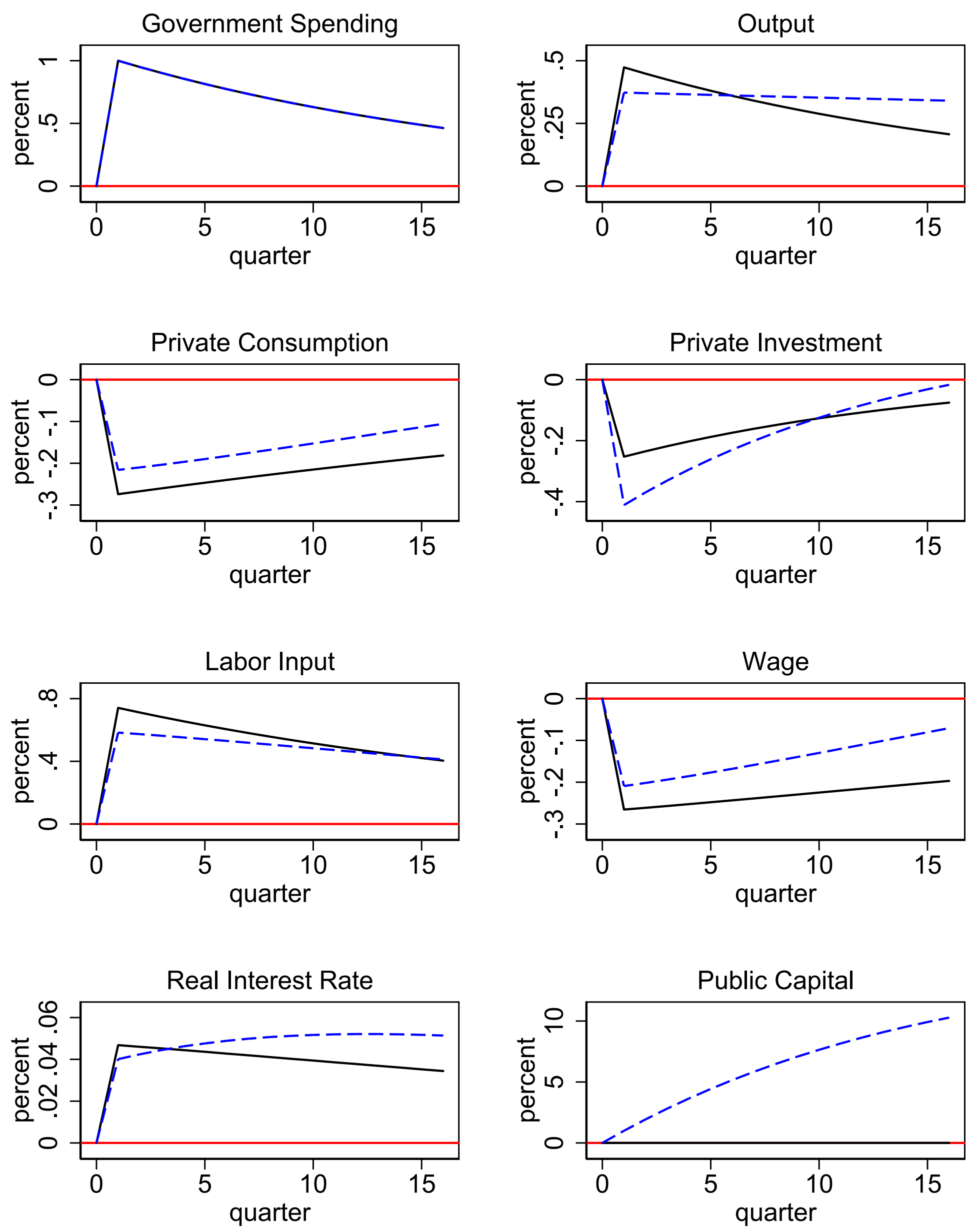
Paper feature summary	Experiment	Govt investment multiplier
Coenen et al. (2012)	2-year stimulus, deficits	
Large scale policy models	Instantaneous multipliers	
+ 2 academic models	No monetary accommodation	0.9
U.S.	1 year monetary accommodation	1.1
	2 year monetary accommodation	1.6
Drautzburg-Uhlig (2015)	ARRA, distortionary taxation later	
Estimated medium scale model	Short-run multiplier	0.2 - 0.5
Distortionary taxes, respond to debt	Long-run multiplier	0.3
Calibrated θ_G = 0.023		
Bouakez, Guillard, Roulleau-Pasdeloup (2017)	AR(1) parameter 0.8	
Calibrated	Impact multipliers	
No private capital (in baseline model)	Normal times, across delays	0.8 - 0.9
Lump-sum taxes	ZLB, no delays	1.8
Time to build, θ_G = 0.08	ZLB, 4-year time-to-build delays	4
Sims-Wolff (2018)		
Estimated medium-scale model	AR(1) parameter 0.93	
Distortionary taxes, respond to debt	1 to 2-year multipliers	0.7 - 0.8
Nonseparable utility in C and G		
Calibrated θ_G = 0.05		
Boehm (forthcoming)	AR(1) parameter 0.86	
Calibrated model, 2-sectors (C, I)	Short-run multiplier (0 to 20 quarters)	0.1 - 0.2
Imperfect labor mobility	Long-run multiplier	1.6
Lump-sum taxes		
θ_G = 0.05		

Table 6. Comparison of Actual to Model Optimum Government Capital and Investment

	Government Capital Percent of GDP	Government Investment Percent of GDP
BEA data, 2018		
Total government capital	73	3.3
Excluding defense	64	2.6
Neoclassical Model Social Optimum		
θ_G = 0.05	63	2.4
θ_G = 0.065	81	3.2
θ_G = 0.12	150	5.9

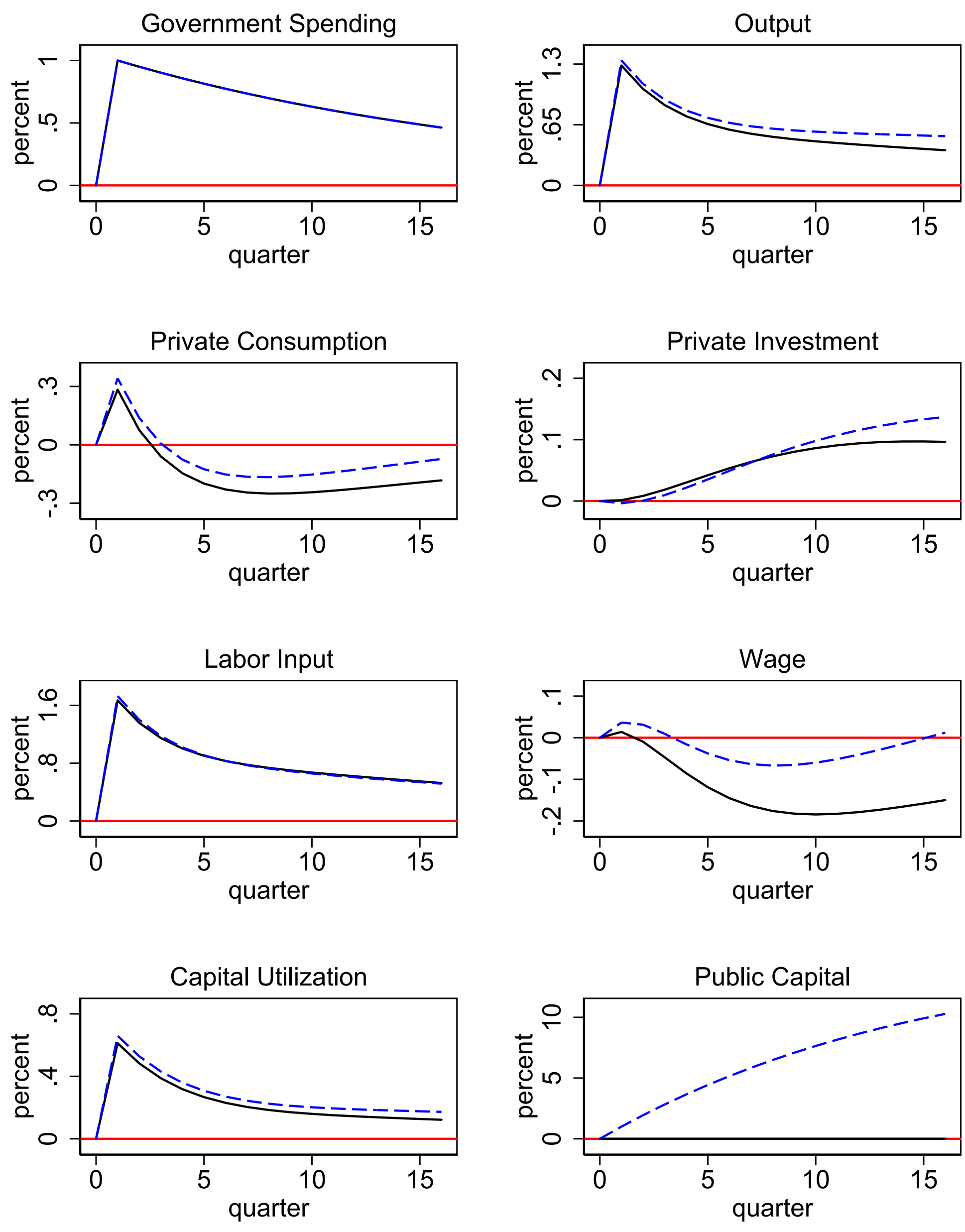
Notes: The data for government capital is current-cost net stock of government fixed assets from BEA fixed asset table 7.1. The data for investment and GDP is from BEA NIPA table 1.1.5. θ_G is the exponent on government capital in the production function. The model optimum is based on an annual depreciation rate of 3.9% and an annual discount factor of 0.96.

Figure 1. Effect of Increases in Government Consumption or Investment Baseline Neoclassical Model



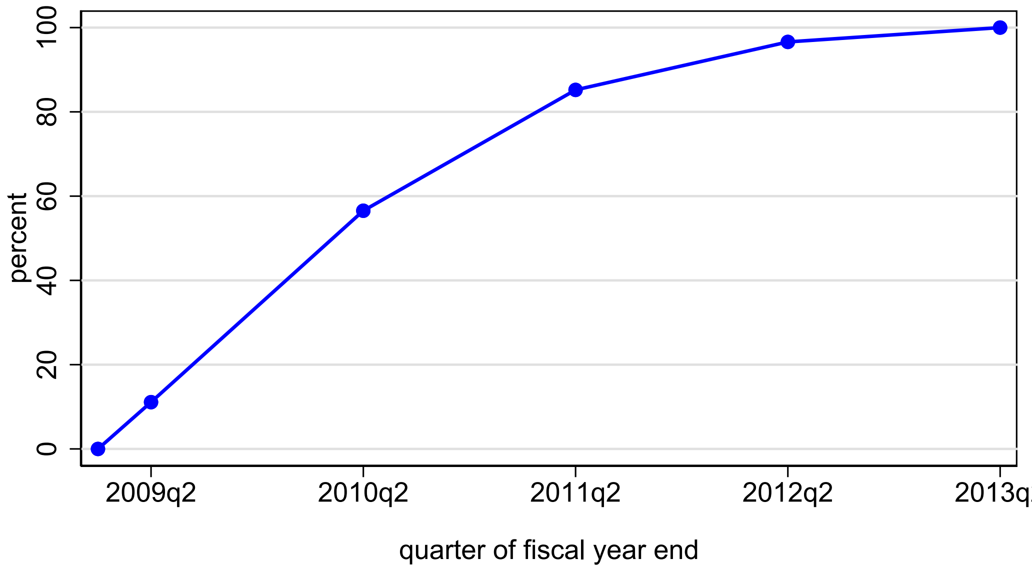
Notes. Solid: government consumption shock; dashed: government investment shock, $\theta_G = 0.05$; Government spending, output, consumption, private investment, and public capital are expressed in deviations from steady state as a percent of output in steady state. Labor input and wages are percent deviations from their own steady state values. Real interest rate is annualized percentage point deviations from its own steady state.

Figure 2. Effect of Increases in Government Consumption or Investment New Keynesian Model



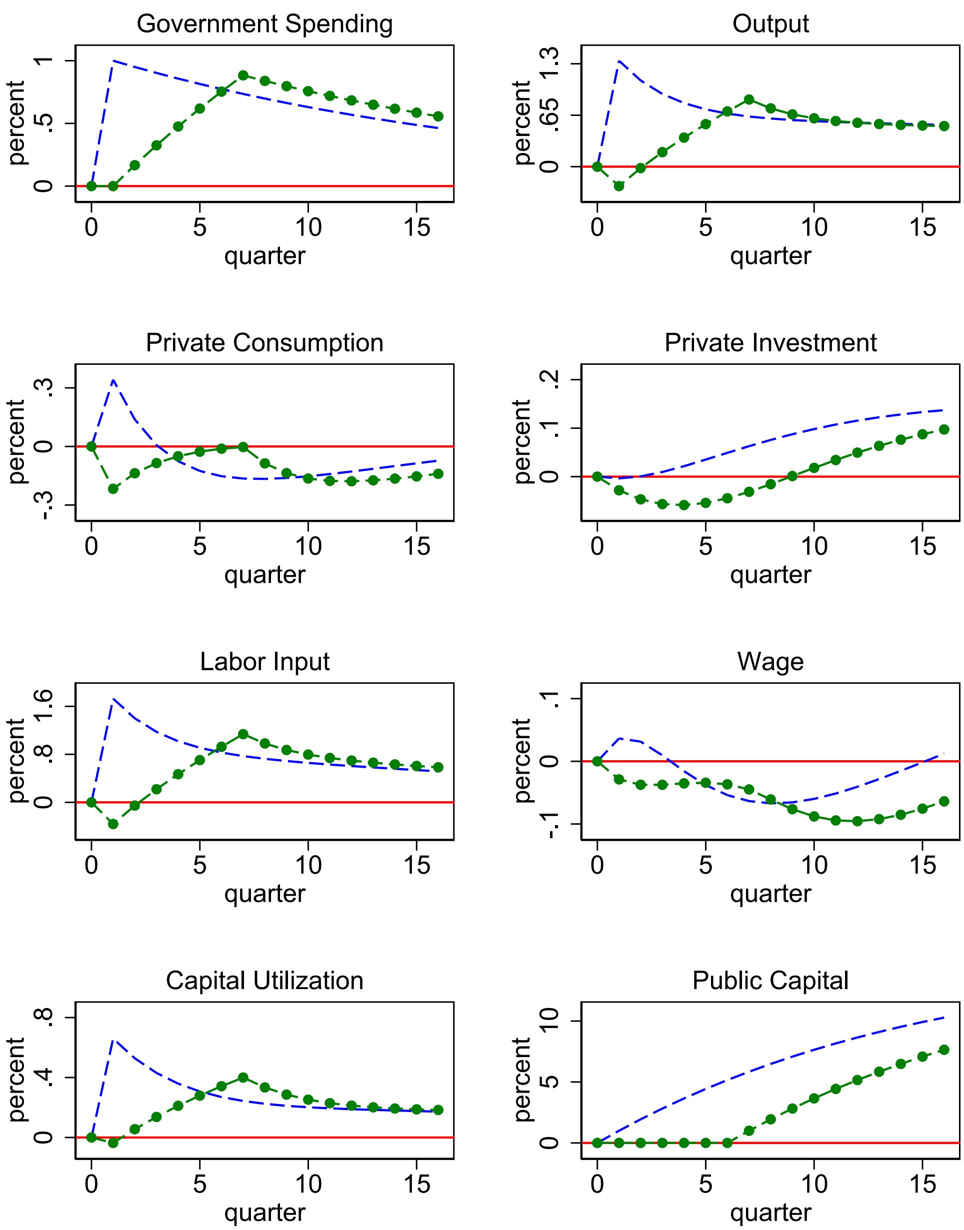
Notes. Solid: government consumption shock; dashed: government investment shock, $\theta_G = 0.05$; Government spending, output, consumption, private investment, and public capital are expressed in deviations from steady state value as a percent of output in steady state. Labor input and wages are percent deviations from their own steady state values. Real interest rate is annualized percentage point deviations from its own steady state.

Figure 3. Federal Highway Administration Outlays from the ARRA Cumulative Percent Spent of Total Appropriation



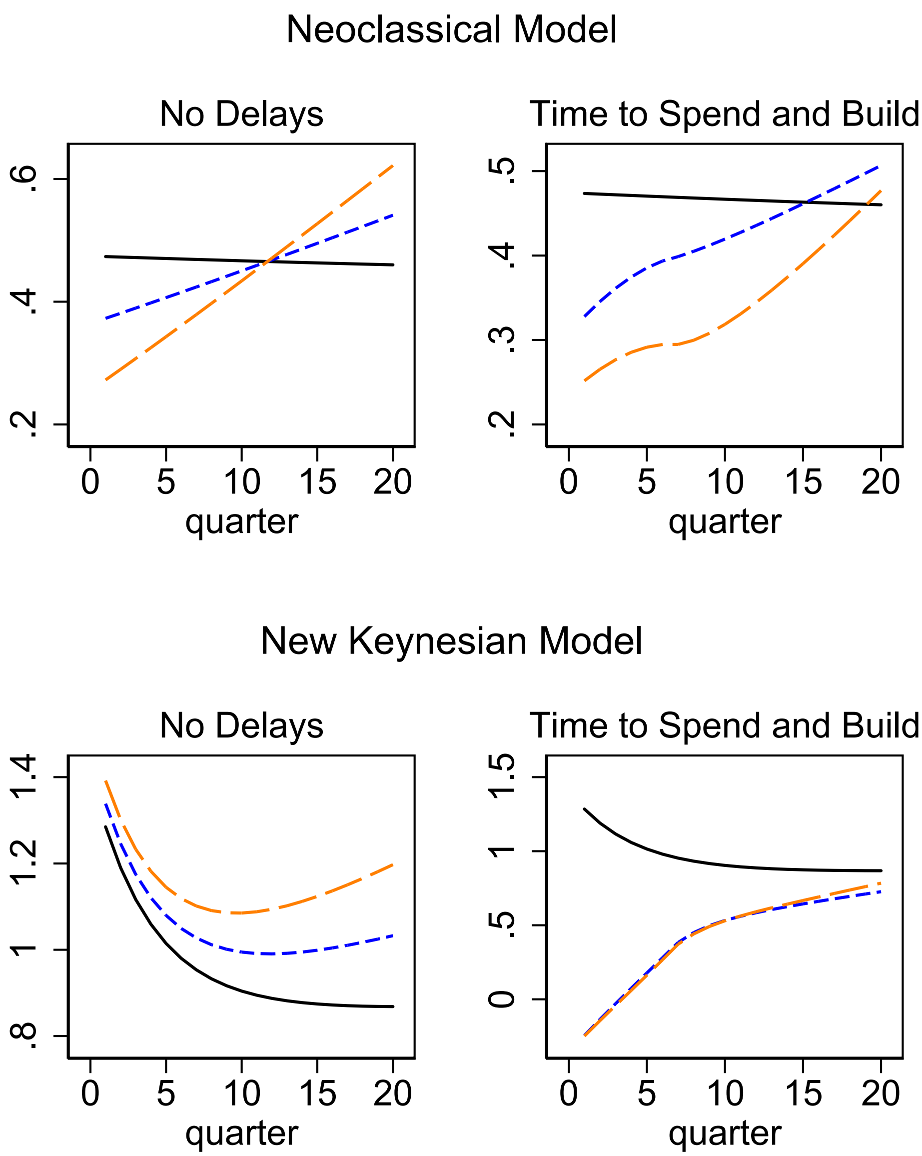
Notes. These data are from Leduc and Wilson's (2017) replication files. I aggregated their state-level data to the national level.

Figure 4. Effect of Increases in Government Investment
New Keynesian Model, with Time To Spend and Time To Build



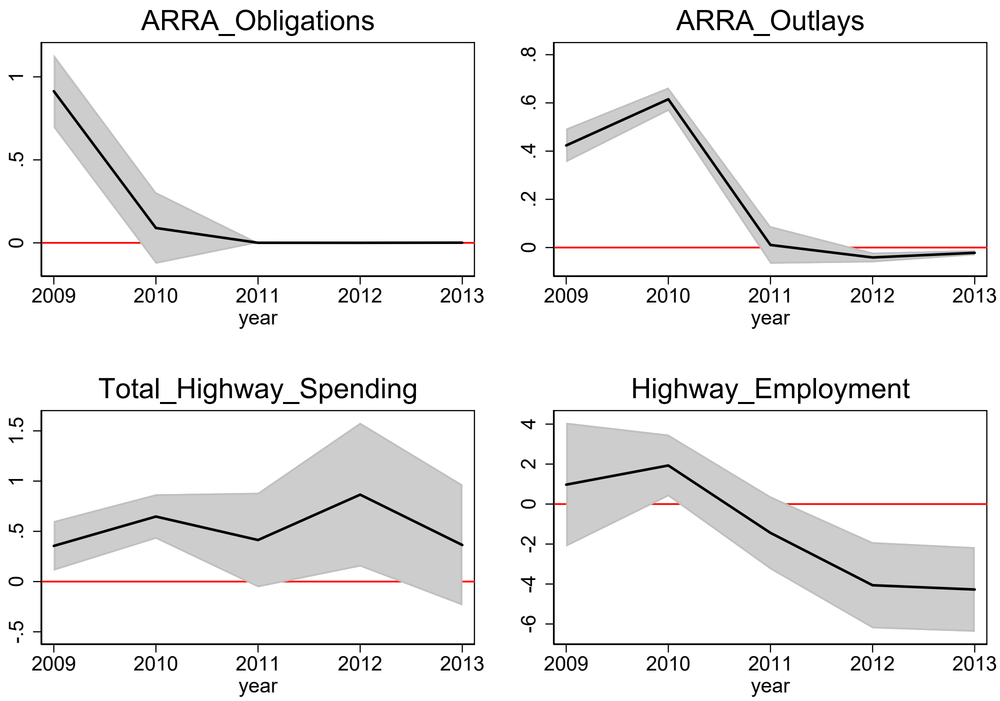
Notes.dashed line: government investment shock, no delays; dashed line with circles: government investment with implementation delays. Government spending, output, consumption, private investment, and public capital are expressed in deviations from steady state value as a percent of output in steady state. Labor input, utilization, and wages are percent deviations from their own steady state values.

Figure 5. Present Discounted Value Integral Multipliers



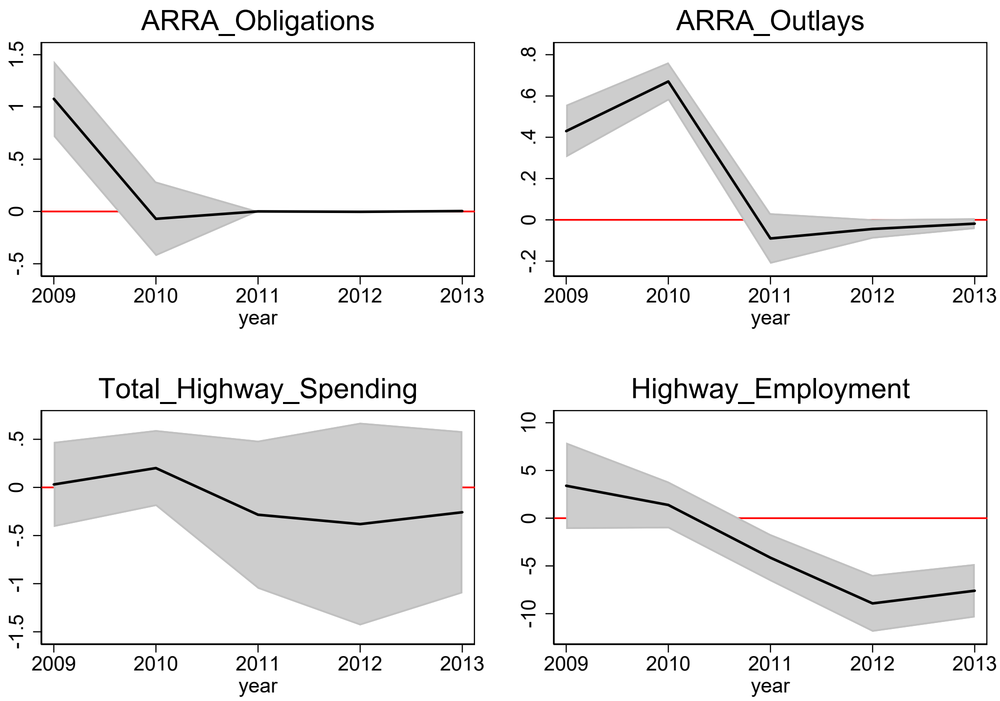
Notes. Solid: government consumption shock; short dashed: government investment shock, $\theta_G = 0.05$; long dashed: government investment, is $\theta_G = 0.1$. These estimates are based on the baseline neoclassical and NK models.

Figure 6. Estimated Impulse Responses to Instrumented ARRA Highway Apportionments: No Controls for Log State Population.



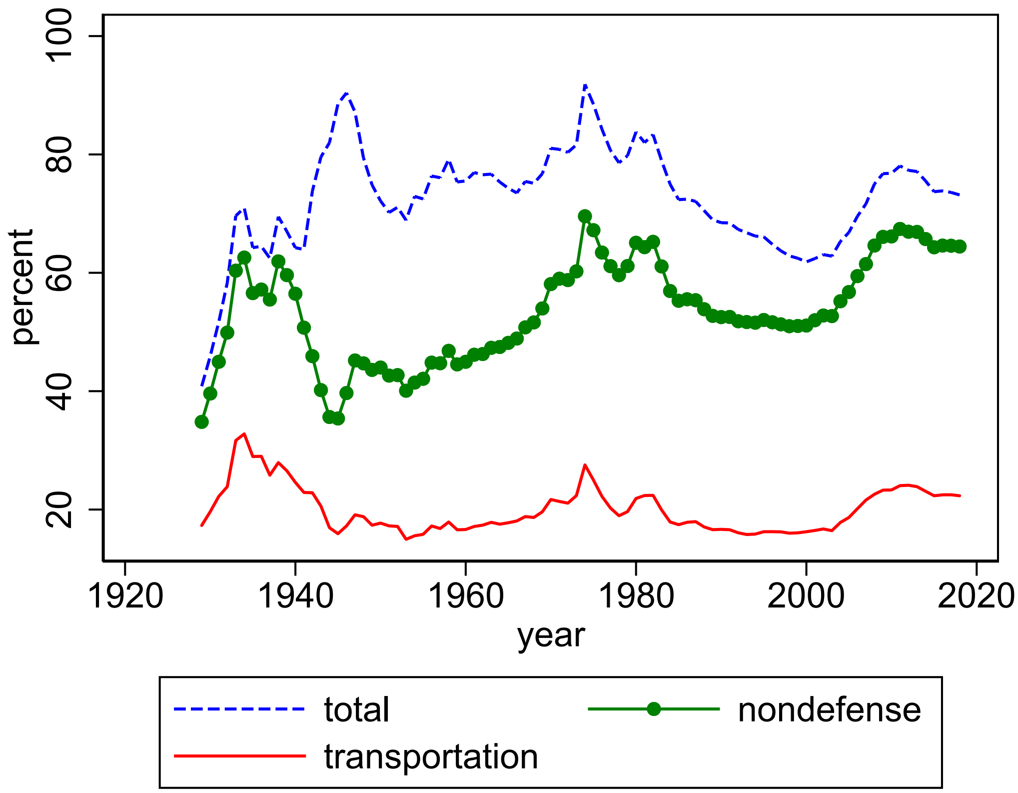
Notes: The three spending graphs show the dollar impact per dollar of ARRA highway apportionments in 2009. The employment graph shows the employment impact in highway, road, and bridge construction employment for each $1 million of ARRA highway apportionments in 2009. In both cases, the ARRA apportionments are instrumented by Leduc and Wilson's (2017) two road factors. The confidence bands are 90 percent bands.

Figure 7. Estimated Impulse Responses to Instrumented ARRA Highway Apportionments: Controls for Log State Population.



Notes: The three spending graphs show the dollar impact per dollar of ARRA highway apportionments in 2009. The employment graph shows the employment impact in highway, road, and bridge construction employment for each $1 million of ARRA highway apportionments in 2009. In both cases, the ARRA apportionments are instrumented by Leduc and Wilson's (2017) two road factors. The confidence bands are 90 percent bands.

Figure 8. Government Capital as a Percent of GDP in the U.S.



Notes: Government capital is current-cost net stock from BEA fixed asset Table 7.1. GDP is current-dollar GDP from the BEA.