

Transportation Capital and its Effects on the U.S. Economy: A General Equilibrium Approach

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Abstract

We analyze the effect of the US transportation system on economic activity by building a dynamic computable general equilibrium model with a taxpayer-funded transportation capital stock. We highlight stark differences between the positive welfare effects of additional infrastructure spending in the long run, and its potentially negative effects when we account for the large transition (time and delay) costs to build. We also quantify large differences between the effects of additional infrastructure spending and efficient transportation policies and we conclude that taxpayer-funded transportation improvements that increase GDP significantly may produce smaller welfare gains than efficient policies that increase GDP modestly.

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1 Introduction

The efficiency of a nation’s transportation system can significantly affect the essential inputs and outputs of an economy, including individuals’ accessibility to jobs and firms’ accessibility to workers, the availability, price, quality, and variety of consumer goods and services, the intensity of competition among and the productivity of firms, and economic growth attributable to agglomeration economies. It is therefore not surprising that many countries have tried to improve their standard of living by spending enormous sums of money on their transportation systems. The United States, for example, spends more than \$5 trillion annually in both money and time on freight and passenger transport services, and has invested more than \$4 trillion in highway, rail, aviation, pipeline, and water infrastructure (Winston, 2013).

In light of those enormous expenditures, it is surprising we have little knowledge about the transportation system’s effect on other sectors, its overall effect on the economy, and the benefits from improving the system’s efficiency. Transportation economists have closely studied the individual components of a transportation system, such as passenger airline service and the federal highway network, but they have rarely studied the interrelationships between transportation and other sectors of the economy. Urban and regional economists have estimated, for example, the effect of airports on metropolitan growth, but they have taken the efficiency of the transportation system as given¹. Trade theorists (Dixit and Stiglitz, 1977; Krugman, 1979, 1980) developed general equilibrium models, but those models incorporated transportation improvements only as a source of lower trade barriers.² Macroeconomists have estimated the returns from investments in public infrastructure capital³ and have used DSGE models to examine productive government investment in a manner broadly similar to this paper (Leeper, Walker, and Yang, 2010), though without our focus on permanent changes, welfare, shopping and commuting time wedges, “costly” time to build, and efficient government spending, the last three of which we find are important for both welfare and GDP responses.

In this paper, we develop an applied general equilibrium model that includes the capital

¹Overviews of transportation economics can be found in co-edited handbooks by Gomez-Ibanez, Tye, and Winston (1999) and de Palma et al. (2011). Those handbooks and Winston (2010) discuss studies of transportation’s effect on metropolitan growth.

²For instance, focusing on trade costs and geographic location, Allen and Arkolakis (2014) calculated that the Interstate Highway System generates an annualized welfare gain of 1.4% of GDP.

³Aschauer (1989), Munnell (1990), and Barro (1991) initiated this literature. Shatz et al. (2011) provide a recent survey. Barro (1990) discusses productive government spending in a model of endogenous growth.

stock of the U.S. transportation system and we quantify how improving the stock by increasing government investment in it or by reforming policy to increase the stock's efficiency enhances the nation's welfare. Our model incorporates four direct effects of increased transportation spending, which: (1) directly increases firm productivity, (2) decreases time spent traveling to shop for consumption goods, (3) decreases time spent traveling to work, and (4) increases distortionary taxes to pay for spending. Our application of applied general equilibrium modeling, in the tradition of Shoven and Whalley (1984) and Kehoe and Kehoe (1994), first focuses on long-run outcomes. We then consider the dynamics of transition, which accounts for factors that increase the time to build infrastructure and for travelers' delay costs during construction.

Investments in transportation infrastructure differ from other forms of government expenditures, such as military spending, foreign aid, and transfers, because they do not directly enter a household's utility function or budget constraint; instead, they indirectly affect a household's utility or budget constraint by affecting the performance, especially the service quality, of the transportation system. When comparing the effects of infrastructure spending on GDP and welfare, it is important to bear in mind that spending requires taxation that reduces welfare, but may not change GDP. At the same time, spending may improve welfare by reducing commute travel time but that would potentially not affect GDP. Thus, a priori it is not clear whether we should expect spending to have a greater effect on GDP or welfare. We find that government expenditures that improve transportation capital increase GDP much more than they increase economic welfare—that is, the resulting reductions in commuting and shopping travel times cause households to exchange the additional leisure for more consumption, which increases GDP, but produces a more modest welfare gain because additional time is spent working and traveling to shop.

Our model yields important insights. First, we find that endogenous responses make up more than half of the overall change in GDP, overshadowing the direct effects of transportation infrastructure on GDP through productivity gains. Consequently, GDP's change is significantly larger than a partial equilibrium model would expect, even as welfare gains are significantly overstated by GDP's increase. Second, we find that a model calibrated to the relatively large GDP multipliers of the United States admits much smaller GDP multipliers for countries with a high transportation capital stock, such as Japan, which we argue is consistent with the evidence on higher costs (or lower productivity) for additional units of transportation infrastructure.

Third, we find that delays in transportation infrastructure building may actually be welfare-enhancing, as it gives private capital time to respond, increasing welfare and effectiveness of new capital stock.

We find that efficient transportation policy reforms that improve the system's efficiency produce larger welfare gains than increasing government expenditures because they do not require additional distortionary taxes to finance the increase in effective infrastructure. For example, efficient pricing of trucks to reduce pavement and vehicle damage and efficient investment in highway durability that optimally trades off up-front capital costs for reductions in long-run maintenance costs could generate billions of dollars of annual welfare gains (Small, Winston, and Evans, 1989; Winston, 2013). We then examine the economy's transition path and find that the gulf between the welfare effects of efficient policies and additional spending expands because increased spending entails large up-front costs that may lead to a welfare loss.

While we find low present value welfare gains from additional spending, we do not find that improving transportation infrastructure is undesirable or unlikely to yield significant welfare gains. Our findings suggest that improving the efficiency of the transportation system represents an important channel for improving the nation's quality of life and that spending large sums of money on the system to increase GDP, as many economists have suggested in the wake of the 2008-2009 recession and its sluggish recovery, may be welfare-reducing.⁴ Indeed, an efficient policy improvement that increases GDP only a small amount, or even decreases it, may raise national welfare more than would an increase in public investment that increases GDP by a large amount.

2 Model Overview

We build a single-good, representative household, dynamic computable general equilibrium model where we assume that firms use labor, physical capital, and transportation infrastructure to produce the final consumption good. By reducing travel times for shipping freight, commuting to work, and going shopping, efficient transportation infrastructure enables firms to be more productive and benefits households. We assume that government expenditures on infrastructure

⁴See, for example, Summers (2016); Krugman (2016) For an opposing view, see Glaeser (2016).

to improve its performance are financed by a labor income tax.⁵

In what follows, we characterize the household’s labor/leisure tradeoff and a firm’s profit-maximizing behavior and indicate how they are affected by the transportation system. We then discuss government policy to improve the system. To simplify the presentation, we exclude from our analysis some additional benefits of more efficient transportation infrastructure that would increase social welfare, including (1) enabling households to live in larger and less expensive houses that are further from the urban center (2) improving the reliability of travel, and (3) facilitating greater industrial competition and product variety. Those omissions indicate that we provide conservative estimates of the welfare gains from more efficient policies and from additional government spending on infrastructure, but they should not affect their relative welfare.

2.1 Household

The infinitely-lived household with discount rate β derives flow utility, U_t , from consumption c_t and disutility from labor L_t , and maximizes net present value of utility:

$$\sum_{t=0}^{\infty} \beta^t \left[\frac{c_t^{1-\sigma}}{1-\sigma} - \psi \frac{\epsilon}{1+\epsilon} (L_t(1+\omega_t) + \xi_t c_t)^{\frac{1+\epsilon}{\epsilon}} \right] \quad (1)$$

where we use the preferences of MaCurdy (1981), which allows for choice of both intertemporal elasticity of substitution $1/\sigma$ and Frisch elasticity of labor supply ϵ .⁶ ψ is the disutility of time spent on non-leisure activities, including work-time L_t . ω_t is the fraction of working time spent commuting, so that $\omega_t L_t$ is the amount of time spent commuting to work at time t , and ξ_t is a conversion factor that expresses how much leisure time is lost for a given level of consumption; hence, $\xi_t c_t$ is the amount of time spent traveling to shop. Improved infrastructure saves households both commuting and shopping time. This utility function captures the idea that unproductive time spent commuting to work or to shop is time that is not spent on leisure.

⁵While there are other ways of funding an increase in infrastructure spending, none have appeared to be politically feasible: Congress has refused to increase the gasoline tax since 1993 and it has not seriously considered introducing a consumption or new capital tax to fund additional spending on transportation infrastructure.

⁶It is known that these preferences do not necessarily have offsetting income and substitution effects of a change in wage on labor supply, as in the classic “balanced growth” preferences of King, Plosser, and Rebelo (1988). While (Aguiar and Hurst, 2007) and Ramey and Francis (2009) find no postwar secular trend in labor hours worked, others, such as Boppart and Krusell (2016) have argued this is inconsistent with longer-run data in the U.S. or in other countries. In line with Heathcote, Storesletten, and Violante (2014), our choices of σ and ϵ will reflect a long-run income effect slightly stronger than the substitution effect.

Households maximize their utility function with respect to both c_t and L_t subject to the period budget constraint:

$$c_t + i_t = w_t L_t (1 - \tau_t^H - \tau_t^G - \tau_t^T) + (1 - \tau_K) r_t K_t + T_t + \pi_t \quad (2)$$

where i_t is the household investment in capital, w_t is the hourly wage, τ_t^H is the tax on labor that is remitted lump-sum to households, τ_t^G is the tax on labor funding government (non-transportation) expenditures, τ_t^T is the tax on labor financing transportation capital expenditures, $(1 - \tau_t^K) r_t K_t$ is the household's nonlabor income net of capital taxes, generated as the product of the real capital rental rate r_t and the quantity of physical non-transportation capital K_t net of gross capital tax τ_t^K , T_t is the lump-sum transfer to the household, and π_t is firm profits remitted to the household.

The law of motion for the physical non-transportation capital stock is subject to a depreciation rate δ and capital adjustment costs controlled by κ (see, for instance, Canzoneri, Cumby, and Diba (2005)), namely:

$$K_{t+1} = (1 - \delta) K_t + i_t - \frac{\kappa}{2} \left(\frac{i_t}{K_t} - \delta \right)^2 K_t \quad (3)$$

The household's problem is to maximize the net present value of utility in equation 1 by choosing paths for consumption, investment, future capital, and labor subject to the budget constraint in equation 2, the capital law of motion in equation 3, and taking the paths of prices, taxes, non-transportation capital stock, and shopping and commuting wedges as given. Letting the Lagrange multiplier for the budget constraint be λ_t , the marginal utility of wealth, the household's first order conditions for the utility-maximizing choices of consumption and labor supply are⁷:

$$\frac{1}{c_t^\sigma} - \xi_t \psi(L_t(1 + \omega_t) + \xi_t c_t)^{\frac{1}{\epsilon}} = \lambda_t \quad (4)$$

$$(1 + \omega_t) \psi(L_t(1 + \omega_t) + \xi_t c_t)^{\frac{1}{\epsilon}} = \lambda_t w_t (1 - \tau_t^H - \tau_t^G - \tau_t^T) \quad (5)$$

In the standard neoclassical growth model, equation 4 sets the marginal utility of consumption equal to the marginal utility of wealth. In contrast, when households in our analysis con-

⁷We do not display the first order conditions with respect to investment and capital next period, but display them in Table A.1. We denote the Lagrange multiplier on capital, Tobin's Q, as Q_t .

sume, they lose leisure time because they must work and commute to pay for their consumption and because they must travel to purchase their goods, which is reflected in our expression for the marginal utility of consumption on the left-hand side of equation 4. Improving the efficiency of transportation capital would reduce the consumption tax on households' time. Equation 5 can be interpreted as equating the marginal utility of leisure with the (post-tax) wage. Note that the time spent traveling to shop affects the marginal utility of leisure, which links both consumption and labor behavior over time. The standard household intertemporal Euler equation is thereby adjusted by the fact that consumption affects leisure hours and the disutility of labor. For instance, knowledge that consumption expenditures, which reduce leisure time, will be higher in the future will spur intertemporal substitution towards labor today.

2.2 Firms

The final consumption good is produced by the representative firm with access to a Cobb-Douglas production technology in labor, capital, and transportation infrastructure.⁸ It rents physical capital K and labor L from households with prices r and w , and uses transportation infrastructure K^T as a public good if travel conditions are uncongested. Output elasticities of physical capital, labor, and transportation capital are α , $1 - \alpha$, and λ_K , respectively, while total factor productivity is A . The production function is therefore given by:

$$Y_t = A_t K_t^\alpha L_t^{1-\alpha} (K_t^T)^{\lambda_K}$$

Following previous macro and micro infrastructure studies, this specification yields a straightforward output elasticity of transportation capital, and the Cobb-Douglas assumption ensures that increases in transportation capital do not generate relatively more physical capital or labor in production. As in Aschauer (1989), the production function exhibits increasing returns to scale. Because firms take transportation infrastructure as given, it can be absorbed into total factor productivity and write:

$$Y_t = A_t^* K_t^\alpha L_t^{1-\alpha} \tag{6}$$

⁸Fernald (1999) analyzed the productivity-enhancing nature of the U.S. highway system and found that industries with a higher share of vehicle expenditures grew faster when the U.S. Interstate System was built, which suggests that there are intra- and inter-sectoral effects that we do not capture in our representative firm analysis.

where

$$A_t^* = A_t(K_t^T)^{\lambda_K}$$

A competitive firm with constant returns to scale in chosen inputs L_t and K_t maximizes production net of labor and capital costs, determining the demand for labor and capital:

$$\alpha A_t^* K_t^{\alpha-1} L_t^{1-\alpha} = r_t$$

$$(1 - \alpha) A_t^* K_t^\alpha L_t^{-\alpha} = w_t$$

Note that an increase in transportation capital will increase both the demand for capital and the demand for labor. If, for instance, the increase in the demand for capital is reflected by an increase in the quantity of capital, rather than simply by a higher price (i.e., if capital supply is not perfectly own-price inelastic), then it will also increase the demand for the other good. Because capital is slow to adjust, the interplay between productivity, capital, and labor will be important for distinguishing between the short- and long-run effects of capital.

2.3 Government

The government spends money on three items: (1) G_t , public services (such as military spending), (2) T_t , transfers, and (3) K_t^T , transportation capital. It funds all expenditure with labor income taxes τ_t^G , τ_t^H , and τ_t^T , as well as capital taxes τ_t^K . Government spending on non-transfer, non-transportation infrastructure (such as the military) and transfers are given by equation 7:⁹

$$G_t + T_t = \tau_t^G w_t L_t + \tau_t^H w_t L_t + \tau_t^K r_t K_t \tag{7}$$

When households solve their constrained maximization problem, they do not take into account their own contribution to their personal transfer. Given government expenditures on public services are additively separable from labor and consumption, they do not impact household behavior although transfers do. The level of taxation matters insofar as it affects the marginal excess burden of taxation.

⁹For clarity of exposition, we separate expenditures on public services or transfers from transportation capital. Modeling a single budget constraint would leave our model unchanged.

2.3.1 Government Infrastructure Investment

Government investment in transportation infrastructure capital is equal to the tax revenue that the government collects from households to fund its transportation capital expenditures i_t^T ¹⁰:

$$i_t^T = \tau_t^T w_t L_t \quad (8)$$

Transportation infrastructure investment enters the capital law of motion:

$$K_{t+1}^T = (1 - \delta_{1,K^T})K_t^T - \delta_{2,K^T}(K_t^T - \overline{K^T}) + \sum_{i=0}^{\overline{T}} \phi_i i_{t-i}^T \quad (9)$$

The law of motion for transportation infrastructure differs in two ways from the standard law of motion with geometric depreciation. First, additional units of effective transportation infrastructure are more expensive than previous units because, for example, of constraints on available land for construction, or because of decreasing returns, so that at the margin it takes more spending to get the same effect as previous spending. Second, transportation infrastructure takes time to build, and during construction may actually reduce the infrastructure that is available for travelers. We introduce the first concept into the law of motion by allowing for a second, “marginal” depreciation rate δ_{2,K^T} , imposed on additional units of capital above the baseline $\overline{K^T}$, in addition to the “average” or initial depreciation rate δ_{1,K^T} . We introduce the second, “costly-time-to-build” aspect of the model by including potentially costly delays via ϕ 's (up to \overline{T} previous years), which control how current and previous investment enters into capital's law of motion.

Because we assume a single unit of transportation infrastructure always has the same output elasticity, we load diminishing returns to additional transportation infrastructure on its cost by modeling a “kink” in the cost of transportation capital via δ_{2,K^T} .¹¹ This kink reflects the idea that an additional effective unit of transportation infrastructure (measured in our model by the amount of infrastructure that would increase production by $100 \cdot \gamma\%$, *ceteris paribus*) may be more costly at the margin. This is consistent with evidence showing diminishing multipliers from transportation infrastructure investment as the stock grows (see, for instance, Doi and Ihori

¹⁰We consider tax smoothing via deficits in an extension.

¹¹While this is not formally modeled as a kink, it acts as one because we do not consider lower levels of transportation capital in our policy experiments, so that in the baseline only δ_{1,K^T} matters.

(2009) and Auerbach and Gorodnichenko (2014)), and with the idea that the largest returns tend to be generated by the initial investments. For example, expanding the number of lanes on a highway would not yield the same productivity gains as the initial construction of the highway and maintenance expenditures tend to yield smaller returns than capital expenditures. The difference between average and marginal costs is also implicitly suggested by the difference between output elasticities estimated using physical transportation infrastructure measures (such as miles of lanes) and monetary measures (dollars spent). We interpret this evidence in our calibration below.

A consequence of our modeling is that $\delta_{2,KT}$, controls the marginal cost of transportation capital, which significantly affects the impact of spending on GDP, the GDP multiplier, and the gain in social welfare from government spending on transportation infrastructure. Specifically, when the marginal cost of constructing transportation infrastructure is high, the GDP multiplier and welfare gain will tend to be low because the additional taxes on households that are needed to finance infrastructure spending will cause economic activity to contract. When the marginal cost of constructing transportation infrastructure is low, the GDP multiplier and welfare gain will tend to be high because the benefits that are generated require little additional distortionsary taxation.¹²

Transportation investment today does not necessarily immediately bear fruit, as reflected in our choices for ϕ in equation 9. First, as noted, transitional construction may actually decrease available transportation capital in the short run. In particular, once a highway infrastructure project begins, a work zone is created, which delays travelers in the vicinity of the project. A work zone is an area of a road where construction, maintenance, or utility work activities occur, and it is typically marked by signs (especially ones that indicate reduced speed limits), traffic-channeling devices, barriers, and work vehicles. According to the Federal Highway Administration, about 888 million person-hours of freeway delay is due to work zones (FHA, 2016) Valued at even half the (private) average hourly wage in 2014 of \$24.50, work zone delays create

¹²As should be clear from the household's budget constraint in equation 2, the law of motion for non-transportation capital in equation 3, and the law of motion of transportation capital in equation 9, this is a single-good model, with the relative price of consumption and marginal investment fixed at one, and the relative price of transportation capital is controlled by $\delta_{1,KT}$ in the baseline and $\delta_{2,KT}$ in the counterfactual. As this is a general equilibrium model, by Walras' Law there is an additional equation that holds in equilibrium. For clarity, the economy's resource constraint is:

$$Y = c + i + i_t^T + G$$

where non-transportation, non-transfer government expenditures $G_t = w_t L_t \tau_t^G$

an annual welfare loss of nearly \$11 billion and the losses persist even if a project is not delayed.

Transportation infrastructure projects also require multiple Federal permits and reviews, including reviews under the National Environment and Policy Act of 1969 (NEPA), to ensure that projects are built in a safe and responsible manner and that adverse impacts to the environment and communities are avoided. During the 1970s, the average time to complete a NEPA study was 2.2 years. That average has increased to 4.4 years during the 1980s, to 5.1 years during the 1995-2001 period, and to 6.6 years by 2011 (AECOM, 2016).¹³ Most recently, Piet and Carole A. deWitt compiled comprehensive data on infrastructure project reviews and concluded that the average time for completing the permitting process has grown to almost 10 years for major highway projects that received their final review in 2015 (Harrison, 2017).

To capture this “costly time-to-build” aspect of transportation infrastructure, take $\bar{T} = 3$, so that we have three years of potential delay, including the initial year of investment, or ϕ_0 , ϕ_1 , and ϕ_2 in equation 9. To understand those parameters better, consider an example where $\phi_0 = -0.5$, $\phi_1 = 0.5$, and $\phi_2 = 1$. The assumed values reflect the idea that if, for instance, two new lanes were being added to a four-lane highway, in terms of usable capacity the project would shut down the equivalent of a single lane (of four) for construction in the first year, reopen that lane in the second year, and complete the project so that the new lanes, along with the original four lanes, could be used by travelers within three years. All our calibrations will assume that $\sum_{t=0}^{\bar{T}} \phi_t = 1$, so that beyond the effects of discounting and transitory changes in capital stock, there is no “loss” in adjusting transportation capital: investing a single final good into investment eventually increases transportation capital by the same amount. Inefficiencies in provision, or decreased effectiveness are instead subsumed into the cost of effective transportation infrastructure γ_1 and γ_2 , rather than ϕ .

2.4 The effects of transportation capital

In our model, an increase in transportation capital affects the economy in four ways: (1) it increases A_t^* , the total factor productivity of firms, (2) it decreases ξ_t , the transportation cost of consumption, (3) it decreases ω_t , the transportation cost of working, and (4) it requires an increase in τ_t^T , the tax rate that raises money for additional transportation capital. We assume

¹³Also, see the Federal Highway Administration, Environmental Review Toolkit: <https://www.environment.fhwa.dot.gov/strmlng/nepatime.asp>

plausible elasticities to capture the effect of a change in transportation capital on effective TFP and the shopping and transportation wedges.

The first three aspects of the model are benefits of the transportation capital stock. Denote the baseline calibrated levels of TFP, the consumption travel wedge, the commuting travel wedge, and transportation capital as \bar{A} , $\bar{\xi}$, $\bar{\omega}$, and \bar{K}^T , respectively. Denote the net percentage change of capital from the baseline as \tilde{K}^T and denote the elasticities of the first three variables with respect to the last variable as λ_K , γ_ξ , and γ_ω . Given this notation, equations 10-12 relate changes in the effective transportation capital stock K^T to changes in productivity and the two transportation wedges.

$$A_t^* = \bar{A}(1 + \lambda_K)\tilde{K}^T \quad (10)$$

$$\xi_t = \bar{\xi}(1 + \gamma_\xi)\tilde{K}^T \quad (11)$$

$$\omega_t = \bar{\omega}(1 + \gamma_\omega)\tilde{K}^T \quad (12)$$

The fourth effect of a change in the transportation capital stock is a change in labor income taxation, defined by equation 8. Where equations 10-12 denote the direct benefits of an increase in transportation capital stock, equation 8 accounts for the costs: if a percentage increase in transportation infrastructure spending does not increase pretax labor income by the same proportion, then taxes must be raised to pay for the capital stock. Equations 8-12 therefore allow for the possibility that increased spending in transportation capital might pay for itself by increasing GDP enough that the government is able to lower taxes even as spending increases.

Ceteris paribus, an increase in government spending on infrastructure increases labor demand because the same production technology that produces additional infrastructure also produces consumption and capital goods. If government infrastructure spending were characterized by more labor intensive production technology, then it would generate a larger increase in the demand for labor and a smaller increase in capital, altering the otherwise constant capital-labor ratio.

3 Calibration

3.1 Household

We calibrate certain parameters to obtain numerical results from our model. In the utility function, we calibrate the Frisch elasticity of labor supply ϵ , the disutility of labor ψ , and the baseline levels and elasticities of the travel costs, or wedges, which transportation time frictions cause between consumption and work. Based on Chetty et al. (2011), we set the Frisch elasticity of labor supply to be 0.75. From the 2015 American Time Use Survey (ATUS) we set the disutility of labor so labor hours per working-age person per year (L_{ss}) is 1510 hours in our steady state, a value broadly consistent with Cociuba, Prescott, and Ueberfeldt (2012) and Shimer (2009).

We also use the 2017 National Household Travel Survey (NHTS) data to set the baseline levels of the transportation and consumption wedges. According to the 2017 NHTS, for working-age persons (including non-workers), more than 94 minutes each day are spent traveling. Of these, approximately 29 minutes a day are spent traveling related to work (including job search), while approximately 66 are spent on travel related to all other activities, such as purchases, household activities and food and drink.¹⁴ Thus, the annual hours lost to transportation for non-work purposes and for work can be expressed as:

$$\bar{\xi}c_{ss} = 401 \tag{13}$$

and

$$\bar{\omega}L_{ss} = 176$$

We set the depreciation rate of physical non-transportation capital to be 0.068, the share-weighted average depreciation rate of structural and equipment capital in Gomme and Rupert (2007), and $\beta = 0.945$ from the same source. Because the depreciation rate of non-transportation capital is of second-order importance in our model, reasonable changes to it do not impact our results. Together β and δ imply a steady state interest rate of 10.8%.¹⁵ In common with other

¹⁴The ATUS shows approximately 17 minutes less time being consumed by commuting. While the size of the the initial time wedges matter, our results were little changed by calibrating to the ATUS instead.

¹⁵Our preferences have a slightly altered Euler equation, but the effect of consumption on labor hours is of second-order importance in determining the interest rate's baseline level.

equilibrium business cycle and growth studies, our interest rate is higher than microeconomic estimates of the real return of capital (see, for instance, McGrattan and Prescott (2005)).

The intertemporal elasticity of substitution (IES) is important, because it helps determine the rate of transition to the steady state. We set the IES to be equal to 0.72, consistent with the estimate in Smets and Wouters (2007).

3.2 Firms

Turning to firms, we set the share of production going to capital (α) to be 0.283, which reflects capital's long-term share in national income (see, for instance, Gomme and Rupert (2007)). We choose \bar{A} , the baseline total factor productivity of production such that GDP per working age person is \$90,342¹⁶, the value in the United States in 2016. We therefore express our numerical results in dollars per working-age capita.

3.3 Transportation infrastructure and government

Based on the National Income and Product Accounts (NIPA) fixed asset tables, we calculate a value for the physical transportation capital stock of \$4.75 trillion dollars, or \$23,114 per working age person¹⁷. While this value helps us interpret values and generate depreciation rates, because we calibrate costs relative to this baseline, deviations from this value will yield very similar numerical results. From the Congressional Budget Office (2015b), U.S. spending on transportation infrastructure averages about 2.5% of GDP. Setting baseline transportation investment to \bar{i}^T to 2.5% of GDP yields a baseline depreciation rate of 9.8%. This is higher than the 4.1% obtained by Holtz-Eakin (1993) but more comparable to the 7% of Canning and Bennathan (2000). If, in fact, less than 2.5% per year of GDP were required to generate \$4.75 trillion worth of transportation capital, then our implied depreciation rate would be lower. The level of the depreciation rate comes solely from this estimate of a capital stock and investment needed to maintain it. However, the level matters little for our final results, and only allows us to hit our 2.5% target. More important is the extent to which the marginal cost of transportation

¹⁶We calculate this value by taking GDP in 2016 (\$18.57 trillion) and dividing it by 206 million people of working age (the difference between the annual averages for BLS series LNU00000000 and LNU00000065, civilian non-institutional population aged 16 or over and 65 or over, respectively.)

¹⁷Using Fixed Asset Tables of the Bureau of Economic Analysis to update Winston (2013), we generate this value from \$3.4 trillion in highways and streets and \$712 billion in public airways, waterways, and transit structures, with pipelines valued at \$235 billion and railroad track valued at \$419 billion

infrastructure exceeds the average. Using the same methods for an increase in transportation stock, our marginal depreciation rate is 21%, which indicates strongly diminishing returns to infrastructure investment.

While a 21% marginal depreciation rate may at first glance seem large, we note that our notion of “effective” physical capital translates any decreasing marginal benefit of transportation infrastructure into increasing cost in our model. For instance, if a country with one unit of capital requires two additional units of capital to receive the same marginal benefits as the first unit bestowed, then we would measure the second two units as one “effective” unit, and have the marginal cost be twice that of the first unit. This naturally lends itself to high marginal costs, and we believe such a value is consistent with the microeconomic literature. When a 1% marginal increase in spending yields the same output elasticity as a 0.5% increase in physical infrastructure, it suggests strongly diminishing returns (or increasing cost per unit of return). Fortunately, Melo, Graham, and Brage-Ardao (2013) break up estimates of the output elasticity depending on whether it was estimated using spending or physical output measures. Consistent with our calibration, the ratio of the physical stock elasticity and the monetary spending elasticity is frequently much greater than one: comparing the ratio of means of the two elasticities across studies yields 2.34 (compared to 2.17 in our model), while the ratio of the median of the two elasticities is 3.8, suggesting far higher costs. Moreover, comparing European countries to the United States, Melo, Graham, and Brage-Ardao (2013) also find a European output elasticity between 42% (mean estimates) or 9% (median estimates) lower than those in the U.S. Combined with the fact that European countries appear to invest half a percentage point more of GDP¹⁸, this is also suggestive of decreasing returns to scale, or increasing cost per effective unit of infrastructure. Finally, as we discuss, Japan’s apparently falling GDP multiplier after massive infrastructure construction is additional evidence of increasing costs of an effective unit of infrastructure.

Ordinary taxation of labor τ^G , which funds government consumption expenditures and gross investment, is set to raise 17% of GDP for government purchases and investment net of transportation infrastructure spending. The tax that funds transfers, τ^H is set so that transfers make up 12% of GDP, as in NIPA. The capital tax is set to 0.29, as in Gomme and Rupert (2007).

We define the long-run transportation infrastructure spending multiplier Ω in equation 14

¹⁸Comparing investment in public infrastructure across countries is difficult. This number is calculated using the IMF Investment and Capital Stock Dataset, 2017, which extended the methodology of Kamps (2005).

below as the change in GDP generated by a permanent increase in transportation infrastructure divided by the cost of that change, where the superscript \prime denotes the counterfactual long-run value of a variable that is compared with its baseline value.

$$\Omega = \frac{Y' - Y_{ss}}{w' L' (\tau^T)' - w_{ss} L_{ss} \tau_{ss}^T} \quad (14)$$

CEA (2014) notes that a large range of output multipliers, from 0.5 to 2.5, has been used for policy analyses, also see Congressional Budget Office (2015b). In our baseline calibration, we assume Ω is 1.5 as CEA (2014) does.¹⁹ Because the multiplier is so important, we examine multipliers clustered in the center of the CEA’s range, from 0.9 to 2. We note that this is the sole “dynamic” target in our calibration: the rest target the steady state.

The three key parameters related to the effects of changes in transportation infrastructure on GDP and welfare are the output elasticity, the commute time wedge, and the shopping time wedge. We use the mean U.S. output elasticity of 0.038 reported in Melo, Graham, and Brage-Ardao (2013)’s meta-study reporting more than 500 estimates. Because the elasticity may be lower or higher (the U.S. median estimate was 0.014) we use the range of estimates in our robustness checks. Unfortunately, there is not much evidence on the effect of an increase in transportation infrastructure on travel times to work and to shop. Shirley and Winston (2004) found that increased spending on the highway capital stock had small effects on travel time and generated very small annual returns. In contrast, efficient pricing is more effective. For example, Hall (2016) finds that by setting congestion prices on half the highway lanes, highway capacity is increased and the annual time spent traveling falls 40.5 hours. We consider efficient policies to increase infrastructure capacity later.

For our analysis of spending, we assume a 5% increase in transportation infrastructure would produce small reductions in annual commute and shopping time, 0.5 hours and 4 hours per year, respectively. This yields elasticities of observed travel time with respect to effective transport stock of -0.060 and -0.19, comparable to the long-run values estimated in Duranton and Turner (2009) of -0.060 and -0.064. While there is a dearth of empirical estimates of time savings (Metz, 2008), a meta-study of 58 major road projects in the U.K. after completion found average time savings of 2.5-3 minutes, which imply higher elasticities and larger time savings of infrastructure

¹⁹These estimates are based off shorter-run stimulus multiplier estimates in Congressional Budget Office (2015a).

investments (Highways England, 2011). Because estimates of travel time savings elasticities have relatively wide standard errors, we provide sensitivity analysis for a wide range of values. We note, however, that we do not include the benefits of more reliable travel time, whose value is comparable to the value of travel time savings (Small, Winston, and Yan, 2005, 2006).

Fortunately, while economists have not estimated to our knowledge the costly time-to-build parameters (ϕ_i 's), there exist engineering studies that attempt to model congestion costs. For instance, Al-Kaisy and Hall (2003) use data on six observed freeway reconstruction zones to estimate work zone capacity to be half that of the baseline, which we calibrate to. While engineering studies typically focus on delay during construction, sample information about highway construction timelines is publicly available from various Transportation administrations. In Illinois, it takes between 3-5 years to repair, repave, and reconstruct a highway, while new construction can take more than ten years (Illinois Department of Transportation, 2013). From the same source, a “typical” funded project with a 6+ year time-horizon has planning taking four years and construction taking more than two. Because we find construction delay and work zone congestion can dramatically reduce welfare, we take conservative values, assuming in our baseline calibration that $\phi_0 = -0.5$, $\phi_1 = 0.5$, and $\phi_2 = 1$, reflecting the capacity loss of Al-Kaisy and Hall (2003) up front and a relatively rapid highway construction. We also examine more realistic delay that could exceed six years as indicated by the Illinois source above, such as $\phi_0 = \phi_1 = \phi_2 = \phi_3 = \phi_4 = 0$, $\phi_5 = -0.5$, $\phi_6 = 0.5$, $\phi_7 = 1$

3.4 Joint Calibration

We denote the 17 equations describing our framework as $f(X; \Theta, K^T) = 0$, where X indicates our endogenous covariates, Θ is a parameter vector, and K^T is an exogenously-set level of transportation capital. We summarize the system of 17 equations and 17 unknowns that hold in equilibrium and that define X , given Θ and K^T in Table A.1. Θ contains our nine exogenous parameters, and $G(X, \Theta)$ has nine corresponding equations that jointly identify the parameters. Table 1 gives the 8 moment conditions in $G(X, \Theta)$ that are used to calibrate the nine parameters in Θ . In a standard CGE framework, we would estimate Θ by minimizing a vector of moment errors that depends on both Θ and endogenous values X (and K^T and $(K^T)'$). But because we assume a fixed GDP multiplier, we solve a new counterfactual system $f(X; \Theta, (K^T)')$ for a new $(K^T)'$ and ensure that the GDP multipliers are equal to our target. Conceptually, targeting the

long-run multiplier is similar to targeting a specific portion of the impulse response function, as in Christiano, Eichenbaum, and Evans (2005).

By targeting the long-run counterfactual output multiplier, we target the effect of transportation spending given current policies, which compromise the effect of spending because they do not efficiently curb congestion. Thus, the impact of congestion, which is to reduce the output elasticity or output multiplier of transportation infrastructure, is absorbed into our model through those parameters.

With nine moments and nine equations, we are able to fit our targets exactly, so that $G(X, \Theta) = 0$ and $f(X; \Theta, K^T) = 0$, and we are able to estimate both Θ and X . The results for Θ are presented in Table A.2, and the results for X are presented in Table A.3.

4 Long-Run Results

Because our calibration targets levels and long-run responses, we first explore the long-run, economy-wide effects of experiments where government: (1) spends funds that are raised through taxation to increase the transportation capital stock 5%, and (2) introduces efficient policy reforms, such as optimal pricing, investment, and production, which also increase the capital stock by 5%. We present the main findings of our experiments in Table 2, and, as noted, report baseline and counterfactual values of our endogenous variables in Appendix Table A.3. Having examined long-run benefits of additional transportation capital stock, and having shown that it robustly increases long-run welfare, we turn to the transition paths to understand why additional transportation capital may be undesirable from a welfare perspective. The two sections highlight a classic idea in the neoclassical growth model: a higher capital stock may make workers better off in the steady state, and aggregate production may be higher, but workers present value of utility may be maximized if the capital stock is allowed to run down. We find that transportation capital may have this effect in our calibrated economy because it is so costly and time consuming to expand transportation infrastructure.

4.1 Increasing Transportation Spending

The difference between baseline government transportation expenditures and the additional annual expenditures to increase the steady-state capital stock 5% is \$245 per worker, as shown in

the first panel of Table 2, or \$50 billion in aggregate, as shown in the second panel of the table. Given that our baseline calibration assumes that every dollar spent on transportation infrastructure increases GDP \$1.50, inclusive of the distortionary effects of taxation, GDP increases \$76 billion per year.²⁰

The importance of our general equilibrium approach for understanding transportation’s effect on the economy can be seen by decomposing the change in GDP into its productivity, capital, and labor effects. To do so, we totally differentiate the production function given in equation 6 and divide it by production to obtain:

$$\frac{dY}{Y} = \frac{dA}{A} + \alpha \frac{dK}{K} + (1 - \alpha) \frac{dL}{L} \quad (15)$$

Based on the values of the endogenous variables in Table A.3 and our assumed value of $\alpha = 0.283$, we attribute a 0.40% increase in GDP from increasing transportation spending to changes in A , K , and L , with 47% of the increase in GDP due to the increase in productivity, 25% due to increased capital and 28% due to increased labor.²¹ Given that more than half of the increase in output comes from the behavioral responses of capital and labor, rather than from an increase in productivity, a partial equilibrium analysis that accounts for only the direct effect of increased productivity would understate the increase in aggregate output by half. However, a partial equilibrium model that instead interpreted the increase in GDP directly as an output elasticity generated by increased productivity alone would badly overstate the welfare gain, because the lion’s share of welfare gain from the increase in GDP generated by labor and capital is subsumed in costs.

Equation 15 identifies an important lesson for transportation economists interested in understanding transportation infrastructure’s impact on the macroeconomy. By assuming a multiplier, we pin down dY/Y , and by assuming an output elasticity, we pin down dA/A . Regardless of the accuracy of our model, given our calibration of dY/Y and dA/A , it must be the case that the lion’s share of the increase in output comes from endogenous responses in general equilibrium.

²⁰Dupor (2017) provides evidence that the 2009 Recovery Act did not increase national highway infrastructure spending because states responded to the increase in federal highway spending by reducing their spending. We do not account for “crowding out” effects here.

²¹While we do not separate the intensive and extensive elasticities in our analysis, we can calculate the employment gain from additional spending. Assuming an extensive margin intertemporal elasticity that is one third the size of the elasticity of total hours yields an employment increase of 0.05%, or 136,000 workers in 2016. Because modeling a reduction in the fixed cost of transport tends to decrease intensive participation and increases extensive, we consider this approximation to be conservative.

Consumption and Investment. Although GDP increases by \$368/worker, consumption increases by only \$84/worker, with two-thirds of the increase in GDP accounted for by the increase in government transportation expenditures of \$245/worker. The increase in investment of \$39/worker is also modest and a “phantom” gain, reflecting increased investment requirements instead of consumption. As additional perspective, about half of capital’s contribution to GDP’s increase is accounted for by additional maintenance expenditures.

Equivalent Variation. The effects of government infrastructure spending on national welfare are of interest because GDP does not include items that such spending affects, including travel time savings for work and non-work activities. At the same time, infrastructure spending may increase GDP by inducing households to work a little more to increase consumption at the cost of less leisure, but it may not increase welfare if households are indifferent between work and leisure.

We use the equivalent variation (EV) of an increase in the transportation capital stock to measure the welfare effects of government spending by taking the difference between households’ utility in the counterfactual environment and our baseline. To express the result in dollars, we divide the utility difference by the baseline budget constraint’s Lagrange multiplier λ :

$$EV = \frac{U' - U}{\lambda} \tag{16}$$

As shown in Table 2, the EV is \$139 per working-age person for an aggregate annual welfare gain of nearly \$29 billion. Welfare increases because commuting and shopping travel times are reduced and because wages are increased, but welfare decreases because government spending is funded by an increase in taxation. At the same time, GDP increases by significantly more than the welfare gain because: (1) Much of the increase in GDP comes from an increase in labor supplied (see Appendix Table A.3), which does not raise utility because at the margin, households were indifferent between work and leisure before spending was increased, (2) An increase in investment in physical or transportation capital would increase GDP, but it would not be valued directly in utility. For example, if investment increases by \$10 and consumption increases by \$1, then the increase in GDP is much greater than the increase in utility, and (3) GDP may rise although households would be less happy if the income effect from increased taxation causes them to work more only if new government expenditures are not valued at all. The income effect is relevant here, though its importance is reduced by other factors due to our

choice of preferences and labor income tax.

We can decompose the five sources of the gains to utility by totally differentiating the utility function:

$$du = \frac{dc}{c^\sigma} - \psi (L(1 + \omega) + \xi c)^{\frac{1}{\epsilon}} ((1 + \omega)dL + Ld\omega + \xi dc + cd\xi) \quad (17)$$

The sources include the increase in consumption, the increase in labor, the savings in commuting travel time, the savings in consumption time, and the extra loss to utility. Dividing by λ , as in equation 16, we can convert utility gains to monetary gains and present the values for each source in Table 3.

The second column of the table shows that in utility terms, each working age person gains \$98 directly from consumption, holding constant shopping time. This is largely offset by the disutility from more work, a \$62 loss, and a \$14 loss in additional shopping time. Fortunately, those losses are offset by gains in commuting time of \$13 and by shopping time savings of \$104 attributable to faster non-work trips, which account for the majority of households' trips.

4.2 Transportation Efficiency

Reforming transportation infrastructure pricing and investment policies to make them more efficient and reducing the cost of inputs will generally result in greater benefits over time. For example, efficient (axle-weight) pricing of heavy trucks to reduce pavement and vehicle damage and efficient investment in highway durability that optimally trades off up-front capital costs for reductions in long-run maintenance costs fits this characterization. Efficient pricing of heavy trucks will immediately generate benefits by forcing some truckers to shift to trucks with more axles to reduce their damage to the pavement, thereby reducing maintenance expenditures. Over time, efficient investment (financed by the revenues from efficient pricing) will rebuild the highway to make the pavement more durable, and combined with efficient pricing it will greatly extend the life of the highway capital stock and further reduce expenditures to maintain it. Small, Winston, and Evans (1989) estimate that the annual steady-state benefits from this policy amount to more than \$15 billion in current dollars. In addition, rebuilding and strengthening the highway capital stock would enable it to accommodate trucks with larger carrying capacity, thereby reducing the number of trailers on the road and increasing productivity. Similar benefits will be generated by efficient pricing of and investment in the nations bridges, with efficient charges for trucks based on their gross weight.

As another example, efficient highway congestion pricing for cars and trucks combined with efficient investment (financed by the revenues from efficient pricing) to expand highway capacity would generate large annual steady-state benefits from reduced travel delays and generate additional benefits from improvements in land use that result in less sprawl and greater population densities (Langer and Winston, 2008).

The Congressional Budget Office (Congressional Budget Office, 2015b) reports that the real price of inputs, including materials and labor, which are used to build, operate, and maintain transportation infrastructure have increased 25% since 2003. In addition, the input prices of capital equipment and labor that are used for infrastructure projects are significantly inflated by Buy America requirements and Davis Bacon regulations that stipulate that “prevailing wages,” interpreted in practice as union wages, be paid on any construction project receiving Federal funds.

Given the presence of inefficiencies in infrastructure provision discussed in section 2.3, and the potential efficiency improvements discussed in this section, we explore the effects of improving transportation infrastructure by reforming public policy to (1) reduce the delays to projects’ starting and completion times, (2) purchase inputs from the lowest-cost suppliers, and (3) efficiently price and invest in roads to prevent pavement lifetimes and traffic congestion. Note that such reforms do not require increases in distortionary taxation. We examine the results under the assumption that such reforms increased the infrastructure capital stock by 5%. In other words, we are assuming that the efficient policy reforms effectively improve the value of the capital stock \$200 billion annually. This is a plausible assumption given that the estimated annual benefits in the literature from reducing project delays, input costs, maintenance expenditures, and congestion approach that order of magnitude.

As we did previously, we analyze the economic effects of more efficient transportation policy by increasing the transportation infrastructure capital stock. However, we hold the level of government spending constant because we are not increasing the stock by increasing spending. Our findings from this experiment are shown in the third column of Table 2 and a detailed summary of the endogenous variables is presented in the third column of Appendix A.3.

A policy-related increase in transportation capital that does not require higher income taxes generates large fiscal externalities that are captured by our general equilibrium model. Because taxes are not increased, labor supply is expanded and the demand for capital increases, resulting

in a modest increase in investment and significantly greater consumption. Importantly, because total expenditure is held constant as the economy expands, labor income taxes fall, slightly increasing labor supply. Compared with the scenario that increases government spending, annual GDP increases by \$50 less per working age person, or \$10 billion in aggregate, while annual welfare increases by an additional \$224 per working-age person, or \$46 billion in aggregate. Taking a closer look at the source of the welfare gain, the third column of Table 3 shows that it is largely due to greater consumption (less the additional time spent shopping). To be sure, the superiority of efficient policy reforms to greater spending on welfare grounds may not be surprising, but the point has generally been ignored in policy debates about improving the transportation capital stock. Importantly, we provide quantitative evidence that the difference in the magnitude of the welfare gain from the different approaches may be quite large. We also show that the GDP gain from an efficiency increase may be smaller even as the welfare gain is much larger.

Another way of interpreting our efficiency improvements is as a measurement of the marginal excess burden of taxation (MEB) with spending on transportation infrastructure. Measured as the reduction in goods production due to taxation keeping counterfactual infrastructure expansion the same, income effects and direct productivity effects cause MEB to be negative (-0.2), illustrating that the criticisms of Goulder and Williams (2003) are particularly pertinent when considering transportation capital. Considering welfare, MEB is 0.91 in our model. This is comparable, for instance, to the 0.71 reported in Feldstein (2006) for an across-the-board labor income tax increase.

4.3 Robustness

We calibrated our model based on assumed parametric values for the improvement in the commuting and shopping transportation wedges, TFP, and the targeted multiplier (which controls the marginal cost of transportation infrastructure). We therefore conduct robustness checks to determine the sensitivity of our findings to the assumptions we made about those parameters. We conduct our robustness checks for the scenario of improving the infrastructure capital stock by increasing government spending. The checks should also apply to the second scenario of improving the capital stock by policy reforms because both scenarios use the same parameters and make the same assumptions, which we subject to testing.

We first check how welfare is affected by our assumptions about the GDP multiplier and the output elasticity by showing in Figure 1 that welfare improves as long as the multiplier is moderately higher than 1.0, and that conditional on a positive welfare gains, welfare gains grow larger with higher output elasticities. Given our baseline assumptions of a GDP multiplier of 1.5 and an output elasticity of 0.038, we generally obtain significant welfare gains under alternative assumptions. Indeed, even with a multiplier of 1.04 and output elasticity of 0.01, we obtain (slightly) positive welfare gains.²² At the same time, our findings also indicate that when the marginal cost of infrastructure becomes too high, it is possible that infrastructure spending can cause welfare to decline even if GDP increases. This possibility motivates the importance of policy reforms that improve the efficiency of transportation policies and that reduce the marginal cost of increasing infrastructure. One lesson from Figure 1 is that high output elasticities are not enough to guarantee welfare gains, and may even suggest larger welfare losses with a multiplier below one. Multipliers above one do suggest utility gains, and the output elasticity determines how large those gains are.

Although we use the marginal cost of transportation infrastructure to set the GDP multiplier, its value is not well established in the literature, so we conduct sensitivity analysis to explore how our results would change under a plausible range. Figure 2 shows that between a range of one (constant returns to scale) to 4 (strongly diminishing returns to scale, comparable to the ratio of median monetary and physical elasticities in Melo, Graham, and Brage-Ardao (2013)), we obtain a range of GDP multipliers between 0.90 and 3. Thus, although uncertainty about the marginal cost of increasing infrastructure exists, a plausible range of $\delta_{2,KT}$ produces a range of GDP multipliers that is aligned with the empirical literature.

Finally, we examine the importance of our parameters that capture the effect of transportation infrastructure on the shopping time wedge and the commuting time wedge. We allow those parameters to range from 0 (no effect on travel time) to higher values, 50% higher shopping time, and 100% higher commuting time savings. For instance, the green (bottom) line at -0.2 suggests that if there were no reduction in shopping time travel, and only a 12 minute annual gain in time savings, welfare increase from a 5% improvement in infrastructure would be valued at \$58/capita. As expected, welfare improves significantly as the travel time wedges are reduced (see figure 3).

²²The large range, 0.9 to 2, of transportation multipliers in Congressional Budget Office (2015b) does admit welfare losses, specifically when the multiplier slips below 1.02, which is in the lower end of the range.

In sum, our sensitivity analyses indicate that our finding that transportation infrastructure spending increases welfare, which is a starting point for using our general equilibrium model to compare the effects on GDP and welfare of increasing infrastructure spending and of improving policy efficiency, is robust to reasonable parametric assumptions. We again point out that the simplifying assumptions that we have made to facilitate the model's tractability, including holding residential and workplace location constant, not accounting for improvements in the reliability of travel, and holding industry competition and product variety constant, cause us to understate the benefits from a more efficient transportation system.

4.4 A Further Test of Our Model: Explaining Japan's Low Public Infrastructure Multiplier

We have applied our model to the U.S. economy, which has relatively high spending multipliers. We provide another external validity check of our model by using it to analyze infrastructure spending in an economy with apparently low spending multipliers, namely, Japan, and to reconcile the difference between the multipliers.

Japanese spending on public infrastructure as a share of GDP has, for many years, been much higher than such spending by other OECD countries (Doi and Ihori, 2009). At the same time, Japan's public infrastructure investments have done little to stimulate its economy Glaeser (2016), and Doi and Ihori have estimated that the cost-benefit ratios for each category of its capital spending have exceeded one. Using data long after Japan had built a substantial transportation capital stock, Auerbach and Gorodnichenko (2014) find suggestive evidence that Japanese multipliers were below one after 1985, though they appear to be significantly greater than one in the full sample.

We reconcile the difference between the long-run U.S. and Japanese multipliers in the context of our model by taking our estimates of transportation capital's costs and benefits from the U.S. system and re-calibrating to Japan. Specifically, we re-calibrate disutility of labor ψ , baseline productivity \bar{A} , the transportation capital stock, and overall labor income tax rates to Japan's labor hours per working-age capita GDP per working-age capita, Japan's spending on transportation infrastructure as a as a fraction of GDP, and Japan's measured tax rates.²³

²³Labor and GDP targets come from OECD statistics, spending on infrastructure from Doi and Ihori (2009), and measured tax rates from Gunji and Miyazaki (2011).

We also change overall tax rates τ^K . Our targets and calibration parameters are available in Appendix Table A.4.

While Japan’s spending as a fraction of GDP is Japan’s calibrated transportation capital stock is significantly higher than that of the U.S., their baseline GDP per working-age person is 30% lower. Combined with increasing cost per effective unit of transportation infrastructure, this yields a per-capita transportation capital stock that is 44% higher than that of the U.S. The same exercise as in our main experiment, a 5% increase in effective transportation capital, yields a multiplier of 0.96, significantly lower than the calibrated U.S. multiplier of 1.5, and within the range of the estimates reported above, with a utility loss of \$0.09 per dollar spent.

Because the increase in the capital stock implied by Japanese infrastructure spending is so much larger than the increase in the capital stock implied by U.S. infrastructure spending, it is important to provide a more accurate characterization of depreciation when the capital stock is increased by such a large amount. We therefore allow for a more general depreciation rate, which increases as the amount of capital increases, given by:

$$\delta = \delta_0 e^{\rho K}$$

We fit δ_0 and ρ to our U.S. economy²⁴ and apply the results to Japan’s calibration. We find that increasing infrastructure spending to 7% of GDP corresponds to a GDP multiplier of 0.41, or a utility loss of \$0.64 per dollar spent. We conclude that our model can also produce plausible results that are consistent with a low long-run GDP multiplier, such as Japan’s, given that there are increasing costs to building additional units of transportation infrastructure. While increasing costs per effective unit of infrastructure play a central role in Japan’s low GDP multiplier from transportation capital, lower hours per working-age person and higher capital taxation (including corporate taxes) also play a role.

5 Considering the transition path

Although for our long-run, steady-state experiments we find that moderate increases in transportation spending can produce long-run annual welfare improvements to the U.S. economy for a variety of output elasticities, GDP multipliers, and shopping and commuting time benefits, our

²⁴This yields a $\delta_0 = 2259$, $\rho = 2.08$.

long-run framework has not accounted for various changes in infrastructure costs and benefits discussed previously that evolve over time. We therefore parameterize transportation capital’s law of motion to capture those changes and to explore how the present value of the welfare effects of spending and policy reforms are affected.

As before, we conduct experiments where the transportation capital stock increases by 5% in the long-run.²⁵ Our dynamic findings, shown graphically in Figure 4, indicate that period GDP and utility increase in the long run as described in the previous section, but the transition to achieve a permanent increase in investment at its new steady state takes fifteen years, at which point the capital stock has moved 93% of the way to the new steady state.²⁶

We begin by considering the dynamic effects of increasing the long-run capital stock by increasing government spending. Because higher taxes are required to fund the additional infrastructure investment and capital infrastructure capacity is reduced initially, GDP remains stagnant, and utility actually falls in the short run. Taking the costs of the transition path into account thus changes the calculus of whether an increase in the transportation capital stock funded by tax revenue increases welfare. As shown in Figure 4, although GDP has increased above the baseline immediately, flow utility takes ten years to become positive, turning the equivalent variation (the net present value difference in utilities, valued in dollars) into a \$16 loss (compared with a \$2,167 gain if the “long-run” welfare gain were applied in NPV).²⁷ Because people discount the future, large up-front costs today may outweigh permanently higher utility in the future. Our model indicates that this possibility applies to transportation infrastructure investment because of the necessity to commit large up-front expenditures and amounts of time before any benefits to transportation users can be realized.

A nontrivial proportion of the loss in utility from the transition path can be explained by our assumptions about the costly time-to-build parameters ϕ . But even if we set ϕ_0 to one and $\phi_1 = \phi_2 = 0$, so there are no costs to travelers and no loss of transportation capital associated with the time-to-build (beyond the standard capital investment delay), we calculate that the

²⁵We assume that labor income taxes going to transportation infrastructure adjust in each year to pay for the new, higher, fixed investment that year, while other taxes, used to pay for a fixed level of transfers and other government expenditures, slowly fall. While there is room to improve utility through tax smoothing, it is quantitatively unimportant. Such an exercise does make clear that in dealing with transportation capital rather than ordinary government expenditures, tax smoothing must consider both tax wedges and time wedges, so that actual taxes may not be constant.

²⁶Complete dynamic results for all endogenous variables can be found in Appendix Figure A.1.

²⁷The mapping from long-run gain to net present value gain comes from discounting the welfare gain by β , i.e. multiplying our welfare gain by $\frac{\beta}{1-\beta}$.

equivalent variation still amounts to a net present gain of \$369 (rather than a \$2,167 gain under a transition-free increase) because there is still a cost of transitioning to a new steady state.²⁸ For instance, if investment were immediately raised to its new long-run steady state value, there would be many periods during which households pay higher taxes but the infrastructure capital stock and the physical capital stock had not reached their steady state level—and households would not realize the benefits of this new steady state.

Faced with a costly transition path, households may be unwilling to postpone consumption or work more hours to build up a larger transportation capital stock. In our analysis, households would not find it utility maximizing to remain at a higher transportation capital level; instead they would find it beneficial to run down the capital stock, invest less, consume more, and work less because reduced investment would enable taxes to be reduced. In the long run, households would have permanently lower utility, but the short-run benefits from avoiding a costly transition would offset that loss and increase their net present value of utility. Our results point to potentially significant benefits from policies that reduce the time-to-build infrastructure and that of better policy, especially ones that reduce the time-to-build infrastructure and construction-related congestion, and that use efficient pricing to reduce congestion and improve pavement durability.

5.1 The timing of transportation infrastructure investment

In a 2014 panel of 44 leading economists, not a single economist disagreed (and 36 agreed or strongly agreed) with the statement that the U.S. could increase average incomes by spending more on roads, railways, bridges and airports, given that it has “underspent on new projects, maintenance, or both” IGM (2014). Although this view is consistent with our long-run results, it fails to account for how the transition path of capital, where projects incur long delays, increase congestion, and have benefits far in the future, adversely affect the present value of household’s utility.

Although regulatory-induced delays are arguably a politically unavoidable source of the “time to build” costs in our model, many economists still argue that “shovel-ready” projects that enable new transportation capital to be built very quickly are desirable (Summers, 2008).

²⁸Similarly, physical capital adjustment costs do not cause great losses, though they do contribute: the NPV welfare loss when $\kappa = 0$ (no physical capital adjustment costs) increases welfare by \$83.

Surprisingly, we conclude that this could cause welfare losses compared with our baseline path in which capital is gradually adjusted. Indeed, we find that by acting as a news shock and allowing private households time to adjust, regulation-induced delay may be welfare enhancing because of transportation infrastructure's long-run affect on the economy's physical capital

Expenditures on transportation capital have different effects than other government expenditures because they increase productivity and reduce commuting wedges. When productivity increases, the demand for physical capital increases, *ceteris paribus*, and the long-run equilibrium value of physical capital rises. But to take advantage of a productivity increase, physical capital must have time to adjust. For example, if the entire U.S. Interstate Highway system were built in a year, only a modest fraction of its benefits would be realized because accompanying physical capital, including motels, hotels, diners, fast-food restaurants, and gas stations would be absent from the system. Completing all investment today means that costs that were going to be incurred over time would be incurred today, but the benefits would lag temporally because the capital stock would adjust slowly to the new physical capital stock. The growing gap between costs and benefits exacerbates the welfare loss (or may cause a decline in the welfare gain) from transportation infrastructure spending.

Our general point is that a welfare loss arises when the rapid addition of capital conflicts with households' desire for a slow transition of capital to smooth consumption and labor. Thus, the benefits of infrastructure spending may increase if the economy is given time to prepare and appropriately adjust its physical capital stock. While the baseline net present value utility loss is \$15 from a 5% increase announced and implemented today, the same exercise in which the economy is given an eight-year warning actually moves the welfare loss to a welfare gain of \$288. As expected, households are able consume less and work more in the years leading up to an infrastructure increase, building up the economy's physical capital stock to both weather the increased taxation and take advantage of increased productivity.

Our examination of the plausible dynamics of the transportation capital stock sheds light on two additional differences between increases in transportation capital caused by increases in government spending and increases in transportation capital caused by more efficient policy, which makes better use of the existing stock and reduces the cost of adding to it. First, during a recession, additional spending that takes infrastructure offline may aggravate the recession in the short run by reducing productivity and increasing congestion (labor and consumption

wedges). Second, if an improvement in efficiency does not take long to implement and if it does not cause less of the existing infrastructure to be available, then it will not aggravate a recession and, in contrast to government expenditures, the sign of the equivalent variation will not change from positive to negative when we consider the transition path.²⁹

Extending this point to future developments in the transportation system, if an innovation such as autonomous vehicles can proceed with vehicle adoption occurring at a steady pace, without significant disruption, the benefits from reduced delays due to better traffic flow and the virtual elimination of accidents will increase continuously.

Finally, some economists, such as DeLong and Summers (2012), have suggested that transportation infrastructure spending may be particularly desirable in periods with near-zero interest rates. Similarly, one criticism of using our model to discuss countercyclical policy is that our model displays no “slack resources” or aggregate demand externality. In both situations, the core tradeoffs we identify remain. In the first case, the economy can cheaply put off tax payments while reaping productivity benefits when the road is completed. Allowing for debt financing with low interest rates below the marginal product of capital, our model does admit welfare gains from infrastructure spending. However, such low interest rates also allow for welfare to be increased by other methods, such as government borrowing and subsidizing (or directly purchasing) physical capital, taking advantage of arbitrage opportunities. In the second case, using “slack” resources may reduce the cost of infrastructure, but does not change the core tradeoffs we identify.

6 Conclusion

We have shown how a transportation system affects an overall economy by developing a computable general equilibrium model where improvements in transportation infrastructure, which are attributable to taxpayer funded government spending or to more efficient government policy, result in greater firm productivity and reductions in commuting and shopping travel time. The methodological benefits of our approach is that we are able to account for: (1) general equilibrium interactions between capital and labor, (2) long-run effects of increased productivity, including increased capital investment, (3) dynamic effects of the time cost to build infrastructure, and (4)

²⁹There is evidence that investment spending multipliers are higher during recessions than expansions Auerbach and Gorodnichenko (2012), which potentially alleviates this concern.

fiscal externalities of increasing GDP while holding other transfers and expenditures constant.

We find that it is important to distinguish between an infrastructure spending policy's effect on GDP and welfare because improvements in GDP may overstate the improvements in an economy from increased infrastructure spending. Specifically, a 5% increase in transportation infrastructure financed by taxpayers generated a \$50 billion increase in GDP, but a notably lower \$29 billion welfare gain. This divergence occurs because GDP may increase without increasing welfare when households are indifferent to a marginal increase in work. Given transportation infrastructure acts as a complement to labor, it is also possible to increase labor even as welfare decreases because of increased taxation.

Our model helps shed light on several issues for transportation and macroeconomic researchers. For transportation researchers, our emphasizes the idea that partial equilibrium models are likely to dramatically understate GDP gains from transportation infrastructure, or, if they calibrate to GDP gains, are likely to overstate the welfare gains of the increase in GDP. For macroeconomists, a simple extension of our model find that Japan's much higher spending on transportation infrastructure is likely to yield GDP multipliers below one, consistent with recent evidence. Finally, we find that regulation-induced delays in transportation capital spending may actually be welfare-enhancing, by acting as a news shock, and allowing households time to respond by building up the capital stock before spending occurs, which itself enhances the production gains from productivity increases.

We find that the welfare gains from improving the efficiency of infrastructure policy are likely to be larger than the welfare gains from increasing infrastructure spending because they avoid the detrimental effects of increased taxation on labor, and because government consumption in the form of increased transportation infrastructure partially crowds out private consumption. We also find that the relative welfare gains from improving infrastructure policy efficiency instead of increasing spending are greater when, in a more realistic analysis, we account for the dynamics of infrastructure investment because of the large time costs incurred. In fact, accounting for dynamics indicates that increases in government infrastructure spending may reduce the present value of U.S. welfare, and that politically-induced delays in infrastructure spending may actually be welfare-enhancing.

Although we hope that our analysis helps to elevate the importance of an efficient transportation system to the performance of a macroeconomy, we strongly advise caution about

using transportation policy inappropriately to achieve macroeconomic goals. As we have shown, it is possible that a taxpayer-funded improvement in the transportation system that increases GDP significantly produces a smaller improvement in national welfare than does an efficient transportation policy that modestly increases GDP.

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Tables

Table 1: Calibrating Moments in $G(X, \Theta)$

Description	Equation	Source
Labor hours	$L=1510$	ATUS
GDP	$Y=90342$	NIPA
Transfers as a fraction of GDP	$\frac{wL\tau^H}{Y} = 0.12$	NIPA
Wasted time shopping	$\xi c = 402$	ATUS
Transportation multiplier	$\frac{Y' - Y}{w'L'(\tau^T)' - wL(\tau^T)} = 1.5$	CEA (2014)
Transportation as a fraction of GDP	$\frac{i_t^T}{Y} = 0.025$	Congressional Budget Office (2015b)
Counterfactual change in times wasted shopping and commuting	$(\xi' - \xi)c = -4$ $(\omega' - \omega)L = -0.5$	Shirley and Winston (2004) for conservative values
Gov. expenditures as a fraction of GDP	$\frac{wL\tau^G}{Y} = 0.17$	NIPA

Table 1: This table depicts our 9 equations and 9 parameters: ψ , \bar{A} , τ^H , δ_{1,K^T} , δ_{2,K^T} , $\bar{\xi}$, γ_ξ , γ_ω , τ^G .

Table 2: Long-run baseline and counterfactual GDP aggregates and equivalent variation

Variable	Baseline	Higher	More efficient
		spending	policy
Per-working age person (dollars)			
Consumption	63,227	63,311	63,511
Investment	9,499	9,537	9,532
Government non-transportation expenditure	15,358	15,358	15,358
Government transportation expenditure	2,259	2,504	2,259
GDP	90,342	90,710	90,660
Equivalent variation	.	139	363
Aggregate (billions of dollars)			
Consumption	1952	1960	1959
Investment	3156	3156	3156
Government non-transportation expenditure	3,156	3,156	3,156
Government transportation expenditure	464	515	464
GDP	18,566	18,641	18,631
Equivalent variation	.	29	75

Table 2: All figures in the top panel are in dollars per working age person, all figures in the bottom panel are in billions of total dollars. The two are related by a factor of 206 million working-age persons. This table depicts the main inputs into GDP in the baseline model, as well as a counterfactual in which capital infrastructure is increased by 5% (paid for by labor taxation) and one in which capital infrastructure is increased by 5% through efficiency-enhancing measures. Alongside GDP, it also depicts the equivalent variation of a change for working-age persons.

Table 3: Decomposition of long-run utility gains

Variable	Value in equation 17	Higher spending	More efficient policy
Consumption increase	$dc/(\lambda c)$	98	331
Labor increase	$\iota(1 + \omega)dL$	-62	-38
Commuting time savings	$\iota \cdot L \cdot d\omega$	13	13
Additional loss to shopping	$\iota \cdot \xi \cdot dc$	-14	-47
Shopping time savings	$\iota \cdot c \cdot d\xi$	104	104
Overall gain	dU/λ	139	363

Table 3: Values in dollars per working age person. This table breaks down utility gains and losses from an increase in transportation infrastructure into five sources: (1) the increase in consumption, (2) the increase in labor hours (holding the commuting wedge constant) (3) the decrease in the commuting wedge (holding labor hours constant) (4) the increase in shopping time (holding shopping wedge constant) (5) the decrease in the shopping wedge (holding consumption constant). For notational convenience, we denote $\iota = -\frac{1}{\lambda}\psi(L(1 + \omega) + \xi c)^{\frac{1}{\epsilon}}$ and evaluate all non-differential terms at the baseline calibration.

Figures

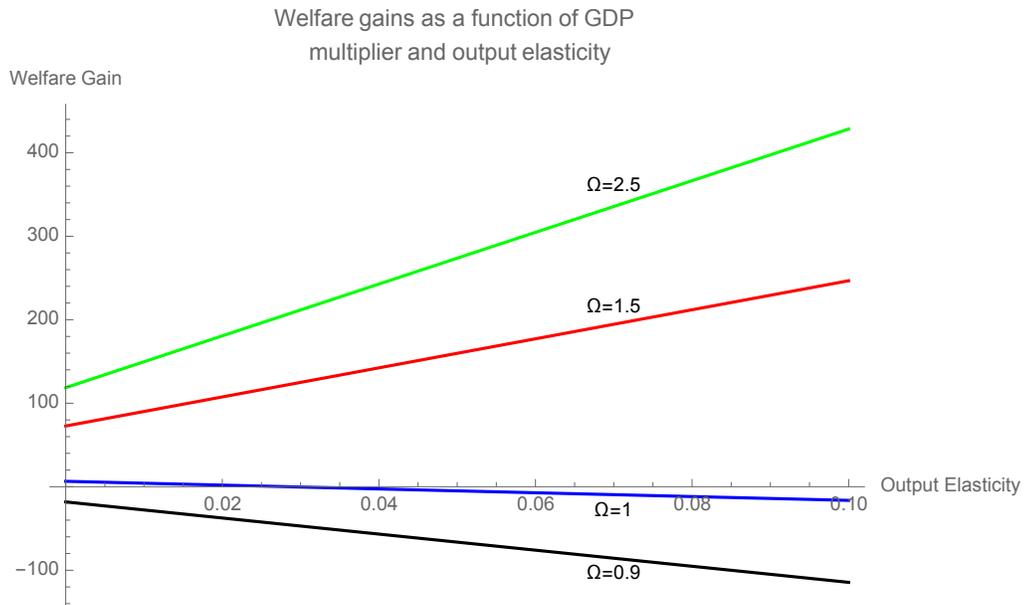


Figure 1: This figure depicts the long-run flow welfare gains (in terms of annual dollars per working age person) under a spectrum of output elasticities (λ_K) ranging from 0 to 0.1 and GDP multipliers ranging from 0.9 to 2. Individual lines refer to the value of the GDP multiplier (from top to bottom, 0.9, 1, 1.5, and 2.5), while the x-axis describes the output elasticity.

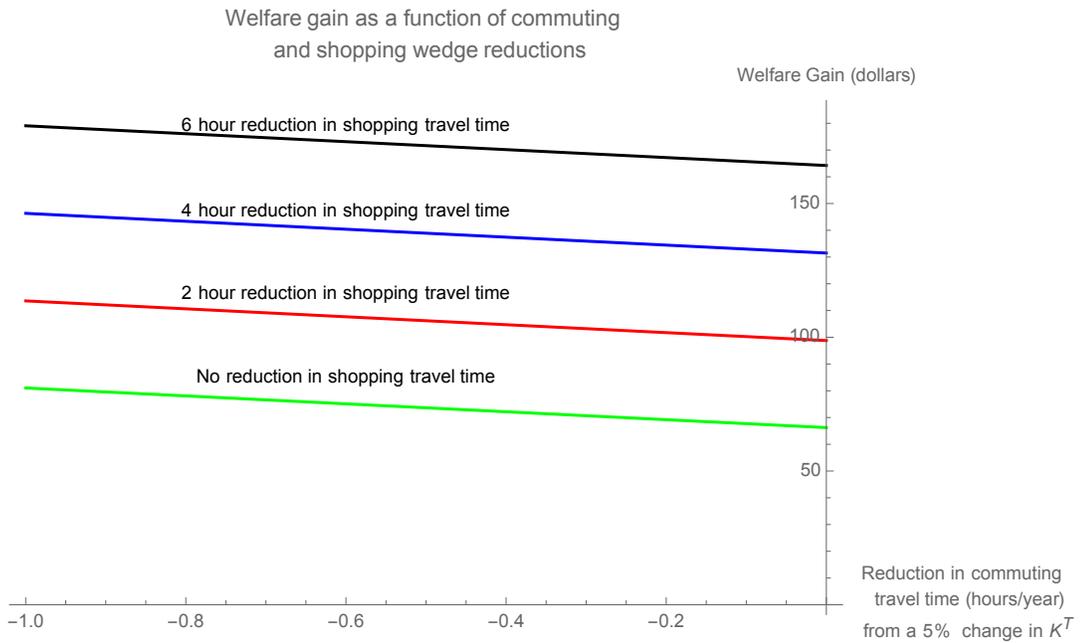


Figure 2: This figure depicts the GDP multiplier results of allowing the increase in marginal cost of additional transportation infrastructure δ_{2,K^T} to be set exogenously (rather than calibrated to fit a specified GDP multiplier). The x-axis depicts $\frac{\delta_{1,K^T} + \delta_{2,K^T}}{\delta_{1,K^T}}$. Reasonable marginal cost increases result in GDP multipliers within the range of those implicit in Congressional Budget Office (2015b) and estimated in CEA (2014).

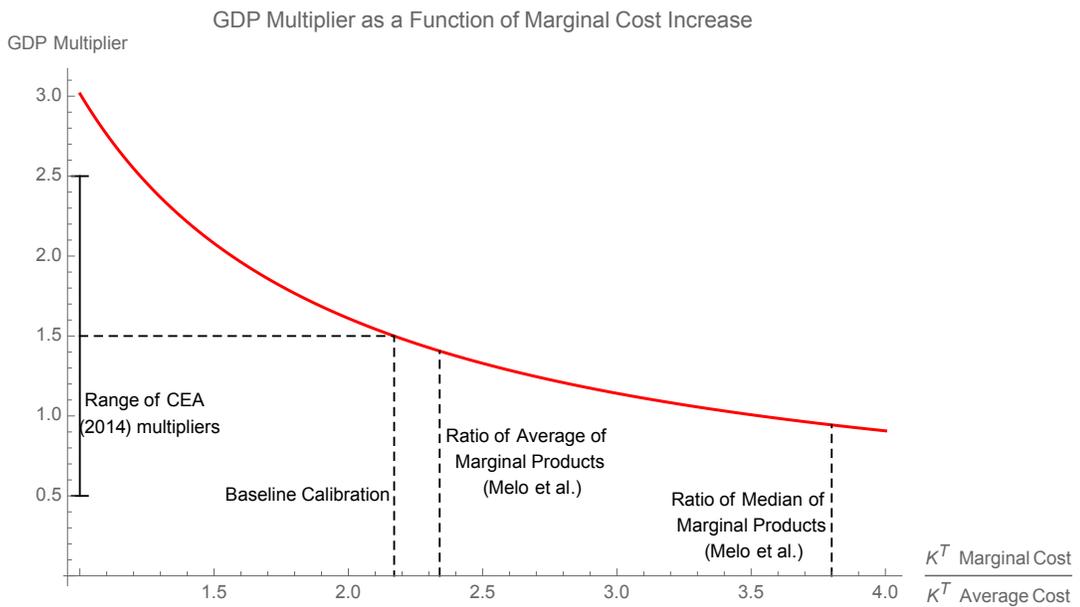


Figure 3: This figure depicts welfare gains as a function of commuting time reduction and shopping time reduction.

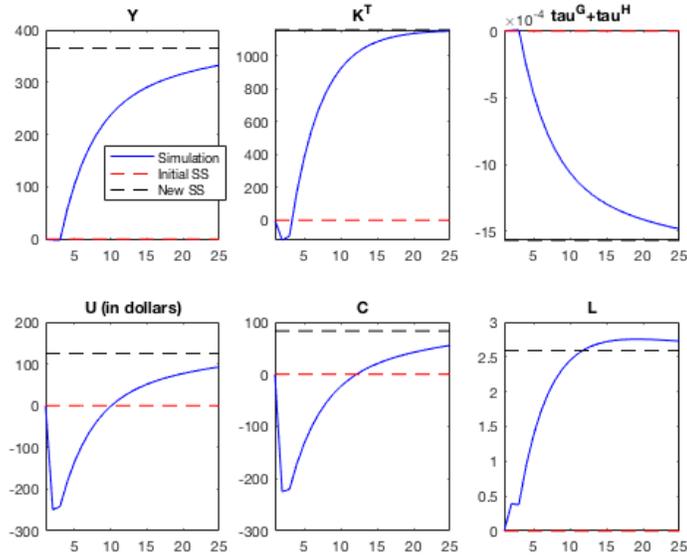


Figure 4: This figure depicts the reaction of the economy to a sudden, unexpected, and permanent increase in transportation infrastructure investment i_K large enough to increase K^T by 5%. Each subplot contains three lines: the dashed red line denotes the original steady state, the dashed black line denotes the new steady state, and the blue line shows the economy's transition path. All variables are shown in levels corresponding to their steady state values, with consumption, GDP, and capital in dollars per working-age person, L in hours per year per working age person, U in utiles, and $\tau^G + \tau^H$ the combined average non-transportation expenditure and transfer tax rate. The tax used to fund transportation capital, as well as other endogenous variables, are depicted in Appendix Figure A.1.

Appendix A: Figures and Tables

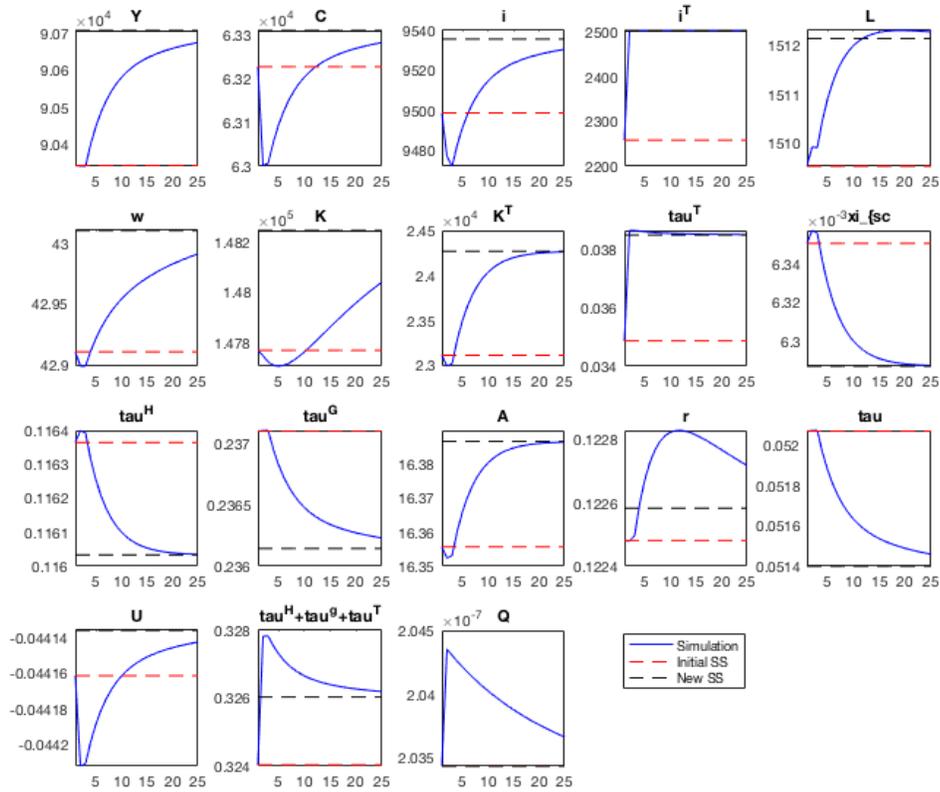


Figure A.1: This figure depicts the reaction of the economy to a sudden, unexpected, and permanent increase in transportation infrastructure investment i_K large enough to increase K^T by 5%. Each subplot contains three lines: the dashed red line denotes the original steady state, the dashed black line denotes the new steady state, and the blue line shows the economy's transition path. All variables are shown in levels corresponding to their steady state values, with consumption, GDP, investment, and income variables interpretable in dollars per working-age person.

Table A.1: Equilibrium conditions in $f(X; \Theta, K^T)$

Description	Equation
FOC with respect to c	$\frac{1}{c_t^\epsilon} - \xi_t \psi(L_t(1 + \omega_t) + \xi_t c_t)^{\frac{1}{\epsilon}} = \lambda_t$
FOC with respect to L	$(1 + \omega_t) \psi(L_t(1 + \omega_t) + \xi_t c_t)^{\frac{1}{\epsilon}} = \lambda_t w_t (1 - \tau^H - \tau^G - \tau^T)$
FOC with respect to i_t	$Q_t \left(1 - \kappa \frac{(i_t - \delta K_t)}{K_t}\right) = \lambda_t$
FOC with respect to K_{t+1}	$Q_t = \beta \lambda_{t+1} r_{t+1} - \beta Q_{t+1} \left(1 - \delta + \frac{\kappa}{2} \left(\delta^2 - \left(\frac{i_{t+1}}{K_{t+1}}\right)^2\right)\right)$
Budget constraint	$c_t + i_t = w_t L_t (1 - \tau_t^H - \tau_t^G - \tau_t^T) + r_t K_t + T_t$
Transfers	$T_t = w_t L_t (\tau_t^H + \tau_t^K)$
Non-transportation expenditures	$G_t = w_t L_t \tau_t^G$
Effective TFP	$A_t^* = \bar{A} (1 + \lambda_K) \tilde{K}^T$
L.O.M. of K_t^T	$K_{t+1}^T = (1 - \delta_{1,K^T}) K_t^T - \delta_{2,K^T} (K_t^T - \bar{K}^T) + \sum_{j=t}^{t-2} \phi_{t-j} i_t^T$
Funding for transportation	$i_t^T = w_t L_t \tau_t^T$
L.O.M. of K_t	$K_{t+1} = (1 - \delta) K_t + i_t - \frac{\kappa}{2} \left(\frac{i_t}{K_t} - \delta\right)^2 K_t$
Labor demand	$w_t = (1 - \alpha) A_t^* K_t^\alpha L_t^{1-\alpha}$
Capital demand	$r_t = (1 - \tau_t^K) \alpha A_t^* K_t^{\alpha-1} L_t^{1-\alpha}$
GDP	$Y_t = A_t^* K_t^\alpha L_t^{1-\alpha}$
Definition of ξ	$\xi_t = \bar{\xi} (1 + \gamma_\xi) \tilde{K}_t^T$
Definition of ω	$\omega_t = \bar{\omega} (1 + \gamma_\omega) \tilde{K}_t^T$
Definition of Utility	$U_t = \frac{c_t^{1-\epsilon}}{1-\epsilon} - \psi \frac{\epsilon}{1+\epsilon} (L_t(1 + \omega_t) + \xi_t c_t)^{\frac{1+\epsilon}{\epsilon}}$

Table A.1: This table depicts our 17 equations and 17 unknowns: c_t , L_t , i_t , Q_t , λ_t , T_t , G_t , A_t^* , K_t^T , K_t , i_t^T , w_t , r_t , Y_t , ξ_t , ω_t , U_t . Q_t is the Lagrange multiplier on the capital law of motion, and G_t is non-transportation government expenditures. Note that when we denote $f(X; \Theta, K^T) = 0$, we solve each calibrating equation so that it equals zero. For interpretability, we use both sides of the equality. When solving the model, we solve and report for the after-tax interest rate.

Table A.2 Calibration

Parameter	Symbol	Value	Source
Intertemporal elasticity of substitution	σ	1.38	Smets and Wouters (2007)
Frisch elasticity of labor supply	ϵ	0.75	Chetty et al. (2011)
Capital's output share	α	0.283	Gomme and Rupert (2007)
Depreciation rate of capital	δ	0.064	Gomme and Rupert (2007) (See description)
Government expenditure tax	τ^G	0.237	$G(X, \Theta)$
Working transportation time loss	$\bar{\omega}$	0.11	ATUS
Consumption transportation time loss	$\bar{\xi}$	0.006	$G(X, \Theta)$
Baseline depreciation rate	δ_{1,K^T}	0.097	$G(X, \Theta)$
Marginal depreciation rate	δ_{2,K^T}	0.114	$G(X, \Theta)$
Total factor productivity	\bar{A}	16.35	$G(X, \Theta)$
Disutility of labor	ψ	$1.98 \cdot 10^{-10}$	$G(X, \Theta)$
Transfer tax rate	τ^H	0.05	$G(X, \Theta)$
Capital tax rate	τ^K	0.29	Gomme and Rupert (2007)
Capital adjustment costs	κ	8	Canzoneri, Cumby, and Diba (2005)
Elasticity of A with w.r.t. $(K^T)'$	λ_K	0.038	Melo, Graham, and Brage-Ardao (2013)
Elasticity of ξ w.r.t. $(K^T)'$	γ_ξ	-0.24	$G(X, \Theta)$
Elasticity of ω w.r.t. $(K^T)'$	γ_ω	-0.08	$G(X, \Theta)$
Discount rate	β	0.95	Gomme and Rupert (2007)
Costly time-to-build parameters	$\{\phi_0, \phi_1, \phi_2\}$	$\{-0.5, 0.5, 1\}$	Al-Kaisy and Hall (2003); Illinois Department of Transportation (2013)

Table A.2: This table depicts our important parameters and gives a guide as to the sources of their direct calibration. $G(X, \Theta)$ denotes parameters calibrated jointly to match targets in the data.

Table A.3: Long-run baseline and counterfactual endogenous variable values

Variable	Baseline	Transportation capital increases by 5%	Transportation efficiency increases by 5%
Consumption	63,227	63,311	63,511
Labor	1,510	1,512	1,511
Wage	43	43	43
Capital Income	18,099	18,172	18,162
Transfer	10,841	10,871	10,867
Total Factor Productivity	16.36	16.39	16.39
Expenditures Tax	0.052	0.052	0.052
Transport Tax	0.035	0.038	0.034
Production	90,342	90,710	90,660
Shopping time conversion	0.0064	0.0063	0.0063
Commuting wedge	0.116	0.116	0.116
Utility	-0.044161	-0.044133	-0.044088
Capital	147,770	148,370	148,290
Investment	9,499	9,537	9,532

Table A.3: All values except labor, productivity, taxes, and conversion rates are in dollars per working-age person. Total factor productivity is unitless while the taxes are in percent terms.

Table A.4: Japan Calibration

Variable	Target	Value
GDP	63484	63484
Labor hours	1418	1418
Infrastructure spending as a fraction of GDP	0.07	0.07
Marginal labor income tax rate	0.33	0.33
Marginal capital income tax rate	0.55	0.55
Variable	Symbol	Value
Disutility of labor	ψ	2.77
Total factor productivity	\bar{A}	14.85
Transportation capital per working-age person	\bar{K}^T	33,418
Non-transportation labor income tax	τ^G	0.19
Marginal capital income tax rate	τ^K	0.55

Table A.4: The first panel depicts the four new targets for Japan: (1) GDP per working-age capita (in dollars) (2) labor hours per working-age capita, (3) spending on infrastructure as a fraction of GDP, and (4) marginal labor income tax rate) as well as the directly-calibrated capital tax. The second panel depicts parameters estimated.