TRANSPORTATION AND THE PERFORMANCE OF THE U.S. ECONOMY:
A GENERAL EQUILIBRIUM APPROACH

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Introduction

Civilization would revert to the Stone Age without a modern transportation system. Household heads would be forced to take jobs and family members would be forced to take vacations that were close to home; consumers could purchase only those goods that were sold at local outlets and produced with local inputs; firms would not be able to achieve significant scale and scope economies because their production would be limited to a small market; monopolies would be prevalent because competition from non-local producers would not be possible; and economic agents would have little opportunity to benefit from sharing information and engaging with each other.

The practical implication is that the extent and efficiency of a nation’s transportation system significantly affects individuals’ accessibility to jobs and firms’ accessibility to workers, the availability of consumer goods and services and their price, quality, and variety, the intensity of competition among and the productivity of firms, and economic growth from agglomeration economies. Accordingly, most countries’ annual expenditures on transportation are enormous. 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 transportation infrastructure (Winston (2013)).

Given the transportation sector’s huge size and its effect on virtually every other sector in an economy, it is important to develop quantitative knowledge of how a transportation system affects an economy’s performance and how an economy can benefit from improvements in the system’s efficiency. Transportation economics has closely studied the individual components of a transportation system such as airline
services and the highway system, but it has not offered a broad assessment of the system and its relationship to the performance of other sectors.\(^1\) At the same time, macroeconomics has limited its study of transportation to the returns from public infrastructure investment.\(^2\) Yet, it is quite common to come across anecdotal evidence reported in the media that indicates a variety of ways that transportation affects large parts of the economy and how improvements in the system could provide widespread benefits. To take some examples, a stalled housing market could be revitalized by reductions in commuting times from the suburbs; sales of new cars could increase if congestion throughout the rail freight system were reduced so new cars could reach dealers’ lots quicker; improvements in airline and airport services in a city could attract firms to locate their headquarters in that city and stimulate regional growth; repairing transportation infrastructure could lower firms’ production costs and stimulate export activities; and so on.

It would therefore be fruitful to incorporate the key features of the U.S. transportation system in a general equilibrium model to analyze the system. Although they have often been criticized, general equilibrium models have become an accepted part of macroeconomics. We use a general equilibrium model to take a first step toward developing quantitative evidence that transportation’s importance to an economy may be

\(^1\) Overviews of the field of transportation economics can be found in co-edited handbooks by Gomez-Ibanez, Tye, and Winston (1999) and de Palma, Lindsey, Quinet, and Vickerman (2011).

\(^2\) Aschauer (1989) and Munnell (1990) initiated this literature. Shatz, Kitchens, Rosenbloom, and Wachs (2011) is a recent survey.
far more important than economists appreciate and that policies that improve the efficiency of the system can have substantial effects on economic growth.

In what follows, we develop the model formally for households, firms, and the housing sector and determine general equilibrium in the economy. We calibrate and solve for this equilibrium numerically, based on data and parameters that apply to the United States, and analyze how the transportation system affects the U.S. economy’s performance. We find that improvements in the transportation system brought about by a modest increase in government spending can raise the nation’s welfare substantially. More importantly, given the inefficiencies throughout the system, we find that improving the system’s productivity without increasing government spending can raise welfare even more.

**The Model**

The four sectors that comprise the economy in our model rely on and enact policies for transportation: households, firms that produce consumption goods, a housing production sector, and the government. Households’ use of transportation to commute to work and to travel for leisure or shopping is governed by their residential and workplace location choices that result in them either living in the city or the suburbs and either building houses or producing consumption goods. In the spirit of a monocentric model in urban economics (Brueckner (2011)), households that reside in the suburbs commute to work in the city, which produces a wedge between the leisure they sacrifice and the labor employers receive. The representative family pools wages from its members, allocates consumption appropriately, and gains additively separable utility from per capita
consumption of the consumption goods, housing in the city and the suburbs, and the leisure of members living in the city and in the suburbs.

A continuum of monopolistically competitive firms produces consumption goods and uses transportation to ship those goods and receive intermediate goods. Each firm faces a downward-sloping idiosyncratic demand curve determined by the elasticity of substitution for its good. We distinguish between what we call city, regional, and international firms based on their geographic use of transportation services that they purchase. Firms effectively rent the transportation capital stock that facilitates the provision of those services. Accordingly, we include transportation capital as an input in a firm’s production function and their use of it is determined by their production of the consumption goods. The price of that input, however, is often implicit; for example, trucks pay gasoline taxes to use the highways instead of paying cost-based pavement-wear charges.

Housing is a distinct sector in our analysis because it characterizes land use, which affects and is affected by the transportation system. Producers of housing in a city can exploit population density to make housing efficiently, but they eventually face diminishing returns to scale. In contrast, producers of housing in the suburbs make housing less efficiently but diminishing returns take longer to occur. The difference between housing production processes in a city and the suburbs enables us to capture greater sprawl as a city population increases and increased density as city wealth increases.

Finally, the government sets prices for public transportation services and invests in public transportation infrastructure, such as highways, airports, ports, and public transit
capital stock. Private firms such as freight railroads invest in their infrastructure, namely, track and way and structures. Government investments in transportation capital, which we assume are financed by a lump-sum tax on households, can affect intracity, intercity, and international passenger and freight movements that benefit households and firms.

Formally, the equilibrium in the economy will be characterized by four sets of equations: households’ constrained utility maximizing decisions on location, consumption, housing consumption, and labor; monopolistically competitive firms’ profit-maximizing production decisions; competitive firms’ profit-maximizing housing production decisions; and the government’s transportation capital investments financed by a lump-sum tax on households. As with most general equilibrium models, endogenous variables are determined simultaneously and uni-directional causality rarely occurs. For example, transportation capital increases firms’ productivity which increases their use of transportation capital.

Because investments in transportation take time to generate benefits, we model the “long run” and examine the steady state for the calibrated economy rather than its dynamics. Thus households are free to adjust their locations and labor choices and firms are free to adjust their production decisions.

**Household Behavior**

Because the households’ location choice is whether its members should live in the city or the suburbs (we refer to a given location \(i\) where \(i=1\) for “the city” and \(2\) for “the suburbs”), transportation is relevant for its behavior. A serious drawback to living in the suburbs is that it increases the time costs of commuting. Those commuting costs act like a tax wedge: in this case, there is a difference between the time individuals lose for
leisure and the time firms pay them for working.\(^3\) We denote this wedge as a tax \(t_1\) on suburban household labor. Households spend unpaid time waiting in traffic, which produces a rent gradient such that housing outside of the city is cheaper than housing in the city so individuals are indifferent between living in and outside of the city. Similarly, there is an additional cost to living in the suburbs related to shopping trips. Both urban and suburban households lose time due to shopping. For those living in the urban area, the parameter \(x_{sc}\) converts consumption (measured in units of the numeraire good) into time units, denoting the amount of leisure time lost to shopping. Suburban households lose the same amount, as well as an additional “wedge” due to their extra time costs. We denote this extra suburban wedge as \((1 + t_2)\), so that \((1 + t_2)_{sc}\) denotes the leisure time a household in the suburbs loses due to shopping time. Individuals in the suburbs therefore will end up reducing leisure in two ways: first, they lose an additional factor of working time \(t_1\) in working time due to commuting, and second they lose \(x_{sc}\) due to shopping time wasted.

We now construct the household’s utility. For simplicity we consider a final composite good and denote aggregate consumption of it by \(C\) and its price by \(P\). Let \(h_i\) be the consumption of housing per person in location \(i\), \(l_i\) is labor per person in units of free time devoted to the intermediate good that is used to manufacture the final good in location \(i\), and \(l_{hi}\) is labor per person in units of free time on construction of houses in location \(i\). Workers in location \(i\) working for intermediate good firms and housing firms

\(^3\) For the vast majority of commuters, there are also additional vehicle operating costs that come from the decision to work, such as fuel and maintenance expenditures. For simplicity, we do not account for those.
earn hourly wages of \( w_i \) and \( w_{h_i} \), respectively. No labor is used in the production of the final good, which is effectively a simple combination of the relevant intermediate goods. Let \( N_i \) be the fraction of people in location \( i \), is the Lagrange multiplier for the budget constraint, and is the Lagrange multiplier for the number of people (normalizing the total population to be equal to one). Let be firms’ profits of the consumption and housing sectors in location \( i \), respectively. Profits are remitted to households. Households completely own the firms; for simplicity, we do not consider foreign ownership. The relative utility of housing is represented by and the relative utility of leisure is represented by \( y_i \). Lower case variables, such as \( c, h_1, h_2 \), denote the relevant per-capita versions of consumption, urban housing and suburban housing. Aggregate government revenues, financed through a lump-sum tax on households, are denoted \( G \).

We specify a household’s logarithmic utility from consumption of the composite good, housing, and leisure in the city and the suburbs as:

\[
L = N_1 \left( \log c_1 + \log h_1 + \log(1 - \ell_1 - \ell_{h_1} - x_{cc_1}) + N_2 \left( \log c_2 + \log h_2 + \log(1 - \ell_2 - \ell_{h_2} - x_{cc_2}) \right) \right)
\]

subject to the aggregate budget constraint and the family member constraints:

\[
\begin{align*}
&= N_1 c_1 + N_2 c_2 \\
&= N_1 h_1 + N_2 h_2 + G \\
&= N_1 + N_2 = 1
\end{align*}
\]

\[4\] In practice, the federal gasoline tax, frozen since 1993 at $0.184 per gallon, is a major source of highway transportation infrastructure funding. We discuss current and efficient transportation pricing later and assume for now that government spending on transportation is financed by a lump-sum tax on households.
The household’s constrained utility maximization problem yields first-order conditions for the choice variables, \( c_1, c_2, h_1, h_2, l_1, l_{h_1}, l_2, l_{h_2}, N_1, N_2 \), and the Lagrange multipliers, \( \lambda_1, \lambda_2, \lambda_h \). Those twelve equations represent the solution to the household's optimization problem given the final consumption good price, housing prices, wages, and taxes. However, before proceeding we need to determine the price that enables the household to create a final consumption good out of intermediate consumption goods and we need to determine the price of housing.

**Production Costs and Transportation**

Transportation capital—ports, roads, airports, and the like—is an exogenous input into firms’ production functions. Efficiency improvements in this capital stock can reduce delivery times and increase reliability both of which cause optimal inventories and production costs to decrease.

We assume that six stocks of transportation capital are available, intracity, intercity, and international freight and passenger capital, and that they affect firm i’s unit cost of production, \( f_i \), as a public good (under uncongested conditions). Because firms’ geographical scale of operations will vary—some may operate solely within a city and primarily rely on intracity transport for both their inbound and outbound shipments while others may operate worldwide and rely on international, intercity, and intracity transportation services—their production costs will vary accordingly. We further assume that the fraction of transportation capital that a firm uses from the available stocks is proportional to its use of labor \( l_i \). Letting \( k_{j,i} \) denote the amount of capital \( j \) firm \( i \) uses, \( K_j \) denote the total amount of available transportation capital of type \( j \), and \( L \) represent the
total labor used by intermediate good firms, the idiosyncratic transportation capital a firm uses in production will be:

\[ k_{j,i} = \frac{I}{L} K_j \]  

(4)

For an individual firm, its Cobb-Douglas production function with seven inputs (six representing various types of transportation capital) and total factor productivity \( A_i \) is given by:

\[ Y_i = A_i k_{1,i}^{a_1} k_{2,i}^{a_2} k_{3,i}^{a_3} k_{4,i}^{a_4} k_{5,i}^{a_5} k_{6,i}^{a_6} l_i^{a_7} \]  

(5)

Although transportation capital enters the production function, the firm only pays directly for labor (recall, transportation capital is funded by a lump-sum tax on households), we can write its profits as:

\[ \pi_i = P Y_i - w l_i \]  

(6)

A firm’s transportation capital is dependent on both its labor choice and the choices of other firms, so we can plug in the expression for \( k_{j,i} \) to obtain:

\[ \pi_i = P A_{i} \frac{I}{L} k_{1,i}^{a_1} \frac{I}{L} k_{2,i}^{a_2} \frac{I}{L} k_{3,i}^{a_3} \frac{I}{L} k_{4,i}^{a_4} \frac{I}{L} k_{5,i}^{a_5} \frac{I}{L} k_{6,i}^{a_6} l_i^{a_7} - w l_i \]  

(7)

When we assume constant returns to scale, the \( l_i \) exponents sum to one; i.e.,

\[ 1 = a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 \]

and the aggregate transportation capital stocks and aggregate labor can be combined into a single, “adjusted” TFP term:

\[ \pi_i = P \tilde{A} l_i - w l_i \]  

(8)

where we denote “effective” TFP as \( \tilde{A}_i \), an efficiency parameter that firms take as given, although it includes endogenous parameters determined in equilibrium. Transportation
capital impacts firm activity through \( \tilde{A}_i \); increased transportation capital, holding total labor constant, increases the efficiency of firms, with weights given by the \( \alpha \)’s.

\[
\tilde{A}_i = \frac{A_i \left( K_1^{\alpha_1} K_2^{\alpha_2} K_3^{\alpha_3} K_4^{\alpha_4} K_5^{\alpha_5} K_6^{\alpha_6} \right)}{L^{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6}}
\]  

(9)

From the firms’ perspective, public good transportation capital simplifies to a constant returns to scale technology with adjusted productivity, as reflected above. This formulation yields a simple expression for the per-unit cost of production that we can apply to a monopolistically competitive system of firms. Namely, the per-unit cost of production for firm \( i \), accounting for transportation costs, denoted \( \phi_i \), is:

\[
\phi_i = \frac{w}{\tilde{A}_i}
\]  

(10)

**Final Consumption Goods**

Deriving the set of equilibrium conditions for final good production has several parts to it. First, we introduce the intermediate good producing firm's cost minimization problem, from which we extract the per-unit cost, taking into account transportation capital. We use this simple per-unit cost, varying by firm locality, to completely capture heterogeneity in our monopolistically competitive equilibrium. Using per-unit cost, we can introduce a set of CES aggregators that households have access to. CES aggregators are a technology which households use to combine individual firm goods in order to make other intermediate goods or final goods for consumption. For instance, they might combine a couch, television, cable, and chips to produce their final production good of watching television.
Household results from CES aggregators yield downward-sloping idiosyncratic firm demand curves for every type of produced good: every firm faces a downward-sloping demand curve, though the presence of other firms will impact the degree to which those competitive monopolies can profit.

We have two levels of intermediate goods. A continuum of local, intercity, and international firms all produce a set of goods. This continuum of goods is combined to produce a single effective local, intercity, and international good. The intercity and international goods are then combined together by households in another CES aggregator to produce a single "nonlocal" good, which is then combined with the single local goods to produce a final good. Although we use a multi-level setup, the idea is simple: there are many different kinds of firms, producing different kinds of products. International firms primarily compete with one another and are substitutable with one another. Their goods are less strongly substitutable with intercity firms’ goods. Those two entities, considered together, produce a good that is substitutable (to some extent) with local firms’ goods.

**Intermediate Goods and CES Aggregation**

As noted, a household consumes final production goods but it also chooses intermediate goods. Assume we have three types of firms that are characterized by their geographic scope, local, intercity, and international, (denoted in production equations with subscripts 1, 2 and 3, respectively) which also determines the extent of transportation that they use. A continuum of \( N_{i,f} \) of each type of firm exists, each producing differentiated goods. That is, second-level intermediate goods are produced by combining many different first-level intermediate goods of a specific
type. Letting $C_j$ denote the good produced by combining many smaller individual firm goods $c_{j,i}$ with the elasticity of substitution between firms given by:

$$C_j = \sum_{i=0}^{N_{i,j}} \frac{1}{N_{i,j}} c_{j,i} \frac{dx_i}{x_i} \quad j \{1, 2, 3\} \quad (11)$$

Just as the consumer combines all the different types of firms within a locality to produce a single aggregated good, the consumer also combines those single aggregated goods together. Having combined all the local, intercity, and international firm goods together to produce $C_1$, $C_2$, and $C_3$, respectively, the consumer then combines those three goods to produce a final good. Specifically, the consumer first combines intercity and international goods in a CES production function to produce an intermediate “nonlocal” good (denoted as type 0), which is then combined with local goods in a CES production function to produce final goods:

$$C_0 = \frac{1}{C_2} + (1) \frac{1}{C_3} = \frac{1}{C_1} + (1) \frac{1}{C_0} \quad (12)$$

The well-known results of CES aggregation for consumers gives us a set of downward-sloping idiosyncratic demand curves relating the quantity consumers demand of an individual firm’s good with the ratio of its idiosyncratic price with the aggregate good’s cost, aggregate good’s consumption, and the elasticity of substitution between firm goods. At the same time, the firm takes the aggregate good’s cost and quantity, $P_j$ and $C_j$, as given, and simply has an equation relating its price to its quantity, a demand curve that presents a quantity-price tradeoff for a monopolist:
Firms face a per-unit cost of production, that we defined earlier as part of its cost minimization problem. We assume homogeneity of idiosyncratic productivity by firm type: within the same locality, all firms have the same $A_i$. Consequently, we can denote idiosyncratic cost for firm $i$ as $f_j$, dependent solely on its industry. They also face a fixed cost of entry (that does not vary for a given locality) $n_j$. Firm profits can therefore be expressed as:

$$p_{i,j} = c_{i,j} - f_j - n_j$$

and the profit maximizing price is:

$$p_{i,j} = e^{\frac{1}{e} - 1} f_j$$

Given the profit-maximizing idiosyncratic price for local firms, we can express the aggregate price for the aggregate good by locality as:

$$P_j = e^{\frac{1}{e} - 1} j N_j$$

Namely, that price is a function of the number of firms, firm per-unit cost, and the elasticity of substitution between firms. As might be expected for substitutes, when $e > 1$ aggregate price drops as the number of firms rises. Accordingly, we can derive the firm’s choice of quantity to be a function of aggregate consumption, prices, the elasticity of substitution, and per-unit costs:

$$c_{i,j} = C_j e^{\frac{1}{e} - 1} P_j$$
As noted, households combine the aggregate goods together using a “production” function. The minimum price for the nonlocal and local goods, assuming a constant returns to scale constant elasticity of substitution production function, can be expressed\(^5\)

\[
P_0 = \left( P_2^i + (1 \quad P_3^i) \right)^{\frac{1}{\theta}} \quad P = \left( P_1^i + (1 \quad P_0^i) \right)^{\frac{1}{\theta}}
\]  

(18)

and relative demands as a function of relative prices are given by:

\[
\frac{C_1}{C_0} = \frac{P_0}{P_1} \quad \frac{C_3}{C_2} = \frac{P_2}{P_3}
\]

(19)

Finally, we do not restrict the number of firms for a given type. Instead, we allow free entry in each locality to drive long-run profits to zero such that:

\[
i, j = 0 \quad j \quad \{1, 2, 3\}
\]

(20)

which holds for all firms \(i\) in each \(j\) due to the homogeneity of firms within the type of locality. The number of firms is therefore determined as the solution to the long-run profit condition above.

**The Housing Sector**

Urban and suburban housing are produced by competitive firms subject to a decreasing returns to scale technology. For simplicity, we do not distinguish between rental and owner-occupied housing. Aggregate housing \(H_i\) has a single input: labor for housing in location \(i\), denoted \(\ell_{h_i}\). Because \(\ell_{h_i}\) is measured as labor per-person, we multiply it by the quantity \(N_i\) to get total labor input:

\[
H_i = A_{h_i} \left(N_i \ell_{h_i}\right) \quad ^8
\]

(21)

\(^5\) See, for instance, chapter 7 of Ferguson (1969).
where $A$ and $\alpha$ are parameters.

We denote profits $\pi_i$, the price of a home $P_h$, the total amount of homes per person $h_i$, and wages for home builders $w_h$. The per-person housing stock $h_i$ is found by dividing the aggregate housing stock, $H_i$ by the total number of people living in a location. A housing firm’s profits are given by:

$$\pi_i = P_h h_i - N_i h_i w_h$$

(22)

As noted, improvements in one or more of the transportation capital stocks may affect the housing sector by changing the relative demand for housing in the city and the suburbs.

**Government and the Transportation Capital Stock**

The government sector improves the transportation capital stocks by making additional public investments that are financed with revenues from its lump sum tax ($G$). We assume that costs are covered by this tax so the government does not run a deficit. We also impose the condition that investments in an additional unit of one capital stock will raise the average and marginal cost of another type of capital stock, which captures diminishing efficiency of government investment.\(^6\) Letting $x_G$ be a conversion factor relating yearly government investment with its impact on the transportation stock and $a>1$ to reflect diminishing efficiency, the government has a budget constraint:

$$G = x_G (K_1 + K_2 + K_3 + K_4 + K_5 + K_6)^a$$

(23)

Because we assess the long-run effects of a government investment in the transportation capital stock, we consider an annual investment, repeated ad infinitum, and

\(^6\) Increases in government demonstration projects are an example of wasteful spending that reduces the efficiency of the transportation capital stock.
we account for depreciation General equilibrium models often attempt to explain the dynamics of macroeconomic aggregates, but that is not the focus of this paper.

**Calibration**

We offer a computable general equilibrium model of the impact of transportation capital stocks on the U.S. economy. We choose calibration to assign numbers to a set of parameters from the existing literature. This is a widespread economic practice: for instance, Kyland and Prescott (1982) calibrate a number of parameters in their dynamic examination of the co-movements of macroeconomic covariates, while Shoven and Whalley (1984) take that approach in a static examination of the impacts of taxation on international trade.

Our calibrations are in some cases direct, either from existing literature or with our model offering direct calculations of parameters, and in other cases, they generate the endogenous parameters of our model, conditional on parameters, and compare them with the data. Any measurement we generate, either from data or from our simulation, we refer to as data or population moments and theoretical or simulated moments, respectively. We use the generalized method of moments, taking a weighted sum of squared Euclidian distances between the moments generated from the data and their theoretical simulated counterparts and minimizing them through the choice of parameters. This is calibration, rather than estimation, because our theoretical counterparts only have a single observation and there is no concept of a law of large numbers to ensure convergence and offer standard errors.
Households

Households maximize utility from leisure, housing, and consumption. The role of $\xi_{xx}$ is a parameter that represents the amount of leisure time lost due to shopping for consumption (for instance, travel time to the mall). Based on the American Time Use Survey, we set $\xi_{xx}$ to be a 1.3% tax to represent the proportion of time “wasted” in shopping trips. We choose the extra penalty suburban families pay in commuting to work $\tau_2$ to represent a 5% increase in time wasted. As reported in Winston (2010), time spent commuting in the United States is equal to approximately $760$ billion dollars a year, or normalized as a percentage of GDP, approximately 6%. Letting $Y$ denote GDP, the sum of all consumption and government expenditure and using notation defined above, we choose the parameter $\tau_1$ (which denotes the suburban time lost to commuting) using the equation:

$$\frac{w_2\ell_2 + w_2\ell_h}{Y} = 0.06$$

(24)

From the Bureau of Labor Statistics, we target the amount of time spent working at 20% of free time:

$$N_1(l_1 + l_h) + N_2(l_2 + l_h) = 0.2$$

(25)

We use the 2010 Census to document that 80.7% of the U.S. population live in “urban” areas, including both urbanized areas and urban clusters, and we use that figure to measure the proportion of the population living in urban versus rural areas. To measure prices, we set urban housing stock as our numeraire good and determine other relative prices endogenously. Since 1929, gross private domestic investment in housing has, on average, composed 4.19% of GDP and private consumption and other investment
has composed 75.48% of GDP; we assume government investment and consumption comprise the remaining 20.32%. The remaining parameters pertaining to households, utility from housing ( ), disutility from labor ( ), and the elasticity of substitution between different types of intermediate consumption goods ( , , , ) are calibrated in the process of minimizing our quadratic form, discussed below.

**Housing Sector**

Based on the proportion of the population living in urban areas, we assume the value of urban housing capital accounts for 80% of the total value of the housing stock. We measure the expenditure on (investment in) aggregate housing from National Income and Product Accounting tables, which give the aggregate value of residential investment. Because we do not account for government spending other than on infrastructure, we adjust GDP to include only investment, consumption, and government expenditures on transportation infrastructure. Those values, as a fraction of GDP, and our assumed split of urban and suburban housing yield the target moments for the share of GDP from consumption, urban housing, and suburban housing, respectively:

\[
\frac{(N_1c_1 + N_2c_2)}{Y} = 0.873 \quad (26)
\]

\[
\frac{N_1P_h h_1}{Y} = 0.042 \quad (27)
\]

\[
\frac{N_2P_h h_2}{Y} = 0.010 \quad (28)
\]
with government expenditure on transportation infrastructure accounting for the remaining 7.5%. The housing elasticities \( (a_h) \) are chosen to yield reasonable elasticities of production, ranging from 0.001 to 0.005.

**Firms**

We value the total production done by local firms as 20% of the total consumed value, intercity firms’ total production as 70% of total consumed value, with the remainder produced by international firms.

\[
\frac{N_{1,p_i}P_{i,c_{i,1}}}{Y} = 0.2 \quad (29)
\]

\[
\frac{N_{1,f_i}P_{i,c_{i,3}}}{Y} = 0.7 \quad (30)
\]

The target value for international firms is somewhat below its long-run average value of production of 16% of total consumed value, but it is a plausible target. Little data exists to determine the proportion of consumption coming from local and intercity firms but our assumed values seem reasonable.

We then determine the demands, costs, and profits for the different set of firms by calibrating their TFP's \( \Lambda, A_{h_1}, A_{h_2} \), fixed cost of entry into intermediate consumption good production \( v_i, i \in \{1,2,3\} \) the CES share parameters \( (\xi \text{ and } \mu) \) , and the CES elasticities \( \sigma, \sigma, \text{ and } \omega \).

**Transportation Capital Stocks**

We use the available data to measure the transportation capital stocks \( (K_i)'s \) and transportation input elasticities \( (a_{i,j})'s \). We normalize the capital stocks to be equal to one: their actual value in production will therefore be partially reflected by the TFP parameter, which we allow to move freely in the calibration.
As noted, the transportation stocks $\alpha$’s will not represent the share of total production paid to those factor inputs, and their calibration would be difficult with that concept in mind. But we can still interpret their effects in terms of input elasticities following, for example, Melo, Graham, and Brage-Ardao (2013). We are not aware of previous research that includes the six types of capital stock introduced here, but our range is not outside the range used by Melo, Graham, and Brage-Ardao (2013). Consistent with recent empirical studies of transportation infrastructure (Winston (2013)), we choose conservative $\alpha$’s. For instance, with an $\alpha$ value of 0.003, holding all else constant, a 1% increase in transportation capital stock 1 increases production 0.003%. Further we assume that transportation infrastructure, inclusive of all effects, generates a government spending multiplier on GDP of 1.01.\footnote{This assumption can be thought of as an identifying assumption in general equilibrium calibration similar to the manner in which sign restrictions help identify monetary policy analyses (for example, Uhlig (2001), Canova and de Nicolo (2000)).} Denoting the experiment with a subscript e, this generates the moment:

$$\frac{y_{e} - y}{\alpha_2 - \alpha} = 1.01 \quad (31)$$

The values of the transportation capital stocks are presented in table 1 and they are derived from estimates of the value of transportation infrastructure that are reported in table 2. The estimation moments are summarized in table 3.

Given all the parameters $\Theta$, we can solve our model and obtain simulated values for the endogenous variables $X(\Theta)$. We can plug those endogenous variables into the preceding moment conditions to get our theoretical values for the moment conditions $f(X(\Theta))$. Finally, we can minimize the distance between those theoretical moment conditions and their true values $Y_{data}$. Our calibration problem is therefore:
\[
\min_{i=1}^{11} \left( f_i(X(\cdot)) - Y_{i,\text{Data}} \right)^2 \tag{32}
\]

It is worth noting that we are calibrating more parameters than we have moments: while this is uncommon, the solution is still identified. Our functional form restricts our fit despite having more parameters than targets, as exhibited by our failure to perfectly fit even the moments we do have. Table 4 displays our parameters calibrated by simulation, although not all of them are easily interpretable. Three values are particularly interesting: diminishing returns to scale for urban and suburban housing; we fit greater diminishing returns in the suburbs to fit our price and population data, something generally absent in monocentric models; and sharply diminishing returns to scale for government investment, a parameter largely driven by our counterfactual moment, targeting a government multiplier of 1.05.

**The Structure of the Model for Analysis**

We have six capital stocks, representing the quality capital stock of urban passenger \((K_1)\), urban freight \((K_2)\), intercity passenger \((K_3)\), intercity freight \((K_4)\), international passenger \((K_5)\), and international freight \((K_6)\). Those capital stocks are an input into production that impacts the unit cost of production for firms, and they may also determine the wedge between time given by suburban workers and received by firms. Specifically, city passenger and freight, as well as intercity passenger capital decrease the tax wedge, the wedge between the time individuals give up to work and the time their employers receive in productive efforts.

According to the ATUS data, individuals spend about 10% of their working time commuting, while they spend 5% of free time spent commuting to shop.
\[ \tau_1 = 0.106 - 0.5 \cdot (K_1 - 1) + 0.1 \cdot (K_2 - 1) - 0.1 \cdot (K_3 - 1) \]
\[ \tau_2 = 0.053 - 0.5 \cdot (K_1 - 1) + 0.05 \cdot (K_2 - 1) - 0.05 \cdot (K_3 - 1) \]  

While impacts on the "travel wedge" are important, all types of transportation impact the effective total factor productivity (\( \bar{A} \)). When more transportation capital is built, the unit cost of production for firms declines. Consequently, firms enter the market, and existing firms continue to produce. Both movements have general equilibrium effects. For example, more capital leads to more firms, which brings more competition and reduces price markups. Reducing markups brings our monopolistically competitive model closer to efficient perfect competition, reducing the gap between the marginal product of labor and the price.

**Findings from the Model**

Table 5 reports some selected endogenous variables from our model. We indicate the baseline numerical values of those variables in the second column. We first use our model to provide perspective on the importance of transportation capital given the current efficiency of the transportation system and then to determine the gains from a more efficient transportation system.

**Importance of Transportation Capital**

We first provide a stylized example of the importance of transportation by calculating the impact of increasing spending on transportation infrastructure by a modest
annual amount, 8%, which, as shown in the second column of the table, increases the transportation capital stock $123 billion. In contrast to previous assessments of infrastructure investment, our analysis will measure general equilibrium responses to the increase in spending. Thus we find that the increase in the capital stock will increase production by local, intercity, and international firms by about 3% each. The commuting wedge will decline from 10.6% of working time to 8.5% of working time for suburban commuters, dropping the amount of time they spend commuting by 20%. The shopping wedge falls from 5% to 3.5% of total time. But the lump-sum financed spending increase impacts the income of all households negatively without distorting their reward to work, causing them to want to work more.

Firms want to hire more labor because of their increased effective productivity, and workers want to work more, due to a decreased commuting and shopping time wedge, and the income effect of taxation. Their willingness to work will be partially muted by an increase in the number of suburban dwellers facing the commuting and shopping wedge. We find a 5.5% increase in suburban population from 31.8% to 37.4%. A rise in wealth will tend to cause an increase in both types of housing stocks, and therefore prices. However, the increase in suburban dwellers will ease the price pressure on urban housing so they actually see a decline in per-unit housing, even as the cost in the suburbs rises. In our simulations, we find an increase in suburban per-unit housing costs of 35%, while urban housing costs decline by 11%.

As firms become more productive, they expand production per firm by 2.2%, and idiosyncratic firm prices decrease by 3.2%. More intensive competition
between firms decreases the total number of firms 2.2%; nonetheless, the overall price of consumption goods declines by 2.3%, partly because of a more efficient distribution of firms, as more foreign firms, more dependent on transportation capital, enter and allow for more efficient final good production. “Measured” productivity increases for firms, as their $\bar{A}$ increases.

Although we targeted an increase of GDP by $1.05 for every additional $1 in transportation infrastructure spending, we did not target the different general equilibrium channels through which this occurs. Specifically, the increase in transportation infrastructure changes behavior by changing labor hours, the number and composition of firms in the economy, their prices and quantities, the location of households in our monocentric model, and an increase in the efficiency of consumption relative to housing. Those channels are dependent on one another, and our model formally models the links between those optimizing agents, sectors, and firms. The result is that aggregate utility, as measured by the equivalent variation, increases by $288$ billion net of the lump sum tax to pay for the increase in transportation infrastructure.

Because utility is additively separable, we can decompose the sources of equivalent variation into three categories: higher consumption, reduced labor hours or more leisure, and more housing consumption. We find that nearly 90% of all of the extra utility comes from increased consumption, with the rest generated from increased housing. However, some of the extra consumption occurs because people actually work more due to the decreases in the transportation wedge and
because the portion of utility generated by leisure declines in magnitude. Indeed, roughly one-third of the increase in consumption is attributable to greater labor productivity due to an increase in transportation capital and two-thirds are generated by increases in labor supply due to a reduction in the transportation wedges.

The Gains from Efficiency Improvements in the Transportation System

The inefficiency of the U.S. transportation system is well-documented (Winston (2013)). There are numerous revenue-neutral or revenue-positive changes in the ways that the transportation capital stocks are used that may make it more efficient. To name a few, new technology can improve traffic flows, more efficient investment can reduce costs, unnecessary and costly regulations can be eliminated and so on.

We explore the potential efficiency gains by improving the transportation capital stock that enters the production function of firms and that impacts transportation wedges faced by households holding expenditures constant. By increasing $K$ 3%, as before holding fixed costs constant, we generate the counterfactual of an increased quality transportation capital stock occurring through revenue-neutral means. This will have two important effects: first, it will cause GDP to increase by less or decrease, as government is no longer taking money from people to purchase things that otherwise would not have been purchased. Second, it will cause utility to increase by much more than preceding case, for the

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8 Microeconomic studies (for example, Light (2007)) find that individuals work less because of congestion and delays.
same reason. The first effect, which we find dominates, essentially adds the quantity that would have been taken away from consumption and leisure and adds it back, as compared with the taxpayer-financed transportation system improvement. In our case, we would expect the $288 billion equivalent variation, plus the $120 billion taxed, for an increase of $408 billion in utility. Instead, as shown in the fourth column of Table 5, we find an increase in the equivalent variation of $418, a difference we attribute to general equilibrium effects and the nonlinearity of the problem.

In a nutshell, the welfare improvement from simple efficiency gains is nearly 50% more than the gains that could be achieved with an increase in spending that achieves an equivalent increase in the capital stock, largely thanks to the monetary savings. The absolute magnitude of those gains in the hundreds of billions of dollars from a modest efficiency improvement suggests that transportation has enormous potential to greatly improve the U.S. economy.

References to be provided
Table 1: Transportation Capital Stocks: Data

<table>
<thead>
<tr>
<th>Capital Stock</th>
<th>Value</th>
<th>Relevant K’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads including interstates</td>
<td>2.8</td>
<td>K₁, K₂, K₃, K₄, K₅, K₆, K₇</td>
</tr>
<tr>
<td>Rail freight track network</td>
<td>0.340</td>
<td>0.62</td>
</tr>
<tr>
<td>Airways, waterways, transit structures</td>
<td>0.568</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 2: Transportation capital stocks: values

<table>
<thead>
<tr>
<th>Capital Stock</th>
<th>Symbol</th>
<th>Level (trillions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban passenger</td>
<td>K₁</td>
<td>0.38</td>
</tr>
<tr>
<td>Urban freight</td>
<td>K₂</td>
<td>0.62</td>
</tr>
<tr>
<td>Intercity passenger</td>
<td>K₃</td>
<td>1.32</td>
</tr>
<tr>
<td>Intercity freight</td>
<td>K₄</td>
<td>1.54</td>
</tr>
<tr>
<td>International passenger</td>
<td>K₅</td>
<td>0.17</td>
</tr>
<tr>
<td>International freight</td>
<td>K₆</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Table 3: Estimation Moments

<table>
<thead>
<tr>
<th>Description</th>
<th>Theoretical Moment</th>
<th>Theoretical Moment</th>
<th>Model Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government spending on transportation/GDP</td>
<td>$\frac{G}{Y}$</td>
<td>0.07</td>
<td>0.088</td>
</tr>
<tr>
<td>Government spending multiplier</td>
<td>$\frac{Y - Y}{G - G}$</td>
<td>1.05</td>
<td>1.06</td>
</tr>
<tr>
<td>Consumption GDP</td>
<td>$\frac{PC}{Y}$</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td>Urban housing GDP</td>
<td>$\frac{N_1 P h_1}{Y}$</td>
<td>0.042</td>
<td>0.03</td>
</tr>
<tr>
<td>Suburban housing GDP</td>
<td>$\frac{N_2 P h_2}{Y}$</td>
<td>0.01</td>
<td>0.006</td>
</tr>
<tr>
<td>Value of time commuting</td>
<td>$\frac{w_1 \ell_1 t_1}{Y}$</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Fraction of time working</td>
<td>$\frac{N_1 (\ell_1 + \ell_{h_1}) + N_2 (\ell_2 + \ell_{h_2})}{Y}$</td>
<td>0.2</td>
<td>0.18</td>
</tr>
<tr>
<td>Proportion of people in city</td>
<td>$\frac{N_1}{Y}$</td>
<td>0.8</td>
<td>0.68</td>
</tr>
<tr>
<td>Fraction of time lost commuting</td>
<td>$\frac{1}{Y}$</td>
<td>0.053</td>
<td>0.053</td>
</tr>
<tr>
<td>Proportion of Production by Local Firms</td>
<td>$\frac{P_1 C_1}{P_1 C_1 + P_2 C_2 + P_3 C_3}$</td>
<td>0.3</td>
<td>0.29</td>
</tr>
<tr>
<td>Proportion of Production by Intercity Firms</td>
<td>$\frac{P_2 C_2}{P_1 C_1 + P_2 C_2 + P_3 C_3}$</td>
<td>0.6</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Table 4: Calibrated Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government cost parameter for transportation infrastructure</td>
<td>$\hat{\xi}_E$</td>
<td>5.92E-04</td>
</tr>
<tr>
<td>Elasticity of substitution between intercity and foreign firms</td>
<td>$\nu$</td>
<td>3.776</td>
</tr>
<tr>
<td>Elasticity of substitution between firms of the same type</td>
<td>$\psi$</td>
<td>2.9487</td>
</tr>
<tr>
<td>Elasticity of substitution between nonlocal and local firms</td>
<td>$\psi_\xi$</td>
<td>3.2005</td>
</tr>
<tr>
<td>Diminishing returns for government transportation investment</td>
<td>$\alpha$</td>
<td>2.6743</td>
</tr>
<tr>
<td>Fixed cost of entry: local</td>
<td>$\nu_1$</td>
<td>0.5592</td>
</tr>
<tr>
<td>Fixed cost of entry: intercity</td>
<td>$\nu_2$</td>
<td>0.4619</td>
</tr>
<tr>
<td>Fixed cost of entry: international</td>
<td>$\nu_3$</td>
<td>0.025</td>
</tr>
<tr>
<td>Weight for local vs. nonlocal firms in CES Production</td>
<td>$\xi_\mu$</td>
<td>0.2808</td>
</tr>
<tr>
<td>Weight for intercity vs. international firms in CES Production</td>
<td>$\xi_\nu$</td>
<td>0.4639</td>
</tr>
<tr>
<td>Diminishing returns for urban housing</td>
<td>$\gamma$</td>
<td>0.0579</td>
</tr>
<tr>
<td>Disutility of labor</td>
<td>$\psi$</td>
<td>2.9924</td>
</tr>
<tr>
<td>Productivity of intermediate good firms</td>
<td>$A$</td>
<td>635.3277</td>
</tr>
<tr>
<td>Productivity of urban housing production</td>
<td>$\Lambda_{h_3}$</td>
<td>6.5117</td>
</tr>
<tr>
<td>Productivity of suburban housing production</td>
<td>$\Lambda_{h_3}$</td>
<td>1.7599</td>
</tr>
<tr>
<td>Diminishing returns of urban housing production</td>
<td>$\alpha_{h_3}$</td>
<td>0.5153</td>
</tr>
<tr>
<td>Diminishing returns of suburban housing production</td>
<td>$\alpha_{h_3}$</td>
<td>0.1441</td>
</tr>
</tbody>
</table>
Table 5: Base Case and Counterfactual Results*

<table>
<thead>
<tr>
<th>Concept</th>
<th>Base Case</th>
<th>Increase Government Spending</th>
<th>Increase Productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP</td>
<td>17,089.0</td>
<td>17,216.0</td>
<td>17,182.8</td>
</tr>
<tr>
<td>Consumption Expenditure</td>
<td>14,926.0</td>
<td>14,967.7</td>
<td>15,050.9</td>
</tr>
<tr>
<td>Urban Housing</td>
<td>536</td>
<td>457</td>
<td>457</td>
</tr>
<tr>
<td>Suburban Housing</td>
<td>116</td>
<td>161</td>
<td>164</td>
</tr>
<tr>
<td>Government Spending</td>
<td>1,511</td>
<td>1,630</td>
<td>1,511</td>
</tr>
<tr>
<td>Total Proportion of Free Time Worked</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>Urban Housing Profits</td>
<td>371</td>
<td>344</td>
<td>345</td>
</tr>
<tr>
<td>Suburban Housing Profits</td>
<td>309</td>
<td>365</td>
<td>369</td>
</tr>
<tr>
<td>Equivalent Variation</td>
<td>N/A</td>
<td>288</td>
<td>418</td>
</tr>
<tr>
<td>EV: Consumption</td>
<td>N/A</td>
<td>257</td>
<td>376</td>
</tr>
<tr>
<td>EV: Housing</td>
<td>N/A</td>
<td>31</td>
<td>42</td>
</tr>
<tr>
<td>Capital Stock</td>
<td>4,110</td>
<td>4233.3</td>
<td>4233.3</td>
</tr>
</tbody>
</table>

*All values but free time worked are measured in billions of dollars. Total proportion of free time worked is a fraction.