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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 quantitative dynamic 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, such as congestion pricing and eliminating laws that artificially inflate input prices, concluding that taxpayer-funded transportation improvements that increase GDP significantly may produce smaller welfare gains than efficient policies that increase GDP modestly.

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 given.[2] Trade theorists (Dixit and Stiglitz, 1977; Krugman, 1979, 1980) developed general equilibrium

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

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models, but those models incorporated transportation improvements only as a source of lower trade barriers.[3] Macroeconomists have estimated the returns from investments in public infrastructure capital,[4] and have used DSGE models to examine productive government investment in a manner broadly similar to this paper (Leeper et al., 2010). We differ from Leeper, Walker, and Yang by focusing on permanent changes and economic welfare and by incorporating shopping and commuting time wedges, the costly time to build infrastructure, and efficient government pricing and investment policy, which we find are important for assessing the effects of infrastructure spending on welfare and GDP.

In this paper, we develop an applied general equilibrium model that includes the capital 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. We find that the transition costs that are associated with building additional infrastructure are important, and that a failure to include them by simply comparing steady states may cause the benefits from increasing infrastructure spending to be seriously overstated.

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. Thus, the welfare effects of infrastructure spending are different from its effect on GDP and the relative effects are ambiguous a priori. For example, spending may improve welfare by reducing commute travel time but may not increase GDP. In addition, spending is financed by taxation that reduces welfare, but may not reduce GDP. We find that government expenditures that improve transportation capital increase GDP far more than they increase economic welfare. In our case, the subsequent reductions in commuting and shopping travel times cause households to substitute the additional leisure time for additional time working and traveling to increase consumption, which increases GDP, but produces a smaller gain in welfare.

Our model yields important insights. First, we conclude that endogenous responses make up more than half of the overall change in GDP, exceeding the direct effects of transportation infrastructure on GDP though productivity gains. Consequently, we obtain a larger change in GDP than we would obtain by using a partial equilibrium model, although the change in welfare is smaller than the change in GDP may suggest. Second, our model, which was initially calibrated to the relatively large U.S. GDP multipliers, calls for much smaller GDP multipliers when it is calibrated for countries, such as Japan, with a transportation capital stock that constitutes a high share of GDP.[5] We argue that this finding is consistent with the evidence that additional units of transportation infrastructure have higher costs (or lower productivity). Third, we find that delays in building transportation infrastructure may enhance welfare by giving private capital more time to respond (for example, by building new gas stations and restaurants along a new highway), thereby improving the effectiveness of the 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 et al., 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.

Our analysis questions the social desirability of spending large sums of money on public infrastructure to increase GDP, as many economists suggested in the wake of the 2008–2009 recession and its sluggish recovery and continue to advocate in the Biden administration as we struggle to recover from the global pandemic.[6] 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, quantitative dynamic 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 shopping trips, efficient transportation infrastructure enables firms and households to be

[3] For 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.

[4] Aschauer (1989), Munnell (1990) and Barro (1991), Baxter and King (1993) initiated this literature. Shatz et al. (2011) and Ramey (2021) provide recent surveys, with Ramey building transportation infrastructure into a Medium-Scale New Keynesian framework. Barro (1990) discusses productive government spending in a model of endogenous growth.

[5] The ease with which our model can be adapted to Japan for macroeconomic analysis is a benefit over more geographically-specific models.

[6] See, for example, Summers (2016), Krugman (2016). For an opposing view, see Glaeser (2016).

more productive. We assume that government expenditures on infrastructure to improve its performance are financed by a labor income tax.[7]

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:

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

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.[8] ψ is the disutility of time spent on non-leisure activities, including work-time L_t. η_t is the fraction of working time spent commuting, so that $\eta_t L_t$ 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.

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

$$c_t + i_t = w_t L_t (1-\tau_t) + (1-\tau_t^K) r_t K_t + T_t + \pi_t \tag{2}$$

where i_t is the household investment in capital, w_t is the hourly wage, τ is the tax on labor, $(1-\tau_t^K) r_t K_t$ 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 et al., 2005), namely:

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

The household's problem is to maximize the net present value of utility in Eq. (1) by choosing paths for consumption, investment, future capital, and labor subject to the budget constraint in Eq. (2), the capital law of motion in Eq. (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 are[9]:

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

$$(1+\eta_t) \psi (L_t(1+\eta_t) + \xi_t c_t)^{\frac{1}{\epsilon}} = \lambda_t w_t (1-\tau) \tag{5}$$

In the standard neoclassical growth model, Eq. (4) sets the marginal utility of consumption equal to the marginal utility of wealth. In contrast, when households in our analysis consume, 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 Eq. (4). Improving the efficiency of transportation capital would reduce the consumption tax on households' time. Eq. (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.

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[7] While 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. Our assumption is consistent with the finding that in the presence of congestion, an income tax-financed increase in spending may be preferable when a quasi-public good directly has both productivity benefits as well as direct benefits (Chatterjee and Ghosh, 2011).

[8] It 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 et al. (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 et al. (2014), our choices of σ and ϵ will reflect a long-run income effect slightly stronger than the substitution effect.

[9] We 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.

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.[10] 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,[11] 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, we can absorb it into total factor productivity and express the production function as:

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

where

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

The first-order conditions that yield the demand for labor and capital are the result of a competitive firm with constant returns to scale in chosen inputs L_t and K_t that seeks to maximizes production net of labor and capital costs (which together imply zero profits remitted to households):

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

Note that an increase in transportation capital will increase both the demand for capital and the demand for labor through A_t^*. 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 has four real expenditures: (1) G_t, public services (such as military spending), (2) T_t, transfers, (3) i_t^T, transportation capital investment, and (4) real interest payments on debt $r_t^G D_t$, which may be at a different interest rate r_t^G than the economy's. We assume that debt issued by the government is obtained by foreigners, as agents in the model prefer the higher interest rate of physical capital. We return to this issue when we consider infrastructure spending in a low-interest rate economy. Government funds all expenditure with labor income taxes τ_t, capital taxes τ_t^K, and new debt $D_t - D_{t-1}$. The government's budget constraint, which balances government expenditures with government funds, is given in Eq. (7).

$$G_t + T_t + \gamma_1 exp(\gamma_2 K_t^T) i_t^K + r^G D_t = \tau w_t L_t + \tau_t^K r_t K_t + (D_t - D_{t-1}) \tag{7}$$

Our most important change to the government's budget constraint is in modeling the cost of transportation infrastructure. Similarly to Greenwood et al. (1997)'s model of equipment capital, the cost of a unit of i_t^T is nonlinear. Specifically, the cost of an additional unit of investment grows as the transportation capital stock grows, with the relationship governed by estimated parameters γ_1 and γ_2.[12] This cost behavior captures the idea, which we support with evidence below, that as the transportation capital stock of a mature system grows, decreasing returns or resource constraints set in such that the marginal cost of an effective unit of transportation capital increases significantly.

Government transportation capital investment i_t^K follows the transportation capital law of motion:

$$K_{t+1}^T = (1 - \delta_{K^T}) K_t^T + \sum_{j=0}^{\overline{T}} \phi_j i_{t-j}^T \tag{8}$$

[10] Fernald (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.

[11] As Ramey (2021) notes, there are two output elasticities. The first is the output elasticity in the production function (λ_K below). But because of long-term general equilibrium effects, there is also a steady-state output elasticity. We discuss this second in the form of an output multiplier, rather than an output elasticity, and denote it Ω.

[12] We thank an anonymous reviewer for suggesting modeling costs in this way.

While most of our government budget constraint and capital laws of motion are standard, we modified the government's budget constraint (Eq. (7)) and law of motion of transportation infrastructure (Eq. (8)) in three important ways. 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 rising political economy constraints, so that at the margin it takes more spending to get the same effect as previous spending. Evidence points to a difference between average and marginal cost of transportation infrastructure. For instance, a meta-study (Melo et al., 2013) shows that the output elasticity of transportation capital measured in monetary terms is less than half that measured in physical terms, consistent with an increasing monetary cost for the same physical mile. And Brooks and Liscow (2020) find that between 1960–1980, the cost of an additional mile of U.S. transportation infrastructure grew threefold.

Second, we model the "costly-time-to-build" aspect of transportation infrastructure in Eq. (8). As noted, transitionary construction may actually decrease available transportation capital in the short run ($\phi_j < 0$). 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 per year 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 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 better understand our "costly time-to-build" modification, take $\overline{T} = 3$, so that we have three years of potential delay, including the initial year of investment, or ϕ_0, ϕ_1, and ϕ_2 in Eq. (8). Consider the example where $\phi_0 = -0.5$, $\phi_1 = 0.5$, and $\phi_2 = 1$. Our 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, re-open 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 by the third year. All our calibrations will assume that $\sum_{t=0}^{\overline{T}} \phi_t = 1$, so that beyond the effects of discounting and transitory changes in the capital stock, there is no "loss" in adjusting transportation capital.

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 η_t, the transportation cost of working, and (4) it requires an increase in τ_t, the labor income tax rate used to raise money for additional transportation capital. We assume plausible elasticities to capture the effect of a change in transportation capital on effective TFP and the shopping and transportation wedges.

The first three effects on the economy capture the 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 $\overline{A}$, $\overline{\xi}$, $\overline{\eta}$, and $\overline{K^T}$, respectively. Denote the net percentage change of capital from the baseline as $\widetilde{K}^T$ and denote the elasticities of the first three variables with respect to the last variable as λ_K, γ_ξ, and γ_η. Given this notation, Eqs. (9)–(11) relate changes in the effective transportation capital stock K^T to changes in productivity and the two transportation wedges.

$$A_t^* = \overline{A} \exp(\lambda_K \widetilde{K}^T) \tag{9}$$

$$\xi_t = \overline{\xi} \exp(\gamma_\xi \widetilde{K}^T) \tag{10}$$

$$\eta_t = \overline{\eta} \exp(\gamma_\eta \widetilde{K}^T) \tag{11}$$

The fourth effect of a change in the transportation capital stock is a change in labor income taxation, which could be determined from Eq. (7). 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. On the other hand, increased spending in transportation capital might pay for itself by increasing GDP enough so that the government is able to lower taxes, though we do not find this to be the case.

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 less labor intensive production technology, then it would generate a smaller increase in the demand for labor and a smaller increase in capital, altering the otherwise constant capital–labor ratio.

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

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 cause frictions 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 h in our steady state, a value broadly consistent with Cociuba et al. (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 min each day are spent traveling. Of these, approximately 29 min 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:

$$\bar{\xi} c_{ss} = 401 \tag{12}$$

and

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

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] 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 0.38, which reflects capital's more recent share in national income (see, for instance, Karabarbounis and Neiman, 2014). We choose $\bar{A}$, the baseline total factor productivity of production such that GDP per working age person is \$90,342,[16] 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 person.[17] We set the depreciation rate of transportation capital to 2.5%, which is somewhat higher than 2% suggested by the U.S. Bureau of the Census because we include non-investment maintenance costs of 20%, but it is lower than 4.1% obtained by Holtz-Eakin (1993) and 7% obtained by Canning and Bennathan (2000).

We estimate the two transportation cost parameters from Eq. (7) by targeting the fraction of GDP spent on transportation infrastructure (2.5%) and the output multiplier, discussed below. In our baseline, we estimate γ_1 to be 2.28 and γ_2 to be $3.00 \cdot 10^{-5}$. Taken together, these suggest that at low levels of transportation capital, additional physical units cost little. However, as transportation capital levels rise, additional units cost more. To get a grasp on what our parameters mean, consider the case in which current U.S. infrastructure was reduced by 50%. In such a case, the cost per physical unit would nearly double (rise by 93%) in our model. This is qualitatively consistent with the 300% rise in physical costs in U.S. infrastructure from 1960–1980 documented by Goulder and Williams (2003).

An important feature of our analysis is that the findings are not sensitive to a particular functional form chosen for transportation costs that are included in Eq. (7) because only the ratio of marginal and average costs are relevant for the steady state comparisons. Accordingly, we could have specified, for instance, varying depreciation rates or linear instead of exponential costs without

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

[15] Our 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.

[16] We 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.).

[17] Using 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.

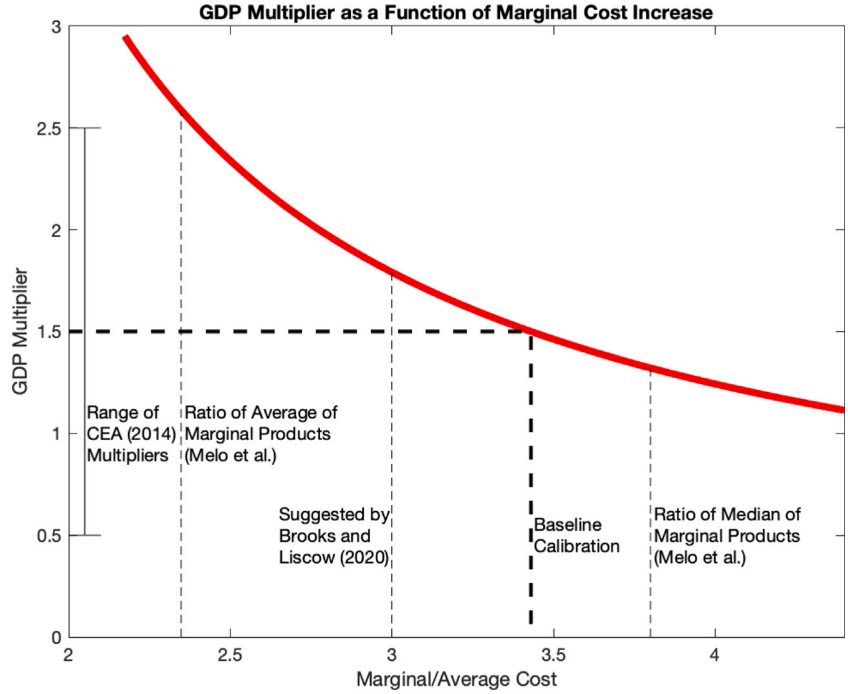

Fig. 1. This figure depicts the GDP multiplier results of allowing the increase in marginal cost of additional transportation infrastructure (controlled by γ_1 and γ_2) to be set exogenously (rather than calibrated to fit a specified GDP multiplier). The x-axis depicts the ratio of marginal cost of an additional unit of transportation infrastructure divided by the average cost. Reasonable marginal cost increases result in GDP multipliers within the range of those implicit in CBO (2015) and estimated in CEA (2014).

noticeably affecting the steady-state results. We therefore chose specifications to facilitate interpretation of the analysis.[18] Given the importance of the ratio of the average and marginal transportation cost, we used an output multiplier to directly calibrate it, with a plausible base case value of 1.5, and we subject it to sensitivity analysis over a range from 0.9 to 2.5. Importantly, our approach improves upon a naïve calibration that specifies an output multiplier but holds behavior constant by not accounting for endogenous responses as we do here.

We also perform an out of sample sensitivity test of our model. In our baseline calibration, our assumed output multiplier informs the difference between marginal and average transportation cost. As an alternative, we treat the output multiplier as endogenous by assuming a ratio between the marginal and average cost. We find very similar results when we do so using the meta-studies in Melo et al. (2013). Melo et al. (2013) report two different output elasticities: a monetary elasticity and a physical elasticity. The difference between the two can be interpreted as the difference due to rising cost. For instance, if a 1% marginal increase in spending yields the same output elasticity as a 0.5% increase in physical infrastructure, it suggests increasing cost per unit of return. 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 3.4 in our model), while the ratio of the median of the two elasticities is 3.8, suggesting far higher costs. Fig. 1 depicts how our estimates of the ratio of marginal and average cost vary by the choice of GDP multiplier (or, equivalently, how the GDP multiplier varies by the choice of the ratio of marginal to average costs). We conclude that our results for the multiplier would not be substantially changed had we not targeted it and instead targeted the ratio of marginal to average costs using the implicit estimates available from Melo et al. (2013). For instance, had we used the ratio of median of marginal products, our multiplier would have been 1.32 rather than 1.5, while if we had used the ratio of averages, our multiplier would have been 2.5. While our choice lies in the middle, we also examine a range of multipliers.

Ordinary taxation of labor τ, which funds government consumption expenditures and gross investment, is set to raise 31.5% of GDP: 17% for government purchases and investment net of transportation infrastructure spending, 12% for transfers, and 2.5% for transportation capital investment. The capital tax is set to 0.29, as in Gomme and Rupert (2007). Finally, the interest rate on government debt is set to be 2%, reflecting a significant gap between private interest rates and the rates at which the government can borrow.

[18] Closed-form equations for γ_1 and γ_2 as a function of average cost of transportation capital c_1, marginal cost of capital c_2, and baseline transportation capital $\overline{K^T}$ are: $\gamma_1 = \frac{c_1}{\delta^K} e^{\frac{c_1 - c_2}{c_1}}$ and $\gamma_2 = \frac{c_2 - c_1}{c_1 \overline{K^T}}$. If we take the average and marginal cost as the deep structural parameters that should map to γ_1 and γ_2, our baseline calibration would be $c_1 = 0.11$, $c_2 = 0.19$.

Because we calibrate to the output multiplier in CEA (2014), we define our static model output multiplier to be consistent with their source. Specifically, we follow the CBO and define the static transportation infrastructure spending multiplier Ω in Eq. (13) below as the change in GDP generated by a permanent increase in transportation infrastructure divided by the cost of that change. Letting $Cost$ be expenditures on new transportation infrastructure, the "direct effect" on the economy:

$$\Omega = \frac{\Delta Y}{\Delta Cost} \tag{13}$$

CEA (2014) notes that a large range of output multipliers, from 0.5 to 2.5, has been used for policy analyses, also see CBO (2015). 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 of our moments target the steady state. As we have noted, we would have generated similar results had we instead targeted the difference in marginal and average cost of infrastructure.

The three key parameters related to the effects of changes in transportation infrastructure on GDP and welfare are the output elasticity, the commuting time wedge, and the shopping time wedge. We use the mean U.S. output elasticity of 0.038 reported in Melo et al. (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.[20] 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 h. 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 h and 4 h 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 min, which imply higher elasticities and larger time savings of infrastructure investments (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 et al., 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 of infrastructure investment. 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; we calibrate to that estimate. 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 et al. (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.

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

[20] This is also consistent with more recent findings of heterogeneity in economic benefits of transportation infrastructure (Allen and Arkolakis, 2019).

Table 1
This table depicts our 9 equations and 9 parameters: ψ, $\bar{A}$, τ^H, γ_1, γ_2, $\bar{\xi}$, γ_ξ, γ_η, τ^G. While not present in Table 1, depreciation rates are linked to the fourth equation via i_t^T and Eq. (8).

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	$\frac{T}{Y} = 0.12$	NIPA
Wasted time shopping	$\bar{\xi}c = 402$	ATUS
Transportation multiplier	$\frac{\Delta Y}{\Delta Cost} = 1.5$	CEA (2014)
Transportation as a fraction of GDP	$\frac{i_t^T}{Y} = 0.025$	CBO (2015)
Counterfactual change in times	$(\xi' - \xi)c = -4$	Shirley and Winston (2004)
wasted shopping and commuting	$(\eta' - \eta)L = -0.5$	for conservative values
Gov. expenditures as a fraction of GDP	$\frac{G}{Y} = 0.17$	NIPA

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

Variable	Baseline	Higher spending	More efficient policy
	Per-working age person (dollars)		
Consumption	59,970	60,047	60,188
Investment	12,754	12,812	12,809
Government non-transportation expenditure	15,358	15,358	15,358
Government transportation expenditure	2,260	2,535	2,260
GDP	90,342	90,752	90,728
Equivalent variation	·	122	273
	Aggregate (billions of dollars)		
Consumption	12,324	12,340	12,369
Investment	2,621	2,633	2,632
Government non-transportation expenditure	3,156	3,156	3,156
Government transportation expenditure	464	521	464
GDP	18,566	18,650	18,645
Equivalent variation	·	25	56

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 or debt issuance 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 Table A.3.

After examining the long-run benefits of expanding the transportation capital stock and showing that it increases long-run welfare, we turn to the transition paths to explore why additional transportation capital may be socially undesirable and conflict with our steady state analysis. We highlight a classic idea in the neoclassical growth model that a higher capital stock may make workers better off in the steady state and may increase aggregate production, but workers present value of utility could be maximized if the capital stock can 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 $274 per worker, as shown in the first panel of Table 2, or $56 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 $79 billion per year as required by calibration.[21]

[21] Dupor (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.

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 Eq. (6) and divide it by production to obtain:

$$\frac{dY}{Y} = \frac{dA}{A} + \alpha\frac{dK}{K} + (1-\alpha)\frac{dL}{L} \tag{14}$$

Based on the values of the endogenous variables in Table A.3 and our assumed value of $\alpha = 0.38$, we attribute a 0.43% increase in GDP from increasing transportation spending to changes in A, K, and L, with approximately 42% of the increase in GDP due to the increase in productivity, 38% due to increased capital and 20% due to increased labor.[22] 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 more than 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. This also highlights the importance of our choice in calibrating to an alternative regime, rather than naively taking behavior as given.

Eq. (14) 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. This point is also discussed in Ramey (2021), who derives the long-run aggregate elasticity of government capital $\epsilon^{SS}_{YK^T}$ as a function of the production function output elasticity denoted λ_K, the depreciation rate of government capital δ^K, the level of government capital K^T, capital's output elasticity α, the Hicks elasticity of labor supply ϵ^H, and consumption C. Ramey derives a relationship between the two elasticities:

$$\epsilon^{SS}_{YK^T} = \frac{1}{1+\Omega}\left(\Omega + \frac{1}{1-\alpha}\theta_G\right), \text{ where } \omega = \epsilon^H\frac{\delta^K K^T}{C}$$

The first term inside the parentheses, Ω, makes it clear that output would be increased simply due to an increase in labor supply in response to an income effect from increased government spending, even if the production function elasticity were zero. The second term inside the parentheses clarifies that the output elasticity of capital enhances the long-run effect of transportation capital, because it includes $\frac{1}{1-\alpha}$ which is greater than unity. Similarly, the term outside the parentheses summarizes the augmenting effects of labor supply, which responds to increased private and government capital. Although the relationship between our general equilibrium multiplier and our production function output elasticity is largely governed by Ramey's output multiplier, that relationship also accounts for the effects of changing commuting and shopping time wedges, and holds government spending constant in levels, not as a fraction of GDP.

Consumption and Investment. Although GDP increases by $410/worker, consumption increases by only $77/worker, with two-thirds of the increase in GDP accounted for by the increase in government transportation expenditures of $274/worker. The increase in investment of $58/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:

$$EV = \frac{U' - U}{\lambda} \tag{15}$$

As shown in Table 2, the EV is $122 per working-age person for an aggregate annual welfare gain of nearly $25 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 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.

[22] While 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 0.03%, or 42,000 workers in 2016. Because modeling a reduction in the fixed cost of transport tends to decrease intensive and increase extensive participation, we consider this approximation to be conservative.

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 $\iota = -\frac{1}{\lambda}\psi\left(L(1+\eta)+\xi c\right)^{\frac{1}{\epsilon}}$ and evaluate all non-differential terms at the baseline calibration.

Table 3: Decomposition of long-run flow utility gains

Variable	Value in Eq. (16)	Higher spending	More efficient policy
Consumption increase	$dc/(\lambda c)$	89	251
Labor increase	$\iota(1+\eta)dL$	−56	−46
Commuting time savings	$\iota \cdot L \cdot d\eta$	11	11
Additional loss to shopping	$\iota \cdot \xi \cdot dc$	−12	−33
Shopping time savings	$\iota \cdot c \cdot d\xi$	89	89
Overall gain	dU/λ	122	273

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

$$du = \frac{dc}{c^{\sigma}} - \psi\left(L(1+\eta)+\xi c\right)^{\frac{1}{\epsilon}}\left((1+\eta)dL + Ld\eta + \xi dc + cd\xi\right) \tag{16}$$

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 Eq. (15), 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 $89 directly from consumption, holding constant shopping time. This is largely offset by the disutility from more work, a $56 loss, and a $12 loss in additional shopping time. Fortunately, those losses are offset by gains in commuting time of $11 and by shopping time savings of $89 attributable to faster non-work trips, which account for the majority of households' trips. We discuss the changes in utility caused by more efficient policy below.

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 et al. (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 (CBO, 2015) 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, while Goulder and Williams (2003) calculate a 300% rise from 1960–1980. 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 increase pavement lifetimes and reduce traffic congestion. Note that such reforms do not require increases in distortionary taxation.[23] We obtain results under the assumption that such reforms increased the infrastructure capital stock by

[23] 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. Unfortunately, cities and states are not preparing for autonomous vehicles in a systematic fashion; thus, adoption is likely to occur in fits and starts and disrupt the flow of social benefits Winston and Karpilow (2020).

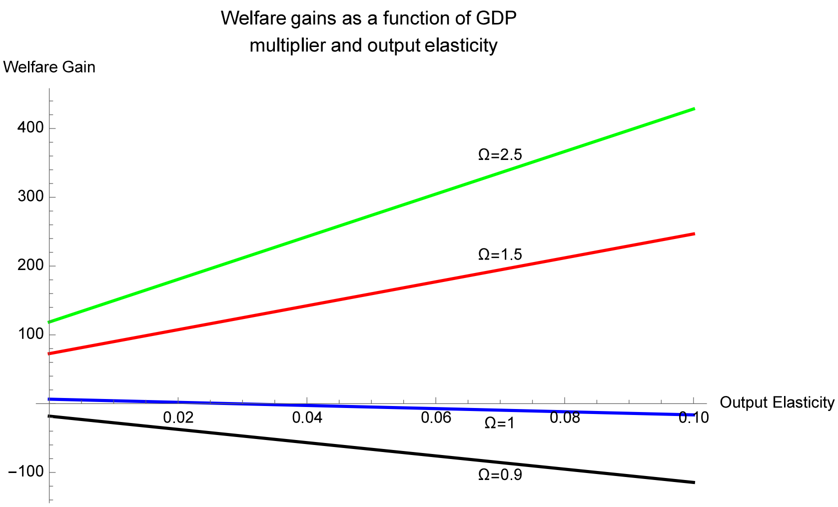

Fig. 2. This figure depicts the long-run flow welfare gains (in terms of annual dollars per working age person) under a spectrum of output elasticities (λ_K) ranging from 0 to 0.1 and GDP multipliers ranging from 0.9 to 2. Individual lines refer to the value of the GDP multiplier (from top to bottom, 0.9, 1, 1.5, and 2.5), while the x-axis describes the output elasticity. Our baseline calibration is the red line (output multiplier of 1.5) with an output elasticity of 0.038.

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.

Our findings from this experiment are shown in the third column of Table 3 and a detailed summary of the endogenous variables is presented in the third column of Table 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 $23 less per working age person, or $5 billion in aggregate, while annual welfare increases by an additional $150 per working-age person, or $31 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.

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 Fig. 2 that welfare improves as long as the multiplier is moderately higher than 1.0, and that conditional on being positive, 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.[24] 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 Fig. 2 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 the magnitude of the gains.

[24] The large range, 0.9 to 2, of transportation multipliers in CBO (2015) does admit welfare losses, specifically when the multiplier slips below 1.02, which is in the lower end of the range.

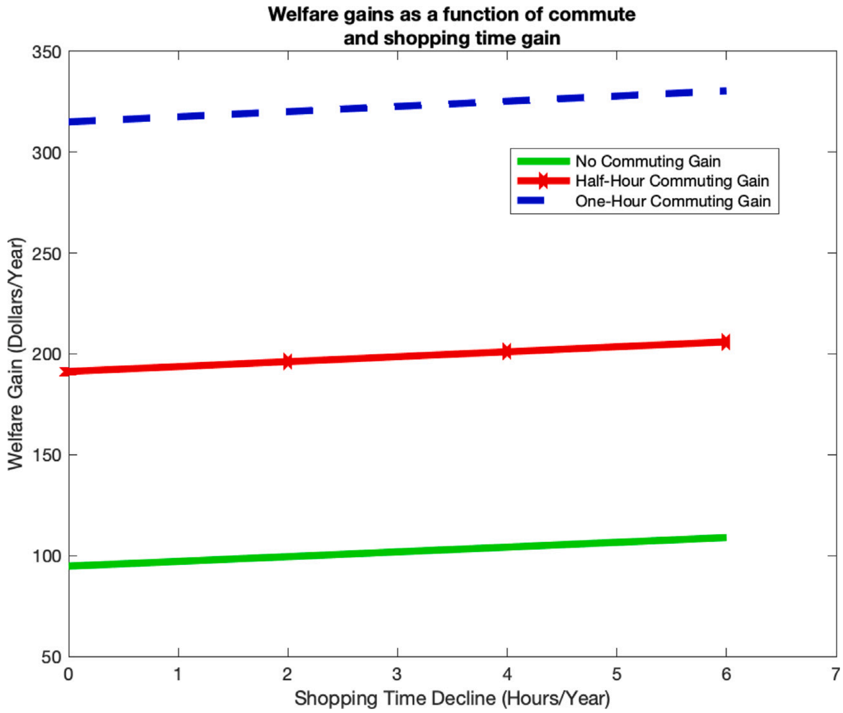

Fig. 3. This figure depicts welfare gains as a function of commuting time reduction and shopping time reduction. Our baseline calibration is the red line with a shopping time decline of four hours per year.

As expected, we show in Fig. 3 that welfare is strongly affected when we consider parameter values that are markedly above and below the base case parameters, which generate the welfare gains (shown in the red line) for a half-hour commuting gain per year and varying declines in shopping time. The results reinforce our initial conclusions that welfare can be significantly improved by reducing travel times and that it is much easier and less costly to achieve those reductions with efficient pricing than with additional infrastructure spending.

We stress 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.[25]

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 the disutility of labor ψ, baseline productivity $\overline{A}$, the transportation capital stock, and overall labor and capital 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 fraction of GDP, and Japan's measured tax rates.[26] Our targets and calibration parameters are available in Table A.4.

25 We thank Nobuhiro Kiyotaki for suggesting this exercise.

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

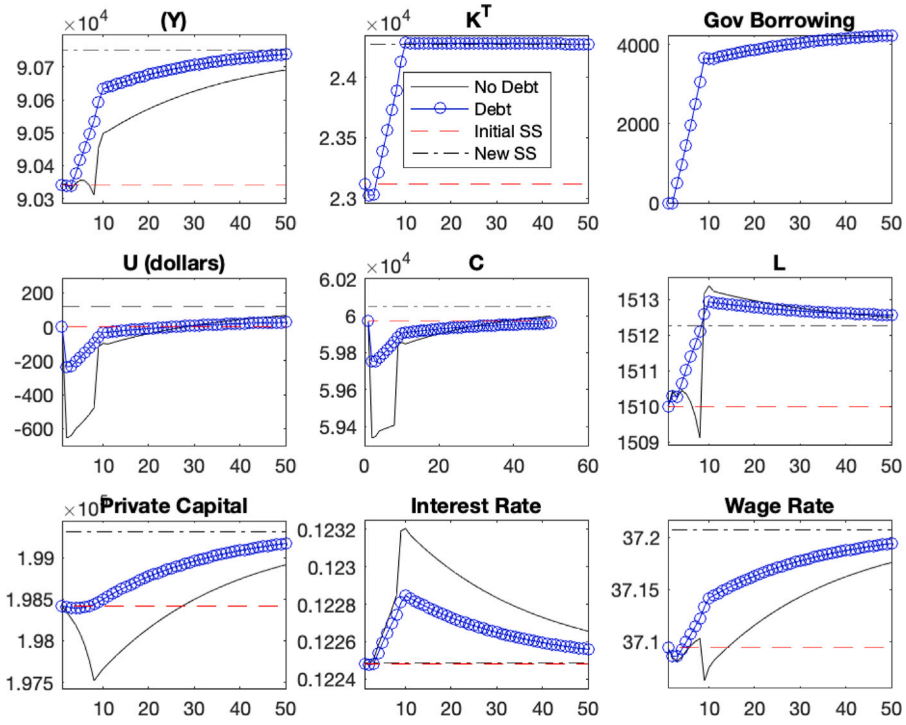

Fig. 4. This figure depicts the reaction of the economy to a sudden, unexpected, eight-year increase in transportation infrastructure investment i_K large enough to increase K^T by 5% by year 10. Each subplot contains four: the dashed red line denotes the original steady state for both economies, the dash-dot black line denotes the new steady state for the no-debt economy, and the blue circle line shows the economy's transition path in an economy with access to cheap foreign debt, while the solid black line shows the transition path under a balanced budget regime. All variables are shown in levels corresponding to their steady state values, with consumption, GDP, government borrowing, and capital in dollars per working-age person, L in hours per year per working age person, U in dollars from the steady state (equivalent variation).

While Japan's baseline GDP per working age person is 30% lower than that of the U.S., its spending as a fraction of GDP is much higher; thus, the level of its transportation capital stock is significantly higher than that of the U.S. 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 0.61, 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 $2.35 per dollar spent. We suggest that our model is useful for explaining multipliers in different countries.

5. Considering the transition path

Our previous analysis compared long-run steady states between different transportation infrastructure regimes. In this section, we account for the costs of transition between regimes, and we find that many of the steady state results are reversed.

To account for transition costs, we conduct three experiments. In each experiment we simulate a constant increase in government transportation investment that raises the capital level by 5%. In the first two, discussed in this section, the government either has a balanced budget, or is allowed to perfectly smooth taxes using foreign debt.[27] In the last experiment, discussed in the next section, the increase in the capital stock is generated by reforms that do not cause higher spending.

We begin by considering the dynamic effects of increasing the long-run capital stock by increasing government spending in Fig. 4. Because higher taxes are required to fund the additional infrastructure investment and capital infrastructure capacity is reduced initially, GDP remains stagnant for a significant period, and utility falls significantly in the short run. In both the balanced budget and debt smoothing scenarios, utility falls significantly, but by far less in the debt-access scenario.[28] In both scenarios, the short-run loss of utility exceeds the net present value gain of increasing infrastructure. Specifically, the NPV utility gain from changing immediately from one steady state to the other (as calculated by comparing steady states) is $1957, but considering the transition

[27] In this experiment, the government's net present value budget constraint holds but the debt is assumed to be foreign held. When we conduct tax smoothing with debt held at the market interest rate, households in the model are worse off because they only have access to an investment with net interest rate $(1-\tau_k)r$, not r.

[28] In the debt scenario, we find long-run government debt converges to approximately $4400 per working-age person, yielding $88 higher debt servicing in every period. Consequently, the long-run values for the debt scenario diverge slightly from the no-debt scenario depicted in Figure 4.

path reduces this to a net present value loss of -$3570 (or a loss of -$1099 in the debt model). This strong distinction between comparing steady states and considering the transition path suggests that while our calibrated U.S. economy is above the welfare-maximizing "modified Golden Rule", it is below the consumption/GDP maximizing "Golden Rule". In the case of transportation infrastructure investment, it is necessary to commit large up-front expenditures and amounts of time before transportation users can realize benefits, even when we allow the government access to debt. This causes households to prefer to consume more today and the near future, rather than consuming permanently more in all future periods.

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 equivalent variation still amounts to a net present loss of -$3412 in the balanced budget scenario or -875 in the debt scenario, compared to a $2321 net present value gain in transition-free increase because there is still a cost of transitioning to a new steady state.[29] 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 (or incur debt) but the infrastructure capital stock and the physical capital stock had not reached their steady state level; 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. We have identified efficient policies that offer the possibility of both improved infrastructure and welfare by reducing the time-to-build infrastructure and congestion and by strengthening 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). The thrust of our analysis is consistent with the perspective of transportation economists who argue that the efficacy of infrastructure spending is compromised by inefficient policies that increase the transition path of capital and congestion delays (Winston, 2021). As a result, the present value of households' utility declines significantly.

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). 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. In the future, expansions of the U.S. road system must enable motorists to have adequate access to electric vehicle charging stations.

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. For instance, if we enact the same policies with an eight year delay, so agents in the economy have time to adjust, the aggregate loss in welfare is reduced by $600 per working-age person.

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). This is true even with debt-financing. 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

[29] Similarly, 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 $12.

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.[30]

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. We anticipate this criticism in our debt-financing exercise, finding our overall results are not significantly changed. Of course, if interest rates were zero forever, rather than simply lower, our calculus could change. 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 quantitative dynamic 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) 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 $79 billion increase in GDP, but a notably lower $25 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, we stress 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 finds 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 may lead to a larger increase in GDP than an efficient transportation policy does, but that it enhances welfare by a smaller amount than an efficient transportation policy.

Appendix. Tables

See Tables A.1–A.4.

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

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

Description	Equation
FOC with respect to c	$\frac{1}{c_t^{\sigma}} - \xi_t\psi\left(L_t(1+\eta_t)+\xi_t c_t\right)^{\frac{1}{\epsilon}} = \lambda_t$
FOC with respect to L	$(1+\eta_t)\psi(L_t(1+\eta_t)+\xi_t c_t)^{\frac{1}{\epsilon}} = \lambda_t w_t(1-\tau)$
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	$c_t + i_t = w_t L_t(1-\tau) + r_t K_t + T_t)$
Government Period Budget Constraint	$G_t + T_t + \gamma_1\exp(\gamma_2 K_t^T)i_t^K + r^G D_t$ $= \tau w_t L_t + \tau_t^K r_t K_t + (D_t - D_{t-1})$
Effective TFP	$A_t^* = \overline{A}\exp(\lambda_K\widetilde{K}^T)$
L.O.M. of K_t^T	$K_{t+1}^T = (1-\delta_{K^T})K_t^T + \sum_{j=0}^{\overline{T}}\phi_j i_{t-j}^T$
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	$w_t = (1-\alpha)A_t^* K_t^{\alpha} L_t^{-\alpha}$
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	$\xi_t = \overline{\xi}\exp(\gamma_{\xi}\widetilde{K}_t^T)$
Definition of η	$\eta_t = \overline{\eta}\exp(\gamma_{\eta}\widetilde{K}_t^T)$
Definition of Utility	$U_t = \frac{c_t^{1-\sigma}}{1-\sigma} - \psi\frac{\epsilon}{1+\epsilon}\left(L_t(1+\eta_t)+\xi_t c_t\right)^{\frac{1+\epsilon}{\epsilon}}$

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.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	0.38	Karabarbounis and Neiman (2014)
Depreciation rate of capital	δ	0.064	Gomme and Rupert (2007) (See description)
Labor income tax	τ	0.33	$G(X,\Theta)$
Working transportation time loss	$\overline{\eta}$	0.12	ATUS
Consumption transportation time loss	$\overline{\xi}$	0.007	$G(X,\Theta)$
Cost of Transportation Capital	γ_1	2.28	$G(X,\Theta)$
Cost of Transportation Capital	γ_2	$3.00\cdot 10^{-5}$	$G(X,\Theta)$
Total factor productivity	$\overline{A}$	9.37	$G(X,\Theta)$
Disutility of labor	ψ	$1.85\cdot 10^{-10}$	$G(X,\Theta)$
Capital tax rate	τ^K	0.29	Gomme and Rupert (2007)
Capital adjustment costs	κ	8	Canzoneri et al. (2005)
Elasticity of A with w.r.t. $(K^T)'$	λ_K	0.038	Melo et al. (2013)
Elasticity of ξ w.r.t. $(K^T)'$	γ_{ξ}	−0.24	$G(X,\Theta)$
Elasticity of η w.r.t. $(K^T)'$	γ_{η}	−0.08	$G(X,\Theta)$
Discount rate	β	0.945	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.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.3: Long-run baseline and counterfactual endogenous variable values

Variable	Baseline	Transportation capital increases by 5%	Transportation efficiency increases by 5%
Consumption	59,970	60,048	60,188
Labor	1,510	1,512	1,512
Wages	37	37	37
NonlaborIncome	34,330	34,486	34,477
Transfer	10,841	10,841	10,841
Government Spending	15,358	15,358	15,358
TFP	9.37	9.39	9.39
Labor Tax	0.33	0.33	0.33
Y	90,342	90,753	90,728
Shopping	0.0067	0.0066	0.0066
Commute	0.1164	0.116	0.116
Utility	−0.0447	−0.0446	−0.0446
Capital	198,416	199,312	199,255
Investment	12,754	12,812	12,809

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.

Table A.4: Japan Calibration

Variable	Target	Value
GDP	63,484	63,484
Labor hours	1,418	1,418
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	1.85
Total factor productivity	$\overline{A}$	9.37
Transportation capital per working-age person	$\overline{K^T}$	33,418
Non-transportation labor income tax	τ^G	0.19
Marginal capital income tax rate	τ^K	0.55

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