The Long-run Effects of Transportation Productivity on the US Economy*

A. Kerem Coşar[1], Sophie Osotimehin[2], Latchezar Popov[3]

[1]University of Virginia, CEPR and NBER
[2]University of Quebec at Montreal
[3]Texas Tech University

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Abstract

We quantify the aggregate, regional and sectoral impacts of transportation productivity growth on the US economy over the period 1947-2017. Using a multi-region, multi-sector model that explicitly captures produced transportation services as a key input to interregional trade, we find that the calibrated change in transportation productivity had a sizable impact on aggregate welfare, magnified by a factor of 2.3 compared to its sectoral share in GDP. The amplification mechanism results from the complementarity between transport services and tradable goods, interacting with sectoral and spatial linkages. The geographical implications are highly uneven, with the West and Southwest benefiting the most from market access improvements while the Northeast experiences a decline. Sectoral impacts are largest in transportation-intensive activities like agriculture, mining and heavy manufacturing. Our results demonstrate the outsized and heterogeneous impact of the transportation sector in shaping US economic activity through specialization and spatial transformation.

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1 Introduction

The twentieth century has been marked by a tremendous decline in the cost of transportation (see e.g., Glaeser and Kohlhase, 2004). Given the central role of transportation in the functioning of our economies, lower transportation costs have likely had profound impacts on economic activity. How has transportation productivity contributed to increasing long-run real income? How has it reshaped the geography of economic activity? We examine these questions in the US context.

Several novel stylized facts motivate our analysis. The new BEA-BLS integrated industry-level production account data (Eldridge et al., 2020) shows that over the past seven decades, multifactor productivity (MFP) growth in the freight transportation (non-air, including warehousing) has outpaced aggregate productivity growth in the private economy: in 2016, MFP in freight transportation was 59% higher than its 1947 level, compared to a 32% increase in the rest of the private economy; during the same period, despite the large increase in domestic shipments and in contrast to other service sectors,[1] the share of freight transportation in hours worked experienced a secular decline from 5% in 1947 to 3.6% in 2016,[2] and its value added share declined from 6% to 2.6%.[3]

This period also saw substantial shifts in the geography of domestic trade. We provide evidence on these shifts and analyze the long-run evolution of US domestic trade flows. By linking newly digitized shipment data from the 1963 Census of Transportation (CTS) with the 2017 Commodity Flow Survey (CFS), we estimate a gravity regression that allows the distance coefficient to differ across years.[4] Relegating the details to section 5.3, we find that trade flows are less sensitive to distance today than in the past; specifically, we estimate a 14% reduction in the distance elasticity of manufacturing trade flows over the half-century after 1963, after controlling for changes in the size and regional distribution of industries.

To study the consequences of transportation productivity and rationalize these facts, we propose a multi-region, multi-sector model, with investment and intermediate inputs linking

[1] Using the same data, we calculate the real output increase in freight transportation and goods-producing sectors from 1947 to 2016, and find a very similar rate of increase: 2.91 times for transport vs 2.64 times in goods-producing sectors.

[2] One might suspect that the decrease in the sectoral labor share may be due to a higher than average increase in capital intensity of transportation. Using the same data, we calculate that capital intensity (real physical capital stock/hours) increased 1.79-fold in freight transportation between 1947 and 2016, while it increased 2.14-fold in the rest of the private economy.

[3] These figures are consistent with Glaeser and Kohlhase (2004) who construct a longer time series using historical data and report an 8% GDP share of transport in 1929.

[4] Our digitized data is publicly available at the NBER Commodity Transportation Survey Data page, accessible through the link `https://bit.ly/37i0v56`. Original data tables are available at `https://catalog.hathitrust.org/Record/001108626`.

production across regions and sectors. The model features an explicit transportation sector providing services that are a central input in production: regions produce distinct Armington varieties in the various sectors of the economy, and each variety requires complementary transportation services to be delivered, either within the region or to other regions. The cost of these services depends both on the sector and on the shipping distance. In addition to its key role in the production network, its low substitutability bestows transportation services a critical role in connecting regions and sectors. Another important feature of our model is the presence of capital accumulation, which we incorporate in a tractable way, while maintaining steady-state labor mobility.

We begin by using a simplified version of our model (with no capital and one sector other than transportation) to obtain insights on the determinants of the welfare and regional impact of changes in transportation productivity. We analytically derive, up to first order, the resulting changes in welfare, and in regional output and labor. We show that aggregate welfare depends on the sales share of the transportation sector in GDP, in line with Hulten's (1978) theorem. At the regional level, transportation productivity affects buyer market access through the costs of shipping intermediate inputs in and seller market access through the cost of shipping products out of the region. As a result, regional population shares adjust and specialization patterns shift in line with market access. Our analysis shows that these effects are captured by transportation margins (i.e. the ratio of shipping costs to producer prices), reflecting both the distance between regions and their productivities.

We then quantify the consequences of increased transportation productivity and the resulting decline in shipping costs observed in the US over 1947-2017. Long-run productivity improvements over that period are driven by various factors, such as the diffusion of motorized transportation and the construction of the interstate highway system, subsequent efficiency gains due to the deregulation of the trucking sector, and the improvement in logistics enabled by new technologies. We capture their overall impact as a multifactor productivity term in the production of transport services.

Our quantitative analysis relies on the steady-state equilibrium of the full model. We solve it numerically, thereby incorporating the consequences of the non-linearities associated with transportation, production and consumption, which are not captured in the analytical derivations. We calibrate the model to US 2017 data on input-output linkages, sectoral investment, region-sector employment and domestic commodity trade. For computational feasibility, we aggregate the data to 18 regions and 7 sectors. The commodity trade data is crucial for the calibration, as it allows us to determine sector-specific transportation cost parameters by matching the distance elasticity of regional trade. Another essential input to the quantification is the multifactor productivity changes which we measure between

1947, 1963 and 2017 with the Solow residual. As an external validity exercise, we show that the increase in transportation productivity over the period 1963-2017 is qualitatively and quantitatively consistent with the above-mentioned decrease in the distance elasticity of interregional trade over time.

To evaluate the impact of transportation productivity improvement in the long run, we consider a counterfactual in which transportation productivity is reverted to its 1947 value. The quantitative analysis yields three key results. First, we find that transportation productivity increased US aggregate welfare by 3.3%, an impact 2.3 times larger than the effect implied by transportation's share in GDP (using Hulten's (1978) formula). This aggregate multiplier excludes the standard input-output amplification effect, which is embedded in Hulten's formula. In our setting, there are three other amplification mechanisms. The complementarity between transportation services and tradable products magnifies the consequences of transportation productivity. In addition, the complementarity interacts with sectoral linkages, geography, and productivity to shape the aggregate welfare implications. Finally, the aggregate welfare effect is further amplified through increased capital accumulation, which occurs via the standard capital-multiplier channel.

Second, we show that the aggregate effect masks large and disparate effects across sectors and regions. Transportation productivity improvements enhance labor productivity in mining, agriculture and manufacturing more than in services. This disparity is even more pronounced when computing sectoral labor productivity along the entire chain of production, but it does not translate to gross output changes, which are more even across sectors. Our results show that the improvement in sectoral labor productivity is due to an increase in the use of intermediate inputs. We find that production reallocation towards high-productivity suppliers is consistent with regions' comparative advantages.

Third, we show how improvements in transportation productivity have reshaped the distribution of economic activity across regions. We find that output declines in the north-eastern regions due to migration to northwest and central regions where market access improves most. Our model is thus consistent with the observed spatial transformation of the US economy over the past several decades.

Focusing on within-sector changes, we find that transportation margins are the main factor behind the regional disparities in gross output changes, which is consistent with our analytical results. Hence, regions located far from their customers or with a high productivity—both of which lead to higher transportation margins—benefited the most from productivity gains in the transportation sector.

To further explore the real income implications of transportation productivity, we conduct counterfactual analyses under different assumptions regarding capital accumulation, labor mobility, trade reallocation, sectoral linkages, and substitution elasticities. Our findings highlight sectoral linkages' importance in shaping the effects of transport costs. Abstracting from these linkages, the aggregate multiplier (relative to Hulten's derivation) drops substantially, from 2.3 in the baseline model to 1.3, and the disparity in regional outcomes is largely overestimated.

Finally, we compare our specification, which yields a natural microfoundation for additive per-unit transportation costs, vis-a-vis the multiplicative iceberg transport cost function commonly used in the trade literature. The iceberg specification, which posits trade costs to be proportional to the value of shipped goods, cannot speak to certain data moments related to the transportation sector. Even if one makes the implicit value-added in transportation under the iceberg specification comparable to when transport costs are additive, these two specifications lead to differential region-sector relative price responses to productivity shifts. As a result, the iceberg specification yields different reallocation effects, with gross output changes that are weakly correlated with transportation margins. Moreover, when calibrated to the same data as the baseline model, the iceberg specification is inconsistent with the documented reduction in distance elasticities. Our modeling approach is particularly useful for ex-ante analysis as it provides a more transparent mapping between projected changes in transportation productivity and economic outcomes than the iceberg approach.

Our work is related to several strands of literature. Earlier contributions that incorporate produced transportation services in international trade (Falvey, 1976; Casas, 1983) are highly stylized and restrict attention to the implications of this modeling extension within the Heckscher-Ohlin model of trade. Recent contributions focus on the implications of endogenous transport costs arising from the backhaul problem (Behrens and Picard, 2011; Wong, 2022) and market power in shipping (Hummels et al., 2009; Ishikawa and Tarui, 2018; Asturias, 2020; Ge et al., 2024) on trade and economic geography. We expand this literature by providing a long-run quantitative analysis of the US economy using an otherwise standard workhorse spatial macroeconomic model featuring an explicit transport sector.

We also contribute to the trade literature arguing that the iceberg assumption is neither realistic nor neutral in terms of welfare implications. Without explicitly modeling the transportation sector, Hummels and Skiba (2004) reject a pure iceberg specification of freight costs from international trade data in a partial equilibrium setting. Using data on ice shipments, Bosker and Buringh (2020) estimate that the additive cost component accounts for the largest part of per unit transport costs, thus rejecting the iceberg assumption even for the costs of shipping ice itself. Irarrazabal et al. (2015) and Sørensen

(2014) study the welfare effect of additive vs multiplicative international trade costs focusing on general trade costs and tariffs rather than on domestic transportation costs.

Our paper also relates to the burgeoning literature investigating the role of domestic transportation costs (e.g. Behrens et al., 2018; Allen and Arkolakis, 2014; Coşar et al., 2022), and more specifically to macroeconomic analyses such as Herrendorf et al. (2012) and Adamopoulos (2011). We differ from these two papers in terms of scope and approach. Herrendorf et al. (2012) studies the distribution of activity between the US Midwest and Northeast in the 19th century, while Adamopoulos (2011) explores cross-country income disparities. Moreover, both papers utilize a more stylized model, with only two regions and with assumed comparative advantages. In contrast, our more granular approach integrates rich sectoral and regional data as well as domestic trade flows data to discipline the quantitative exercise.

Within the macroeconomic literature, our work is related to studies of inter-sectoral linkages (e.g Long and Plosser, 1983; Acemoglu et al., 2012; Jones, 2013) and in particular to those emphasizing the role of complementarities across production inputs (Jones, 2011; Atalay, 2017; Baqaee and Farhi, 2019; Osotimehin and Popov, 2023). None of these models distinguish transportation in terms of its low substitutability. Moreover, they feature a single region and thus abstract from spatial interactions across regions. By extending these frameworks to a spatial setting, we uncover additional mechanisms and provide insights on how a sectoral productivity shock contributes to reshaping the geography of economic activity.

Our work is also related to the recent quantitative trade literature that incorporates the economy's input-output structure, e.g., Baqaee and Farhi (2024). In particular, our work is closely related to Caliendo et al. (2017), who build a multi-region, multi-sector quantitative model with spatial and input-output linkages. Our objective, however, is distinct. They study the short-run propagation of shocks originating in the different regions and sectors of the economy, while we focus on the long-run implication of transport productivity. Separate objectives lead to different modeling choices: their framework features interregional iceberg trade costs along with a nontradable transportation sector, without a link between the two, whereas our approach is to model explicitly the distance-related trade costs as the outcome of the production function of transportation sector.[5] This approach allows us to highlight the special role of the transportation sector, yielding aggregate effects that are twice as large as in their model.

[5]We differ from their setting also by including the intersectoral linkages stemming from capital goods, following the recent work of vom Lehn and Winberry (2021) and Foerster et al. (2022). In addition, we incorporate the low elasticity of substitution between intermediate inputs, which shapes the response of the economy to sector-specific productivity changes.

The structure of the paper is as follows. Sections 2-3 describe the model environment and the equilibrium. Section 4 presents a characterization of the model under simplifying assumptions. Sections 5-6 present model calibration and the main results. Section 7 considers alternative specifications to unveil the key determinants of the results. Section 8 concludes.

2 Model Environment

We consider a closed economy consisting of n sectors (other than the transportation sector) and ℓ domestic regions. All markets are perfectly competitive and workers are free to move between all the regions in the long run. Time is discrete. We omit time subscripts on all variables since our analysis will focus on the steady state with time-invariant quantities and prices.

2.1 Production

In each region and within each sector, two types of products are assembled: composite products and commodities. While some of the sectors are services, we denote their output as commodities for brevity. Commodities are either nontradable, denoted by the set $\mathcal{P}_{\mathcal{NT}}$, or tradable, denoted by the set $\mathcal{P}_{\mathcal{T}}$, while composite products are nontradable. In addition, every region produces transportation services, required to ship tradable commodities, within or outside the region. Hence, there are $(2n+1)\times\ell$ products in total. In what follows, we denote sectors other than transportation by i and j, the transportation sector by T, and regions by o and d.

Composite products We define $\tilde{Q}_{id}$ as the composite product i, assembled in region d, with the following production function:

$$\tilde{Q}_{id} = \begin{cases} \left(\sum_{o=1}^{\ell} \left(\frac{1}{\ell}\right)^{1-\gamma} \phi_{io,d}^{1-\gamma} Z_{io,d}^{\gamma}\right)^{\frac{1}{\gamma}} & i \in \mathcal{P}_{\mathcal{T}} \\ Z_{id,d} & i \in \mathcal{P}_{\mathcal{NT}}, \end{cases} \tag{1}$$

where $Z_{io,d}$ are shipments of commodity i from origin o to destination d. The normalization $1/\ell$ helps suppress love-of-variety effect from arbitrary geographical aggregations of regions. The coefficient $\phi_{io,d}$ captures potential home bias in production, with $\phi_{io,d} = 1$ if $o = d$ and $\phi_{io,d} = \bar{\phi}_i \leq 1$ if $o \neq d$. All composite products, including those composed of tradable commodities $i \in \mathcal{P}_{\mathcal{T}}$, are nontradable and used locally as intermediate inputs, as investment goods or as consumption goods.

Commodities In every region, firms produce a distinct and imperfectly substitutable Armington variety of each sectoral commodity. The sector-i commodity of region d is produced using capital, labor and composite products as intermediate inputs:

$$Q_{id} = A_{id} \left[(1-\alpha_i)^{1-\sigma} (B_{id} H_{id})^{\sigma} + \alpha_i^{1-\sigma} \left(\sum_{j=1}^{n} v_{ij}^{1-\rho} \tilde{X}_{id,jd}^{\rho} \right)^{\frac{\sigma}{\rho}} \right]^{\frac{1}{\sigma}}, \tag{2}$$

where H_{id} is a composite of sector-region-specific capital and labor, produced with Cobb-Douglas technology:[6]

$$H_{id} = \theta_i^{-\theta_i} (1-\theta_i)^{-(1-\theta_i)} K_{id}^{\theta_i} L_{id}^{1-\theta_i} \tag{3}$$

and $\alpha_i \in [0,1], v_{ij} \geq 0, \sum_j v_{ij} = 1, \theta_i \in [0,1]$. The composite product jd used as an intermediate good by sector-region id is denoted by $\tilde{X}_{id,jd}$, capturing the nontradability of composite products described above. The parameters A_{id} and B_{id} are sector-region specific Hicksian and labor-augmenting productivities, respectively. The parameters ρ and σ govern the elasticity of substitution between intermediate inputs, and between the intermediate and the primary inputs, respectively. All production function parameters except the productivity terms are common across regions.

Investment Capital is sector-region specific, following the law of motion

$$K_{id,s+1} = (1-\delta_i) K_{id,s} + I_{id,s}, \tag{4}$$

where I_{id} denotes the investment good augmenting id's capital stock. The production of investment goods follows

$$I_{id} = \prod_{j=1}^{n} \eta_{ij}^{-\eta_{ij}} \cdot \prod_{j=1}^{n} \tilde{I}_{id,jd}^{\eta_{ij}}, \tag{5}$$

where $\tilde{I}_{id,jd}$ is the composite product j used to assemble investment good in sector i and region d; $\eta_{ij} \in [0,1], \sum_j \eta_{ij} = 1$. Once invested, the capital stock is immobile across regions and sectors. Despite this feature, capital stocks adjust in response to technology shocks as firms can vary their investment levels.

Transportation Transport services are complementary to the delivery and use of origin-specific varieties in destination regions. In particular, when $Z_{io,d}$ units of commodity io are used in destination d, a total supply of transportation services $Z_{io,d} \cdot t_{io,d}$ is required. This

[6]The term $\theta_i^{-\theta_i}(1-\theta_i)^{-(1-\theta_i)}$ is a convenient normalization that simplifies the price expressions but has no effect on the results. We use a similar normalization for the investment goods.

specification captures the impossibility of substituting transportation services. It is also consistent with the additive (rather than ad-valorem) nature of transportation costs. The transportation parameter $t_{io,d}$ has a sector-specific component reflecting characteristics of commodity i being shipped such as its weight per value, or whether its shape and volume require specialized modes. Its geographic component captures shipping distances. We assume that transportation services must be sourced from the origin of the shipment.

Producing transportation services requires primary and intermediate inputs, like any other sector in the economy. The output of transportation services available in region o is given by:

$$T_o = A_T \left[(1-\alpha_T)^{1-\sigma} (B_T H_{To})^{\sigma} + \alpha_T^{1-\sigma} \left(\sum_{j=1}^{n} \upsilon_{Tj}^{1-\rho} \tilde{X}_{To,jo}^{\rho} \right)^{\frac{\sigma}{\rho}} \right]^{\frac{1}{\sigma}}. \tag{6}$$

The composite input H_{To} is produced using the same Cobb-Douglas functional form in equation 3 with sector-T specific parameters that are common across regions.

In summary, while production technologies are uniform within each sector, regions differ in their sectoral productivities in all sectors except transportation. Sector-region productivities of commodities, (A_{id}, B_{id}), reflect comparative advantages driven by endowments and persistent idiosyncratic factors outside of our model. Transportation productivity parameters, (A_T, B_T) are common to all regions, capturing the mobile and fluid nature of that sector.

2.2 Consumers

Overlapping generations and mobility There is an atomless mass of agents with measure $\bar{L}$, each supplying one unit of labor inelastically. Demographics follow the perpetual youth model: an agent survives to the next period with a constant probability π. Newborn agents of mass $(1-\pi)\bar{L}$ replace those who die so that population remains constant. Agents are born without wealth and are free to move to any region in the initial period of their life, but are immobile thereafter.

The overlapping generations structure helps keep the model tractable. Allowing interregional labor mobility is key for capturing long-term responses to changes in transportation productivity. However, ownership of region-specific assets creates the possibility of complicated migration and portfolio decisions over the life-cycle: agents may find it optimal to cycle between working and saving in a high-nominal wage region, and enjoying consumption out of their savings in a region with a low cost of living. To rule out such dynamics and keep the model tractable, we let agents make a spatial choice only in the first period of their life,[7] such that only newborn workers are mobile across regions.

Preferences and budget constraints Using lower case letters to denote per capita variables and a for age, agents choosing to live in region d maximize lifetime discounted utility given by

$$\sum_{a=0}^{\infty} (\beta\pi)^a \log c_{a,d}, \tag{7}$$

where $\beta < 1$ is the discount factor. The per period real consumption bundle is a CES aggregate of sectoral composite products:

$$c_{a,d} = \left(\sum_{i=1}^{n} \xi_i^{1-\chi} \cdot \tilde{c}_{a,id}^{\chi} \right)^{\frac{1}{\chi}}, \tag{8}$$

where $\tilde{c}_{a,id}$ is the per capita consumption of composite sector-i product in d, $1/(1-\chi)$ is the elasticity of substitution, and $\xi_i \geq 0, \sum_i \xi_i = 1$. We abstract from final consumption of transportation services.

There are competitive risk-neutral financial intermediaries supplying annuities to agents, paying off as long as they are alive. In this context, the life-time budget constraint for each agent living in a region d is as follows:

$$\sum_{a=0}^{\infty} \frac{\pi^a}{(1+r)^a} \left(\sum_{i=1}^{n} \tilde{p}_{id} \tilde{c}_{a,id} \right) = \sum_{a=0}^{\infty} \frac{\pi^a}{(1+r)^a} w_d, \tag{9}$$

where r the risk-free interest rate on bonds, $\tilde{p}_{id}$ is the local price for composite products and w_d is the local nominal wage. Appendix A.1 describes financial intermediaries in detail.

3 Steady-State Equilibrium

After characterizing the consumer and producer optimization problems, this section first defines the steady-state equilibrium. It then offers a proof showing that, given prices and wages, a unique solution for market allocation can be found using linear algebra.

[7] Quantitative spatial equilibrium models follow various approaches to deal with this complication. In Caliendo et al. (2017), agents own shares in a national portfolio aggregating regional land rents. In our case, regional assets are capital stocks, which are accumulated dynamically. Kleinman et al. (2023) features local capital accumulation by immobile landlords.

3.1 Consumer optimization

The standard CES price index P_d for a unit real consumption bundle in location d is

$$P_d = \left(\sum_{j=1}^{n} \xi_j \tilde{p}_{jd}^{-\frac{\chi}{1-\chi}} \right)^{-\frac{1-\chi}{\chi}}, \tag{10}$$

and the consumption of composite commodities is $\tilde{c}_{a,id} = c_{a,d}\tilde{c}_{id}$ where

$$\tilde{c}_{id} = \xi_i \left(\frac{\tilde{p}_{id}}{P_d} \right)^{-\frac{1}{1-\chi}}. \tag{11}$$

Then, with the optimal within-period consumption choices, the budget constraint (9) becomes:

$$\sum_{a=0}^{\infty} \frac{\pi^a}{(1+r)^a} P_d c_{a,d} = \sum_{a=0}^{\infty} \frac{\pi^a}{(1+r)^a} w_d.$$

Intertemporal utility maximization implies that at age a:

$$c_{a,d} = \left[\beta(1+r)\right]^a \cdot \frac{(1-\beta\pi)(1+r)}{1+r-\pi} \cdot \frac{w_d}{P_d},$$

capturing individual consumption growth over time due to savings.

Agents will therefore choose (at birth) the region with the highest real wage. As a consequence, at the steady state of a spatial equilibrium featuring a strictly positive population in each region, real wages ω_d are equalized:

$$\omega_d \equiv \frac{w_d}{P_d} = \omega \quad \forall d. \tag{12}$$

At the steady state, all regions have the same demographic structure—thus, the same average per capita real consumption c:

$$c = \sum_{a=0}^{\infty} (1-\pi)\pi^a c_a = \frac{(1-\pi)(1-\beta\pi)(1+r)}{(1-\beta(1+r)\pi)(1+r-\pi)} \cdot \omega \equiv \lambda(r) \cdot \omega. \tag{13}$$

3.2 Producer optimization

We denote the *producer* price of commodity io by p_{io}. The price of transportation services, purchased at the origin of the shipment, are denoted p_{To}. Then, the *purchaser* price of a unit of tradable commodity Z_{iod} is $p_{io} + t_{iod} \cdot p_{To}$. Given the production function (1) and cost minimization under perfect competition, the price of a composite product i assembled in location d is given by:

$$\tilde{p}_{id} = \begin{cases} \left[\sum_{o=1}^{\ell} \frac{1}{\ell}\ \phi_{io,d}\ (p_{io} + t_{iod} \cdot p_{To})^{-\frac{\gamma}{1-\gamma}}\right]^{-\frac{1-\gamma}{\gamma}} & i \in \mathcal{P}_{\mathcal{T}}, \\ p_{id} & i \in \mathcal{P}_{\mathcal{NT}}, \end{cases} \tag{14}$$

with the corresponding flows:

$$\frac{Z_{iod}}{\tilde{Q}_{id}} = \begin{cases} \frac{1}{\ell}\ \phi_{io,d}\ \tilde{p}_{id}^{\frac{1}{1-\gamma}} (p_{io} + t_{iod} p_{To})^{-\frac{1}{1-\gamma}} & \text{if } i \in \mathcal{P}_{\mathcal{T}}, \\ 1 & \text{if } o = d \text{ and } i \in \mathcal{P}_{\mathcal{NT}}, \\ 0 & \text{if } o \neq d \text{ and } i \in \mathcal{P}_{\mathcal{NT}}. \end{cases} \tag{15}$$

The unit cost of commodity io equals

$$p_{io} = A_{io}^{-1} \left[(1-\alpha_i) q_{io}^{-\frac{\sigma}{1-\sigma}} B_{io}^{\frac{\sigma}{1-\sigma}} + \alpha_i P_{X,io}^{-\frac{\sigma}{1-\sigma}}\right]^{-\frac{1-\sigma}{\sigma}}, \tag{16}$$

where q_{io} is the cost of the capital-labor composite and $P_{X,io}$ is the cost of the intermediate-goods bundle (given respectively by equations (A.4) and (A.5) in Appendix A.2). The implied demand for intermediate goods is

$$\frac{\tilde{X}_{io,jo}}{Q_{io}} = v_{ij} \left(\frac{\tilde{p}_{jo}}{P_{X,io}}\right)^{-\frac{1}{1-\rho}} \cdot \alpha_i A_{io}^{\frac{\sigma}{1-\sigma}} \left(\frac{p_{io}}{P_{X,io}}\right)^{\frac{1}{1-\sigma}}, \tag{17}$$

capturing the two nests in production: one between the intermediate-goods bundle and value added with elasticity $1/(1-\sigma)$, and the other between the various intermediate goods with elasticity $1/(1-\rho)$. The nested CES production function implies the following demands for labor and capital:

$$\frac{L_{io}}{Q_{io}} = (1-\alpha_i)(A_{io}B_{io})^{\frac{\sigma}{1-\sigma}} (p_{io}/q_{io})^{\frac{1}{1-\sigma}} (1-\theta_i) q_{io}/w_o, \tag{18}$$

$$\frac{K_{io}}{Q_{io}} = (1-\alpha_i)(A_{io}B_{io})^{\frac{\sigma}{1-\sigma}} (p_{io}/q_{io})^{\frac{1}{1-\sigma}} \theta_i q_{io}/p_{io}^k. \tag{19}$$

Finally, the demand for investment goods is given by

$$\frac{\tilde{I}_{io,jo}}{I_{io}} = \eta_{ij} \frac{p_{io}^k}{\tilde{p}_{jo}}, \tag{20}$$

where p_{io}^k, the cost of the investment goods bundle, is given by equation (A.6) in Appendix A.2. Same conditions apply to the transportation sector with its own production parameters.

3.3 Equilibrium definition

A steady state equilibrium is a collection of prices $\{p_{io}, \tilde{p}_{io}, q_{io}, p^k_{io}, w_o, P_{X,io}, P_o, r\}$ and quantities $\{Q_{io}, \tilde{Q}_{io}, Z_{iod}, \tilde{X}_{io,jo}, K_{io}, L_{io}, I_{io}, \tilde{I}_{io,jo}, c, \tilde{c}_{io}\}$ such that

(a) prices satisfy the cost minimization conditions (10), (14), (16), (A.4), (A.5) and (A.6);

(b) real wage equalization (12) holds for all locations with $L_o = \sum_{i=1}^n L_{io} + L_{To} > 0$;

(c) the quantities satisfy production functions (1)–(3), (5)–(6) and firms' optimization conditions (15), (17), (18), (19), and (20);

(d) the consumer optimality conditions (11) and (13) are satisfied;

(e) the capital stocks are stationary

$$I_{io} = \delta_i K_{io}; \tag{21}$$

(f) the markets for goods, transportation services and labor clear:

$$\bar{L} = \sum_{o=1}^{\ell} \sum_{i=1}^{n} L_{io} + \sum_{o=1}^{\ell} L_{To} \tag{22}$$

$$T_o = \sum_i \sum_d Z_{io,d} \cdot t_{io,d} \tag{23}$$

$$Q_{io} = \sum_{d=1}^{\ell} Z_{io,d} \tag{24}$$

$$\tilde{Q}_{io} = \sum_{k=1}^{n} \tilde{X}_{ko,io} + \tilde{X}_{To,io} + \sum_{k=1}^{n} \tilde{I}_{ko,io} + \tilde{I}_{To,io} + \tilde{C}_{io}, \tag{25}$$

where $\tilde{C}_{io} = \tilde{c}_{io} \cdot c \left(\sum_{j=1}^n L_{jo} + L_{To} \right)$ is the total consumption of composite product io;

(g) and the financial markets clear:

$$(\lambda(r) - 1) \sum_o L_o w_o = r \sum_o \left[\sum_i p^k_{io} K_{io} + p^k_{To} K_{To} \right]. \tag{26}$$

Condition (g) requires that total nominal consumption minus total nominal wage bill equals income from net assets (physical capital) in the economy. We provide more details in Appendix A.1.

3.4 Solving for the equilibrium allocation

In this subsection we show that, given prices and wages, the quantities in the model are unique and can be obtained from the optimal decision rules of firms and consumers using linear algebra.

Each representative firm's demand for inputs is linear in its own output; similarly, consumer demand is linear in real income. Hence, we can express the flows of commodities using matrix notation. We start by stacking all the products' output in vector Q and the final consumption of all products in vector C, both with dimension $(2n+1)\ell \times 1$ (which includes the commodities, the composite products and transportation services, in all locations); similarly, L and K are the $(2n+1)\ell \times 1$ vectors of labor and capital used in the production of all these products.[8]

From the market-clearing conditions, we obtain the vector of output as a function of consumption:

$$Q = (I - M' - J')^{-1} C,$$

where the vector of intermediate goods used in the production of each commodity (including composite products) is given by $M'Q$, the vector of goods used for investment by $J'Q$ and I is the identity matrix. The matrices M and J, both of size $(2n+1)\ell \times (2n+1)\ell$, denote the matrix of optimal intermediate goods and investment usage. The matrix M has the user in the row and supplier in the columns, with $M_{\tilde{i}d,io}$ given by (15); the corresponding demand for transportation services implies $M_{\tilde{i}d,To} = t_{iod} M_{\tilde{i}d,io}$; and $M_{id,\tilde{j}d}$ and $M_{Td,\tilde{j}d}$ are given by (17). All other elements of the matrix are zero. The vector of investment demand is determined by the demand for capital, obtained by combining (19), (20) and (21). More details about M and J can be found in Appendix A.3.

The matrix $\Omega' \equiv (I - M' - J')^{-1}$ is a generalization of the Leontief inverse to an economy with investment goods.[9] The form of the Leontief inverse with investment goods is not surprising given the continuity between intermediate goods and capital goods (intermediate goods are equivalent to capital goods with a depreciation rate equal to one).

Next, we combine (11) and (13) to express $C = \lambda(r) G' L$, where G is a $(2n+1)\ell \times (2n+1)\ell$ matrix given by $G_{id,\tilde{j}d} = \xi_j \left(\frac{\tilde{p}_{jd}}{P_d}\right)^{-\frac{1}{1-\chi}} \omega$ and 0 elsewhere. Then, the consumption demand from workers across sectors and regions gives rise to demand for intermediate goods and capital, which results in a vector of gross output Q. In turn, the vector of gross output

[8]The production of composite products does not use capital and labor directly, so the corresponding elements in the vectors K and L will be zero; in the same way, since only composite products are used for consumption and investment, the C and I vectors will be zeroes elsewhere.

[9]Each element of the Leontief inverse shows how, through direct and indirect linkages, productivity and demand shocks in one sector affect (up to first order) the price and output in another sector.

induces demand for labor. Let z be the matrix of optimal labor demand given by (18) for $z_{io,io}$ and $z_{To,To}$ and 0 elsewhere. Then $L = zQ$ and putting all the pieces together, we obtain:

$$L = \lambda(r) z \Omega' G' L. \tag{27}$$

Thus, formally the equilibrium labor vector is the solution to an eigenvector problem.

Assumption 1. *For all goods i, there exist indices $q_1, q_2, \cdots q_g$ such that*

$$(\alpha_i v_{i,q_1} + \theta_i \eta_{i,q_1})(\alpha_{q_1} v_{q_1,q_2} + \theta_{q_1} \eta_{q_1,q_2}) \cdots (\alpha_{q_{g-1}} v_{q_{g-1},q_g} + \theta_{q_{g-1}} \eta_{q_{g-1},q_g})(1 - \alpha_{q_g})(1 - \theta_{q_g}) > 0.$$

In addition, there exists at least one tradable good with some indices $s_1, s_2, \cdots s_m$ such that

$$\xi_{s_1}(\alpha_{s_1} v_{s_1,s_2} + \theta_{s_1} \eta_{s_1,s_2})(\alpha_{s_2} v_{s_2,s_3} + \theta_{s_2} \eta_{s_2,s_3}) \cdots (\alpha_{s_m} v_{s_m,i} + \theta_{s_m} \eta_{s_m,i}) > 0.$$

The first condition ensures that all sectors use labor either directly or indirectly. The second one guarantees that at the equilibrium at least one tradable good will be produced in positive amounts, which creates linkages between location. These connections, and the Perron-Frobenius theorem, allow us to prove that the labor vector is unique (given prices).

Lemma 1. *Suppose that Assumption 1 holds; let $r > 0$ be arbitrary and let the vector of wages and prices satisfy the cost minimization condition given r. Let z, M, J, G and Ω be defined as above. Suppose that Ω exists and is nonnegative. Let $sp(z\Omega' G')$ be the spectral radius of the matrix (the largest absolute value of its eigenvalues). Then*

1. *The eigenvalue associated with the spectral radius is strictly positive and simple.*
2. *There is a unique (up to scaling) nonnegative eigenvector L of the matrix $\lambda(r) z \Omega' G$ and it is associated with the eigenvalue $\lambda(r) sp(z\Omega' G')$.*

Proof. In Appendix A.1. □

Theorem 1. *Let $\{p_{io}, \tilde{p}_{io}, q_{io}, p^k_{io}, w_o, P_{X,io}, P_o, r\}$ be a set of prices. Suppose that Assumption 1 holds and the Leontief inverse Ω exists and is nonnegative. Then:*

1. *$\{p_{io}, \tilde{p}_{io}, q_{io}, p^k_{io}, w_o, P_{X,io}, P_o, r\}$ are equilibrium prices if and only if they satisfy the cost minimization conditions, $\lambda(r) sp(z\Omega' G') = 1$, and real wages are equalized.*
2. *If $\{p_{io}, \tilde{p}_{io}, q_{io}, p^k_{io}, w_o, P_{X,io}, P_o, r\}$ are equilibrium prices, then the equilibrium quantity vectors L, Q, C, K are unique for these prices.*

3. *If $\theta_i = 0$ for all i (no sector uses capital), and the prices satisfy the cost minimization conditions, then $sp(z\Omega' G') = 1$ and r satisfies $\lambda(r) = 1$, which is equivalent to $r = \beta^{-1} - 1$.*

The condition $\lambda(r)sp(z\Omega' G') = 1$ is derived from products and labor markets clearing but it also implies clearing in the financial market, an application of Walras Law.

3.5 An algorithm for model solution

We finish the section by describing an algorithm to solve for the steady-state equilibrium. For a given vector of parameters, the model is solved in three nests. In the innermost nest, given a guess of the real interest rate r and the vector of nominal wages, we find all the other equilibrium prices $p_{io}, \tilde{p}_{io}, q_{io}, p^k_{io}, P_{X,io}, P_o$ by iterating on equations (14), (16), (A.4), (A.5) and (A.6). In the second nest, still given r, we iterate over the nominal wage vector w until spatial equilibrium obtains ($w_o/P_o = w_d/P_d \ \forall o, d$). In the outermost nest, after obtaining the matrices z, Ω, G for a given r, we compute $\mu(r) = sp(z\Omega' G')$ and iterate over r until $\lambda(r)\mu(r) = 1$, which pins down the equilibrium real interest rate and hence the rest of the model solution. Theorem 1 ensures that the result of this procedure is an equilibrium.

While the theorem does not guarantee the existence of an equilibrium, this has not been an issue in practice. We also note that other than the OLG structure, our model relates to Allen and Arkolakis (2014) who provide sufficient conditions for the existence of a regular equilibrium featuring a non-degenerate spatial distribution of population in an Armington model with labor mobility, negative and positive externalities. Transport costs in our model are quasi-symmetric according to their definition (see their footnote 8), which satisfies the assumptions of their existence proof. Crucially, we assume away externalities which tend to pose a threat to the existence of a regular equilibrium or its uniqueness.

4 Analytical Insights from a Simplified Model

Before quantifying the effects of transportation productivity changes, we explore the mechanisms of the model and unveil the key determinants of transportation costs' impact. We do so by constructing a simplified version of our model with a closed-form solution.

Consider an economy identical to the one described in section 2 except for the following features. The economy is composed of a transportation sector and one other sector only. The two sectors share the same intermediate-input parameter α. With the local varieties of the commodity and the composite products in the various regions, there are $(2 \times 1 + 1) \times \ell$ products. Moreover, there is no capital and no home bias in the production of the composite product, $\phi_{od} = 1, \forall o, d$.

We normalize $A_T = 1$ and assume that it takes $\bar{t} \cdot t_{od}$ units of transportation services to move the commodity from origin o to destination d. The change in the scaling level $\bar{t}$ is isomorphic to changes in $1/A_T$. To study the consequences of transportation costs, we increase the parameter $\bar{t}$ from 0 to a positive level. In the following, we denote by y' the derivative with respect to $\bar{t}$ of any variable y, evaluated at the zero-transportation-cost equilibrium. All proofs and derivations are in Appendix B.

Welfare The following proposition describes the impact of a change in transportation costs on consumer welfare, which is proportional to real wage in this simple version of the model.

Proposition 1. *Given the assumptions of the simplified model, the welfare effect of a small increase in transportation costs from zero is*

$$\frac{\omega'}{\omega} = -\frac{1}{1 - s^X} \cdot \kappa, \tag{28}$$

where $\kappa \equiv \sum_o \sum_d s_o^Z s_d^Z \kappa_{od}$*, with* $\kappa_{od} \equiv t_{od} p_{To}/p_o$*, the transportation margin paid on commodity* o *in destination* d*,* $s_o^Z = \frac{p_o Z_{od}}{\tilde{P}_d \tilde{Q}_d}$ *the cost share of the variety produced in region* o*, and* $s^X = \frac{\tilde{p}_d \tilde{X}_{d,d}}{p_d Q_d}$ *is the cost share of intermediate inputs, common across regions.*[10]

The welfare change depends on κ which is the sum of transportation margins κ_{od} for all pairwise trade flows between regions, weighed by trade values, or in other words, the transportation output as a share of total gross output. The transportation share of output is scaled by $1/(1-s^X)$, the ratio of gross output to GDP, in an expression reminiscent of Hulten (1978). In line with Hulten's formula, the proposition shows that the key determinant of the aggregate impact of transportation cost is simply the size of the transportation sector. As we will see in the quantitative section, the expression above underestimates the welfare effect of transportation costs since the first-order derivation does not account for the amplification channel coming from transportation services' lack of substitutability.

In the following corollary, we show how the welfare impact is determined by the distribution of A and t.

Corollary 1. *Suppose that there is a continuum of locations such that productivity* A *and* t_{od} *are jointly log-normally distributed,* $\ln A \sim N(\mu_A - \nu_A^2/2, \nu_A^2)$*,* $\ln t_{od} \sim N(\mu_t - \nu_t^2/2, \nu_t^2)$ *and* $\mathrm{Corr}(\ln A_o, \ln t_{od}) = \mathrm{Corr}(\ln A_d, \ln t_{od}) = \rho_{tA}$*. Then,*

$$\kappa = \exp\left(\mu_A + (\epsilon_\gamma - 1)\nu_A^2 + \mu_t + \rho_{tA}(\epsilon_\gamma - 1/2)\nu_t \nu_A\right), \tag{29}$$

[10] The cost shares are common across regions in the zero-transportation cost benchmark because the purchaser prices are identical in all regions.

where $\epsilon_\gamma \equiv 1/(1-\gamma)$.

When $\epsilon_\gamma > 1/2$, trade volumes are highest between pairs of most productive locations. In this case a positive correlation between transportation requirements and productivity increases the negative impact of transportation costs on welfare.

Regional reallocation Transportation costs lead to changes in the relative prices of commodities from different regions and between labor and the composite product (used as intermediate input), and as a result, production and labor reallocate between regions. The following proposition describes the determinants of the regional changes in gross output and labor.

Proposition 2. *Given the assumptions of the simplified model, the change in each region's commodity output and total labor (including transportation) are given respectively by:*

$$\frac{Q_o'}{Q_o} = -\kappa - s^X \epsilon_\sigma \frac{1}{1-s^X}\kappa - \epsilon_\gamma \left(\kappa_{o\leftarrow} - \kappa + \kappa_{o\rightarrow} - \kappa\right) \quad (30)$$

$$\frac{L_o' + L_{To}'}{L_o + L_{To}} = -\epsilon_\gamma \left(\kappa_{o\leftarrow} - \kappa + \kappa_{o\rightarrow} - \kappa\right) + \kappa_{o\rightarrow} - \kappa, \quad (31)$$

where $\epsilon_\sigma \equiv 1/(1-\sigma)$, $\epsilon_\gamma \equiv 1/(1-\gamma)$, $\kappa_{o\leftarrow} \equiv \sum_m s_m^Z \kappa_{mo}$ *is the average transportation margin paid on shipments* to *region o; the coefficient* $\kappa_{o\rightarrow} \equiv \sum_d s_d^Q \kappa_{od}$ *is the weighted transportation margin of shipments* from *location o with weights* $s_d^Q = p_d Q_d / (\sum_m p_m Q_m)$ *being region d's gross output share.*[11]

The magnitude of the regional output drop (equation 30) depends on three effects: the common transportation share κ reflects the aggregate reallocation between the transport sector and commodity-producing sectors. The second term corresponds to the real wage, which falls by $\kappa/(1-s^X)$, and the resulting substitution away from intermediate goods in production. Finally, the last component gives the effect of the change in the purchaser price, which is affected by transportation costs directly as well as through producer costs. Overall, average gross output falls more than final consumption. The expression also shows how the reduction in gross output varies across regions. The output decline is most pronounced in regions with the highest relative price increases, which are typically those with high transportation margins on goods shipped out of $(\kappa_{o\rightarrow} - \kappa)$ or into the region $(\kappa_{o\leftarrow} - \kappa)$. The former is inversely related to market access while the latter captures higher input costs,

[11]Balanced trade and the initial frictionless allocation imply that $s_d^Z = s_d^Q$, that is the expenditure share and share of the value of gross output are the same. Also, real wage equalization and the common labor share imply $s_d^Z = s_d^Q = L_d/\bar{L}$.

including indirect effects through nominal wage adjustments. Since $s_d^Q \propto A_d^{\epsilon_\gamma - 1}$, the market access variable puts more weight on the transportation margins paid by buyers in more productive regions whenever $\epsilon_\gamma > 1$ (as is the case in our calibration). Furthermore, both the input costs and the market access components depend on the distribution of regional productivities. Indeed, in equilibrium $\kappa_{od} = t_{od} A_o$, and therefore the transportation margin increases with the productivity of shipped goods. This feature, a well-known implication of additive transportation costs, suggests that, all else equal, more productive regions or those purchasing from more productive regions will be more sensitive to transportation productivity changes since transportation costs represent a larger fraction of the purchaser price of high-productivity commodities.

The impact on regional employment is similar to the idiosyncratic regional output change, except the extra term $\kappa_{o\rightarrow} - \kappa$ which comes from the labor used to produce transportation services. With $\epsilon_\gamma > 1$, regions with worse market access lose employment when transportation costs increase.

5 Quantitative Analysis: Calibration

To evaluate quantitatively the impact of productivity improvements in the transportation sector, we first calibrate the full model presented in Sections 2 and 3 to 2017 US data. We then consider the change in transportation productivity observed between 1947 and 2017. In what follows, we explain the calibration, present our measure of the counterfactual transportation productivity and provide some external validity by confronting the model's predictions to the observed long-run changes in domestic US domestic trade flows.

5.1 Calibration

We calibrate the parameters of the model to match relevant moments in 2017 US data. In particular, we use interregional trade flows, available from the Bureau of Transportation Statistics Freight Analysis Framework (FAF), as well as data on production, employment, capital, input-output relationships between sectors available form the Bureau of Economic Analysis (BEA). Appendix D provides a detailed description of the data used and of the construction of the empirical targets.

Regions and sectors Since our quantitative analysis is computationally intensive, we use a parsimonious number of sectors and regions capturing the essential variation within the US economy. There are seven sectors in our analysis, one being transportation. In line with the model, we exclude passenger transit and only use freight-related sub-sectors in imputing transport-sector variables. The remaining $n = 6$ sectors are agriculture, mining, heavy and light manufacturing, tradable and nontradable services. The subdivision of the manufacturing sector is guided by their estimated elasticities of regional trade to distance, with heavy manufacturing corresponding to industries with high distance elasticities. The classification of service industries into tradable vs. nontradable follows Jensen et al. (2005). Air transport is classified as a tradable service since its share in domestic freight is minimal.[12] Details are presented in Appendix D.1.

Geographically, we divide the continental US into $\ell = 18$ regions (Figure 1a). Two of these regions are California and Texas, while the others are aggregations of remaining states. Since our external validity analysis uses 1963 domestic trade flows that are only available at the level of 9 Census divisions, we make sure that the 18 regions can further be aggregated to that level.

Boundaries of the transportation sector A sizable share of transportation services are produced in-house by firms rather than being purchased on the market. This dimension is not captured in baseline input-output tables but the Bureau of Transporation Statistics publishes Transportation Satellite Accounts (TSA) to account for imputed in-house transportation services. In addition, transportation is used only as an intermediate input in our model. These two adjustments imply that we need to compute the value added of the transportation sector consistent with the TSA input-output tables and the absence of final use of transportation services. Details are presented in Appendix D.2.

Substitution elasticities and intertemporal parameters We set the elasticity of substitution between intermediates to 0.25, that between the intermediate input bundle and the capital-labor bundle to 0.7. These elasticities are in line with values estimated by Atalay (2017). The consumption elasticity of substitution between sectors is set to 0.25, consistent with the literature on structural change which sets values below 1 for a similar level of aggregation (e.g. Ngai and Pissarides, 2007). The elasticity of substitution between regional varieties is set to 8, at the high end of the values used in the quantitative trade literature since domestic varieties are expected to be more substitutable than international varieties (Allen and Arkolakis, 2014). We set the household's survival probability to match life expectancy at age 25 of 55 years (Table 1 from Arias and Xu (2019)), which implies $\pi = 0.982$. Finally, we set the discount factor to ensure that the long-run equilibrium real interest rate is $r = 0.04$, which implies $\beta = 0.9674$. The values are summarized in Table 1.

[12] According to the 2017 Commodity Flow Survey, the share of air in the value and ton-miles of domestic shipments is 3.4% and 0.3%, respectively.

Capital and investment parameters The parameter of capital in the production function θ_i is computed from the share of the operating surplus over total income reported in the BEA input-output table. Because the data do not adjust for proprietorship, these numbers overestimate the capital share of income. We therefore adjust the shares, in the same proportion for all sectors, in order to match the economy-wide capital share of 0.4 as estimated by the US Bureau of Labor Statistics for 2017.

We compute the sector-specific depreciation rates δ_i from BEA data on current dollar capital stock and current dollar depreciation costs by sector. We aggregate the investment-flows estimates of vom Lehn and Winberry (2021) in order to compute the parameters η_{ij}. We present the details for obtaining the capital and investment parameters in Appendix D.2.

Production and transportation parameters We assume no transportation cost required to purchase tradable services and an infinite transportation cost for nontradable services produced outside the region, and hence set $t_{iod} = 0$ for all (o, d) pairs for tradable services. For the remaining $(n-2)$ sectors, we parametrize the transportation requirement t_{iod} to be a function of distance: $t_{iod} = t_i \times distance_{od}$. Interregional distances follow straight-lines between regional centroids. Intra-regional distances follow the formula $distance_{oo} = (2/3)\sqrt{area_o/\pi}$ (Mayer and Zignago, 2011). We normalize all distances by the smallest intra-regional distance.

We calibrate jointly the transportation requirements with the rest of the production parameters, $(t_i, \xi_i, \bar{\phi}_i, \alpha_i, v_{ij}, B_{io}, B_T)$, to minimize the weighted sum of squared errors between the empirical and model-implied values of the share of each region in each sector's employment, the input-output shares of each sector, the value added share of each sector (adjusted to account for in-house transportation and no final use of transportation services), the ratio of value added to gross output in the transportation sector (which ensures that the sector's exposure to B matches the data), the sector-specific distance elasticities and the out-of-region trade coefficients. We now describe the construction of some of these moments in more detail.

Table 1: Externally Set Parameters

Parameter		Value	Target
Subst. elasticity btw. regional varieties in composite production	γ	0.875	$1/(1-\gamma) = 8$
Subst. elasticity btw. intermediates	ρ	-3	$1/(1-\rho) = 0.25$
Subst. elasticity btw. intermediates and capital-labor	σ	-0.429	$1/(1-\sigma) = 0.7$
Subst. elasticity btw. regional varieties in final consumption	χ	-3	$1/(1-\chi) = 0.25$
Discount factor	β	0.967	Interest rate $(r) = 4\%$
Survival probability	π	0.982	Life expectancy

In line with the US national accounts, we compute the intermediate input shares without including transportation costs:

$$interm_{ij} = \frac{\sum_{d=1}^{\ell} Q_{id}\left(\sum_{o=1}^{\ell} M_{id,\tilde{j}d} M_{\tilde{j}d,jo} p_{jo}\right)}{\sum_{d=1}^{\ell} p_{id} Q_{id}}, \; i = 1, ..., n+1, j = 1, ..., n.$$

The value added in each sector is computed as $\text{VA}_i = \sum_o \left(p_{io}Q_{io} - \sum_j \tilde{p}_{jo}\tilde{X}_{io,jo}\right)$, the shares as $va_i = \text{VA}_i/(\sum_i \text{VA}_i), \; i = 1, ..., n+1$, and the value added to gross output ratio as $\text{VA}_T/(\sum_o p_{To}Q_{To})$; the share of each region in sector i's employment is computed $emp_{io} = L_{io}/(\sum_o L_{io}), \; i = 1, ..., n, d = 1, ..., \ell$. The distance elasticities and the out-of-region trade coefficients are estimated separately for each tradable good as follows:

$$\ln(Z_{iod}) \; = \; \varphi_{1i} \cdot \ln(\text{distance}_{od}) + \varphi_{2i}\mathbf{1}_{o \neq d} + u_{io} + u_{id} + \epsilon_{iod}, \tag{32}$$

where $i = 1, ..., n-2$ and $o, d = 1, ..., \ell$. We target the corresponding elasticities estimated from the empirical interregional trade flows (FAF).

Normalizing $A_{id} = 1$, $\forall i = 1, ..., n+1$, $\forall d = 1, \cdots, \ell$ and $B_{i1} = 1$ $\forall i = 1, ..., n$, we have a total of $n + [(n+1) \times n] + (\ell - 1) \times n + 1 + 2 \times (n-2) = 159$ parameters to calibrate.

Data patterns and model fit Table 2 presents summary measures of the calibration for value added, the distance elasticity and out-of-region coefficient, while the individual employment shares are plotted in Figure 2 and the input-output shares in Appendix E. All the targets are matched well, with a median gap between the model and the target of less than 1.3 percentage points for the employment, input-output and value added shares. The model is also able to capture well the role of geography, as indicated by the distance and the out-of-region coefficients, which closely match the data. Trade flows diminish with distance, and in line with intuition, the sensitivity to distance is higher for sectors whose products are likely to require high transportation costs per dollar of product, such as mining. Another notable data pattern is that economic activity is unevenly distributed across regions, and the regional disparities vary from one sector to another. For example, the mid-Atlantic region, with its large population, accounts for about 15% of employment in both tradable and nontradable services but only for around 7% of employment in agriculture and mining. Our quantitative analysis will shed light on how these spatial patterns influence the regional and sectoral gains from transportation productivity improvement.

5.2 Counterfactual transportation productivity

Our main thought experiment is a counterfactual in which productivity in the

Table 2: Model Fit—Empirical Targets (Data) vs Calibrated Values (Model)

	Value added		Distance elasticity (φ_{1i})		Out-of-region dummy (φ_{2i})	
	Data	Model	Data	Model	Data	Model
Agriculture	0.014	0.029	-2.0	-2.0	-1.8	-1.7
Mining	0.024	0.030	-3.1	-2.9	-0.6	-0.6
Heavy manufacturing	0.062	0.064	-1.6	-1.6	-1.0	-1.0
Light manufacturing	0.070	0.055	-1.2	-1.2	-1.6	-1.6
Tradable services	0.346	0.359	-	-	-	-
Nontradable services	0.454	0.433	-	-	-	-
Transportation	0.030	0.031	-	-	-	-
VA/gross output in transport	0.480	0.481	-	-	-	-

transportation sector had stayed at a past level in a given year before 2017, our baseline calibration date. To back out the value of transportation productivity B_T in the past, we use a Solow residual approach. Combining the production function and the optimality conditions of the firms, applied at the sectoral level yields

$$\frac{dB_T}{B_T} = \left(\frac{dQ_T}{Q_T} - \frac{rK_T}{p_T Q_T} \frac{dK_T}{K_T} - \frac{wL_T}{p_T Q_T} \frac{dL_T}{L_T} - \sum_{j=1}^{n+1} \frac{p_j X_{Tj}}{p_T Q_T} \frac{dX_{Tj}}{X_{Tj}} \right) / \left(\frac{rK_T + wL_T}{p_T Q_T} \right).$$

The value of the productivity change between t and t' can thus be expressed as a function of observables. Specifically, we back out the productivity change using data on gross output, capital, labor and real intermediate inputs, as well as on the (average of t and t') cost shares of the transportation sector. Note that the intermediate inputs include the direct purchases of transportation services by the sector itself, which the model abstracts from. Appendix D.3 gives more detail on the construction of the data required to compute the productivity change. In what follows we will use the imputed relative transportation productivity values for 1947 and 1963 based on the question at hand.

5.3 External validity: interregional trade flows

As an external validity exercise, we first compare long-run changes in interregional trade flows within the US with its model-implied counterpart. To do so, we use novel historical data from the 1963 Census of Transportation (CTS) that we digitized and linked to the 2017 Commodity Flow Survey (CFS). Using past and present-day data, we estimate a gravity

Table 3: Gravity as External Validity

	Data	Baseline Model	Iceberg Model
$\ln(dist)$	-1.198	-1.613	-1.434
	(0.000)	(0.000)	(0.000)
$\ln(dist) \times \mathcal{I}(\text{year} = 2017)$	0.167	0.163	0.0005
	(0.055)	(0.000)	(0.041)
N	324	324	324
Adjusted within R^2	0.854	0.963	0.987
Change in distance elasticity	-14%	-10.1%	0.04%

Notes: All regressions include *iot* (sector-origin-year), *idt* (sector-destination-year) fixed effects for light and heavy manufacturing, and time varying out-of-region dummies. p-values in parentheses, clustering at *od* level.

regression that allows the distance coefficient to differ across years.[13] We then estimate the same regression using model generated trade flows from the calibration to the baseline year 2017, and implied inter-regional flows when transportation productivity B_T is reduced to its 1963 level—a 25% reduction.

Since the publicly available 1963 CTS tabulations report trade flows between the 9 census regions, we aggregate our 18 regions to that level. Another feature of this past census is that it reports only weight of shipments rather than values. We use the same variable from the 2017 CFS, and consistently use quantities (Z_{iod}) from the model. In terms of industries, the 1963 CTS sample includes only manufacturing firms. Hence we restrict attention to two aggregated sectors, light and heavy manufacturing, which we are able to construct by matching the 3-digit shipper groups to 3-digit NAICS industries and aggregate to manufacturing sectors as described above. This results in 324 observations, corresponding to trade flows between 9 census regions (81 flows) for 2 industries (light and heavy manufacturing) in 2 years (1963 and 2017). At this level of aggregation, all flows are non-zero.

We estimate a pooled version of the gravity equation (32) with an interaction effect between (time-invariant) distance and the year 2017. To control for changes outside of our model, we include sector-origin-year and sector-destination-year fixed effects. As shown in the first column of Table 3, we find that US domestic trade has become less sensitive to distance over time, with an elasticity of 1.20 in 1963 and lower by 0.17 in 2017. This is a 14% reduction of in the distance elasticity. Gravity estimated from model-generated flows

[13] To our knowledge, ours is the first paper to use the 1963 CTS data to assess the long-run change in the gravity of domestic US trade. The data is available in https://www.nber.org/research/data/transportation-economics-21st-century-commodity-transportation-survey-data. Kleinman et al. (2023) use 1977 CTS data.

in the second column captures this effect quantitatively well, with the percent reduction ($0.163/1.613 \approx 10.1\%$) closely matching the empirical drop of 14%.

6 Quantitative Analysis: Results

While the external validity exercise compared the gravity of 2017 trade flows with 1963, we can go further back for the purposes of the main quantitative exercise in this section, which is to analyze the long-run economic changes induced by the increase in US transportation productivity. We thus chose 1947 as the most distant comparison year that the data allows.

Using 1947 data in the formula presented in subsection 5.2, we find that transportation productivity increased by 81% between 1947 and 2017.[14] We then study the implications of this increase in transportation productivity by considering the counterfactual economy where we revert transportation productivity to its 1947 level while keeping all other parameters at their baseline values.[15] We measure the consequences of the increase in transportation productivity by computing the welfare, output and production efficiency changes between the counterfactual and baseline values, *relative to the counterfactual values*. That is, for a given variable X, we compute and report $X_{\text{Baseline}}/X_{\text{Counterfactual}} - 1$. We start by defining key outcome variables and their measurement.

6.1 Definitions of key outcome variables

Regional and sectoral output The real output is measured by the output of commodities Q_{io} at the sector-region level and, following standard national accounting practices by $\sum_{i=1}^{n+1} p_{io}^{\text{ref}} Q_{io}$ at the regional and $\sum_{o=1}^{\ell} p_{io}^{\text{ref}} Q_{io}$ at the sectoral level, where p_{io}^{ref} is the price of the commodity at the baseline year.

GDP and aggregate welfare We study the aggregate effect on welfare, implied by equation (13) (and which includes changes both in the real wage and in the interest rate), and on GDP. We compute the real GDP change as it would be reported by the national accounts. That is, we compute real GDP as the sum of final goods, $\sum_{i=1}^{n} \sum_{o=1}^{\ell} \tilde{p}_{io}^{\text{ref}} (\tilde{C}_{io} + \sum_{j=1}^{n+1} \tilde{I}_{jo,io})$, where $\tilde{p}_{io}^{\text{ref}}$ is the price of the composite product at the baseline year.

[14] This is a conservative lower bound compared to the 120% increase calculated from Eldridge et al. (2020). Note that this model consistent figure is higher than the motivating evidence reported in the introduction since we adjust for the gross output/value added ratio to capture TFP (B_T) as defined in our model. The motivating stylized fact is robust to this definition as the cumulative TFP increase in the non-transport private economy was 71%.

[15] That is, if B_T was indexed to 100 in the 2017 baseline, imputed values imply $B_T^{1947} = 55$ and $B_T^{1963} = 75$.

Table 4: **Aggregate Results (percent change from counterfactual)**

Aggregate		Transportation services					
Welfare	Real GDP	Q_T	Q_T w/ fixed inputs	L_T	K_T	Real VA	X_T
3.3	3.0	27.6	33.6	-15.4	-12.8	54.4	5.3

Supply-chain efficiency We introduce a measure of sector-region labor productivity that incorporates the efficiency of labor used along the entire chain of production. This measure, which we denote Φ_{id} and refer to as *supply-chain efficiency*, is defined as the quantity of output divided by the total quantity of labor used directly and indirectly in the production process and is a generalisation of the concept of sectoral TFP in Osotimehin and Popov (2023). We compute it as the inverse of the total labor requirements for each product, $\Phi_{id} = (z_{id}^{total})^{-1}$, with $z^{total} = \Omega\hat{z}$, where $\hat{z} = diag(z)$ is the vector whose elements are the diagonal of z, defined before, so $\hat{z}_{id} \equiv L_{id}/Q_{id}$ and $\hat{z}_{\tilde{i}d} = 0$. The total labor requirement, z_{id}^{total}, includes the labor that enters the production process of product id, but also the labor used by the suppliers of id, as well as the labor employed by the suppliers of the suppliers of id, and so on. While the expression above gives the supply efficiency for the $(2n+1) \times \ell$ commodities, we focus on how transportation costs shape the supply-chain efficiency of products used in a given location. We therefore consider the efficiency of the composite goods $\Phi_{\tilde{i}d}$, which we measure at the sectoral level as $\Phi_{\tilde{i}} = \sum_d \Phi_{\tilde{i}d}(\tilde{p}_{id}^{ref}\tilde{Q}_{id}/\sum_o \tilde{p}_{io}^{ref}\tilde{Q}_{io})$.

6.2 Aggregate welfare and GDP

We find that the 81 percent increase in transportation productivity observed between 1947 and 2017 raises aggregate welfare by 3.3% and real GDP by 3.0%. To put these numbers in context, we turn to Hulten who, in his seminal 1978 paper, shows that the aggregate impact of a sectoral productivity shock can be approximated by the share of the sector times the size of the shock. With transportation accounting for 3.1% of value added before the shock, we find that the consequences of transportation productivity changes are 2.3 times larger than implied by transportation's share in the economy. Note that, by construction, this multiplier does not come from the standard magnification due to Domar weights.[16]

As shown in Figure 3, the gap between Hulten's approximation and the model's aggregate effect widens with the size of the productivity change. With a counterfactual productivity

[16]To compare the results with Hulten's formula, changes need to be written relative to the baseline (and not relative to the counterfactual). Using Hulten's formula, $d\text{Welfare}/\text{Welfare} = va_T \times dB_T/B_T = 3.1\% \times -45\% = -1.39\%$ vs $d\text{Welfare}/\text{Welfare} = (1/(1+0.033)-1) = -3.2\%$ in the model. The multiplier for welfare is $3.2/1.4 = 2.3$. Note that contrary to Hulten (1978), in our framework the relevant size measure is the value added share and not the sales-to-GDP ratio. This is because we consider shocks to labor-augmenting productivity B_i and not to factor-neutral productivity.

level 10 times lower than the baseline, the aggregate multiplier (ratio of change in welfare predicted by the model and by Hulten's formula) rises to 5.9. This result is an illustration of the limits of Hulten's formula in presence of non-linearities, studied in detail by Baqaee and Farhi (2019). The complementarity between transportation services and tradable products interacts with input-output and spatial linkages to magnify the consequences of productivity changes in the transportation sector. In addition, the aggregate effect on welfare and GDP is further amplified by the increase in capital accumulation, through the standard capital-multiplier channel (which is absent from Hulten's framework). We discuss the role of input-output linkages and capital accumulation further in section 7.1.

To understand the magnitude of the aggregate effects, we compute the change in the gross output of transportation services as well as in the inputs used by the sector in response to the higher productivity. As shown in Table 4, the 81% increase in productivity leads to an increase of 27.6% in transportation services, and a 54.4% increase its value added, while at the same time capital and labor inputs are reallocated towards other sectors, which is consistent with transportation services and tradable goods being complementary. This reallocation of inputs suggests that transportation's high productivity growth contributed to its long-run decline as a share of total employment. However, the results also indicate that transportation productivity is not the only factor at play. First, the reduction in the employment share is smaller than in the data. Moreover, by considering productivity changes only in the transportation sector, our counterfactual cannot fully speak to the role of productivity dynamics for the sectoral composition of the economy.[17]

We now turn to the effects of transportation productivity improvement on the economy's various sectors and regions.

6.3 Sectoral efficiency

As shown in section 5, some sectors are intrinsically more sensitive to distance and are, therefore, more likely to be be affected by the shifts in transportation productivity. We examine the impact of transportation productivity in each sector with these patterns in mind. The first panel of Figure 4 plots gross output changes in each sector. As expected, manufacturing is more affected than services but the difference between sectors is smaller than what could have been anticipated, with a gross output increase of around 4% in light manufacturing, and 3% in heavy manufacturing as well as in both tradable and nontradable services. Agriculture is affected to a similar extent as the other sectors whereas mining experiences a decrease in gross output. All these non-intuitive effects are coming from

[17] Evaluating the role of the productivity dynamics for the long-run decline in employment share would involve considering productivity changes in all sectors. This question is outside the scope of the paper.

sectoral complementarities in production and consumption, as well as from sectoral linkages. The second panel of the figure shows the response of sectoral labor productivity. Here, the ordering aligns well with the distance elasticity of trade and the transportation intensity t_i of each sector. Notably, labor productivity gains are more pronounced in agriculture and mining than in other sectors, and the gap between manufacturing and services is now larger. The stronger labor productivity growth in high-t_i sectors stems from their greater reliance on high-t_i inputs. As transportation costs decline, these sectors experience a more substantial reduction in intermediate-input costs, leading them to increase their use of such inputs, thereby boosting labor productivity. In addition to reducing intermediate input costs, the decline in transportation costs also modifies the relative cost of sourcing inputs from various regions. The reallocation of activity occurring as firms shift suppliers is another potential channel behind the sectoral labor productivity increase.

We complement our analysis of the changes in production efficiency with our measure of supply-chain efficiency. In the last panel of Figure 4, we show the supply-chain efficiency of the composite products assembled in a given region. The lower transportation costs yield supply-chain efficiency gains in all sectors. These gains, which incorporate the improvement in the efficiency of the intermediate and capital inputs used along the entire supply chain, are larger than the standard productivity gains. Moreover, we find that the disparity across sectors is much more pronounced than for standard labor productivity. The supply-chain efficiency of mining increases relative to that of services.

6.4 Unequal production gains across regions

Figure 1b maps the changes in regional gross output. The regions that gain the most are in the west, in particular Texas, the Mountain and the West North Central regions. In the northeast and south Atlantic, almost all regions experience a gross output decrease following the transportation productivity improvement. Thus, our model shows that the gains in transportation productivity contributed to the shift of economic activity from the Northeast and Midwest toward the more remote northwest and central regions observed over the past several decades.

What is behind these geographical shifts in production? As discussed in section 4, the increase in productivity and associated reduction in transportation costs affect producers through several channels, the intensity of which varies across regions. In particular, the analytical expressions of Proposition 2 highlight transportation margins as the determinants of the regional response to transportation costs.

To verify this result in the quantitative model, the first row of panel A in Table 5 reports, separately for each sector, the correlation between the regional change in gross

Table 5: Correlates of Gross Output Changes

	Agri.	Mining	Heavy M.	Light M.	Tradable S.	Nontrad.S.
Panel A: baseline model						
corr($dQ/Q, \kappa$)	0.94	0.98	0.96	0.93	-	-
	(1.1×10^{-8})	(1.9×10^{-12})	(1.6×10^{-10})	(2.5×10^{-8})	-	-
corr($dQ/Q, B$)	0.21	0.31	0.18	0.30	-0.04	0.003
	(4.2×10^{-6})	(1.2×10^{-7})	(2×10^{-4})	(1×10^{-4})	(0.40)	(0.38)
Panel B: iceberg model						
corr($dQ/Q, \kappa$)	0.60	0.01	0.26	0.37	-	-
	(0.01)	(0.98)	(0.29)	(0.13)	-	-
corr($dQ/Q, B$)	0.0001	-0.001	0.008	0.009	0.002	-0.001
	(0.81)	(0.02)	(2.7×10^{-6})	(1.6×10^{-7})	(2.9×10^{-5})	(1.1×10^{-6})

Notes: All correlations are within sectors and across regions. Omitting sector-region subscripts, dQ/Q is percentage change in gross output, B is productivity, κ is the average transportation margin paid to ship commodities produced in the region (computed as the ratio of the shipping costs to the sales of the commodities, valued at producer prices); it corresponds to $\kappa_{o\rightarrow}$ in Section 4. The first and third rows report unconditional raw correlations while the second and fourth rows report the partial correlation coefficient from a projection of dQ/Q on B, controlling for regional population changes. p-values in parentheses. The iceberg model is the "same targets" specification, see Subsection 7.5 for details.

output Q_{io} with the corresponding average transportation margin paid by destination regions (i.e. the shipping costs expressed as a percentage of the production value) in the baseline. In line with the analytical results of the simplified model, we find that the products' transportation margins are highly correlated to the output impact of increased transportation productivity. The results imply a large reallocation of economic activity towards high transportation-margin regions, which are the most exposed to changes in transportation costs. To further analyze these reallocations, the second row reports how gross output changes relate to fundamental productivities. Controlling for regional changes in overall population, we find that lower transport costs lead to increased specialization in sectors of comparative advantage in goods (first four columns) but not in services, which are either costless or infinitely costly to trade.

7 Inspecting the Mechanisms

To better understand the mechanisms behind the results of Section 6, we consider several alternative model assumptions. These specifications—reported in Table 6—allow us to show the effects of capital deepening, labor reallocation, sourcing adjustments, sectoral linkages, and substitution elasticities, with the main purpose of identifying the channels behind the aggregate amplification in the model (relative to Hulten's formula). In addition, we show how modeling transportation costs as iceberg costs would modify the results. In all these specifications, we follow our approach in Section 6: we revert transportation productivity to its 1947 level and present the results of the increase in transportation productivity relative to the counterfactual value.

7.1 Capital adjustment

As our model economy incorporates investment, transportation productivity affects welfare also through capital deepening. In this section we decompose the aggregate effect of the change in transportation productivity into a direct effect and the effect of the change in the aggregate capital stock. To find the direct effect of transportation productivity, we set transportation productivity to its 1947 level, while adjusting the real interest rate r to keep constant the real aggregate capital stock, defined as

$$K^{agg} = \sum_i \sum_o p_{io}^{k,\text{ref}} K_{io},$$

where $p_{io}^{k,\text{ref}}$ is the price of sector-region capital in the reference year (note that the capital stock of individual sector-region pairs can change).[18] We find that welfare effect is 0.56 percentage point lower than in the baseline. This experiment is useful also to better understand the difference with the results obtained using Hulten's formula since the latter

Table 6: Aggregate Results under Alternative Assumptions

	Welfare gain (%)	Relative to baseline (p.p)	Aggregate multiplier
Baseline	3.34	0.00	2.3
Fixed Capital	2.78	-0.56	2.0
No mobility across regions	3.41	0.07	2.4
No mobility across sectors	3.35	0.01	2.3
No mobility across regions & sectors	3.64	0.30	2.5
No trade adjustment	3.81	0.47	2.7
No mobility (regions & sectors) *and* no trade adjust.	4.23	0.90	2.9
No sectoral linkages	1.78	-1.55	1.3
Cobb-Douglas, $\sigma = \rho = \chi = 0$	2.43	-0.91	2.3
Lower Armington elasticity, $1/(1-\gamma) = 4$	4.78	1.44	2.6
Iceberg, same targets	2.98	-0.36	2.1
Iceberg, same parameters	3.03	-0.31	2.0

Notes: Changes are computed relative to the counterfactual values. In the three limited-mobility cases, the (weighted) average welfare is reported. The aggregate multiplier is the welfare change over the Hulten predicted change. Hulten predicted change for the iceberg economy is detailed in Appendix C.

[18] We present results using 2017 as the baseline year; the results are almost identical when using the 1947 counterfactual values as a reference.

does not take into account the consequences of capital deepening. With the fixed-capital welfare effect twice as large as Hulten's estimate, we conclude that capital is not the main source of amplification.

7.2 Reallocation

The economy adapts to changing transportation costs by changing the mix of final consumption goods and the intricate multi-stage process of their production. In this section we explore the role of this reallocation. We consider various counterfactuals where we set productivity to its 1947 value while shutting down some dimension of adjustment. We then compute the average welfare increase relative to the counterfactual. Note that the larger welfare results reported in rows 3-7 of Table 6 actually imply a bigger drop from the baseline 2017 welfare since we interpret the effect forward from 1947 with the counterfactual in the denominator.

Imperfect labor mobility First, we consider the role of labor reallocation between regions or sectors. At the start of the experiment, the economy is in the baseline equilibrium (with full labor mobility). Then we set transportation productivity to its counterfactual level, but agents face three different mobility restrictions: they cannot move to a different sector, they cannot move to a different region, or they cannot move at all, neither to a different sector nor to a different region. The mobility restrictions prevent real wage equalization across regions or sectors and imply finding region or sector-specific wages. We discuss the details of the equilibrium and the computation in Appendix F.1.

As lack of mobility hampers real wage equalization, we compute the change in the weighted-*average* welfare relative to the counterfactual in all these three experiments. As such, it is not ex-ante obvious whether one should expect larger or smaller welfare effects.[19] Despite the big population movements seen in the baseline counterfactual, keeping workers geographically immobile brings about only small changes in average welfare.[20] Preventing movement between sectors has similarly a modest additional impact. These results highlight how other margins of adjustment, such as trade, can be a substitute for factor mobility—which is a well-known result in the trade literature. We now explore these margins.

[19] In Appendix F.2 we show theoretically that in a simple version of our model, average welfare can actually be *higher* with no mobility. The intuition is related to the averaging of heterogeneous welfare impacts when the losses of the incumbents are greater than the benefit to the movers.

[20] However, such a prohibition of mobility leads to a large disparity across regions, with winners and losers. We explore this in more detail in Appendix F.1.2.

No trade adjustment The transportation productivity improvement modifies the relative prices of local varieties and, as a result, each producer adjusts its sourcing of different local varieties. To understand the role of trade, we impose the restriction that $Z_{iod}/\tilde{Q}_{id}$ remains at its baseline level, while all other equilibrium conditions hold and all prices continue to be derived from cost minimization. We find that this margin of reallocation has a notable impact on the welfare consequences of the transportation productivity increase. As shown in Table 6, the welfare effect is 0.5 percentage point higher than in the baseline specification.

Interaction of imperfect labor mobility and no trade adjustment Next, we combine the labor and trade adjustment frictions. We find that the effect of the two frictions together is more than additive of individual frictions, confirming the intuition that trade adjustments and labor reallocation over space and sectors are substitutes.

7.3 Sectoral linkages

We examine the role of input-output and capital linkages by considering a version of the model which abstracts from these sectoral linkages but is calibrated to the same targets as the baseline model (expect those related to the linkages). As indicated in row eight of Table 6, neglecting sectoral linkages leads to substantially underestimating the aggregate effects; the aggregate multiplier drops from 2.3 to of 1.3. As already mentioned, one of the key transmission channels is the increase in intermediate inputs. In the absence of input-output linkages, this channel is inoperative, which thus leads to a smaller aggregate productivity gain.

The absence of sectoral linkages leads also to significantly different regional effects. In Appendix F.3.3, we report the change in gross output for each region, as the percentage-point gap from the baseline model's (Figure F4), as well as the sector-region output changes (Figures F5). We find that the simpler structure leads to much more dispersed output changes. For example, the output decline in the South Atlantic region is overestimated by 10 percentage points and the output gain in Texas by 27 percentage points. The large disparity in regional outcomes occurs despite a similar sector-region productivity B_{io}. The productivities in the two models are highly correlated and display a similar dispersion (standard deviation of log productivity of 0.51 vs 0.49 in the baseline). Instead, the disparity in outcomes reflects a heightened sensitivity of reallocation to productivity as the absence of sectoral linkages exacerbates cost differences across regions. These results highlight the essential role of sectoral linkages in the exposure to transportation productivity.

7.4 Substitution elasticities

We evaluate the effects of varying production substitution elasticities. We consider the cases of a lower elasticity of substitution across regional varieties ($1/(1-\gamma) = 4$) and of Cobb-Douglas production functions and preferences ($\sigma = \rho = \chi = 0$). Each time, we re-calibrate the model to match the same targets as described in Section 5. The aggregate results are presented in rows 9-10 of Table 6. In Appendix F.3, we describe the relevant changes to the model, the solution method, and calibration procedure, and present more detailed results (Figures F6-F7).

With Cobb-Douglas production functions, the aggregate multiplier (that is, the change in welfare relative to the value predicted by Hulten's formula) is similar to the baseline. However, the output changes are more dispersed, with a stronger response for regions that expand in the baseline. When the elasticity of substitution across varieties is lower, the aggregate multiplier is higher than the baseline while the output response is less dispersed. The labor productivity response of each region-sector producer is stronger in these two alternative calibrations.

Analyzing how the change in the calibration shape the results can be challenging as all the parameters are modified, not just the elasticities. However, several results align well with intuition here. With a higher input elasticity than the baseline, the Cobb-Douglas specification leads to a stronger increase in intermediate inputs following the reduction in transportation and input costs, and therefore to a higher increase in sectoral labor productivity. With a lower variety elasticity of substitution, buyers are less responsive to the price changes induced by transportation productivity, and therefore the regional responses are more similar across regions. The larger welfare impact found in that case is reminiscent of the role of the trade elasticity in the international trade literature, where a lower elasticity magnifies the gains from trade.

7.5 Comparison with the iceberg specification

For comparison, we consider an economy with iceberg transportation costs, where one must pay $\tau_{iod} \geq 1$ units to obtain one unit of product i sourced from region o; the purchaser's price is thus $\tau_{iod} p_{io}$ instead of $p_{io} + t_{iod} \cdot p_{To}$ in the baseline. The rest of the economy remains identical to the baseline model.

We use two strategies to set the iceberg parameters. In our first approach, we assume costs increasing in the shipping distance, $\tau_{iod} = \overline{\tau} \cdot (\text{distance}_{od})^{\zeta_i}$, and we calibrate all the model parameters to match the observed sectoral value added and intermediate inputs shares, the regional employment shares of each product, as well as the distance elasticities and out-of-region trade parameters; we leave out the ratio of value added to gross output in transportation since there is no natural counterpart for that target in the iceberg model. With this calibration approach, the underlying parameters (unrelated to transportation) may be quite different from our model even though the same targets are used. Our second approach aims to isolate the consequences of incorporating an iceberg transportation cost from the implications of parameter disparities. Therefore, we set non-iceberg parameters to their values in the baseline. To further make the two specifications as close as possible, we set the iceberg parameters τ_{iod} to obtain the same purchaser prices as in our baseline model.[21] Additional details on the solution and calibration of the iceberg model are described in Appendix C.

For both calibration strategies, we study the effects of an economy-wide change in the scale parameter ($\overline{\tau}$) of the iceberg cost that mirrors the change in the productivity of the transportation sector in the baseline. Contrary to our baseline model, there is no natural empirical counterpart to the change in the scale of the iceberg cost. In particular, the change in the labor productivity of the transportation sector, which is a central target for our model, has multiple empirical counterparts in the iceberg model. By construction, in the iceberg model the productivity of "shipping services" is equal to the productivity of the product shipped. To facilitate the comparison with the baseline model, we set the scale of the iceberg parameter in 1947, $\overline{\tau}^{1947} > 1$ relative to $\overline{\tau}^{2017} = 1$, so that the resulting change in the value added share of transportation matches the one obtained in our baseline model.

The results obtained with the iceberg specification are reported in the last two rows of Table 6. For simplicity, we again present the results as changes relative to the counterfactual values. We find that for both calibration strategies, the welfare impact of the reduction in transport costs is close to but lower than the one in our baseline specification. Welfare increases by about 3% in the two iceberg specifications (vs 3.3% in our baseline model) and the aggregate multiplier (relative to Hulten) is also somewhat lower.

These similar aggregate effects hide substantial differences in regional and sectoral outcomes. With the iceberg specification, there is much less variation across regions and sectors. In particular, the initial transportation costs associated with each product is no longer a key determinant of the regional output changes. To highlight this distinction, we conduct a similar analysis as in the baseline and report the results in the third row (panel B) of Table 5. With the iceberg specification, the effect of the transportation margin is much smaller than in the baseline. It is economically and statistically significant only for the agricultural sector. The flatter effect across regions comes from the fact that with

[21] That is, $\tau_{iod}(p_{io})^{\text{iceberg}} = p_{io}^{\text{baseline}} + t_{iod}(p_{To})^{\text{baseline}}$. Note that, contrary to our first calibration strategy, key statistics may differ across the two models. In particular, the value added share accounted for by transportation services, which is computed by adding the value of the transportation services implicitly produced by each sector, may not match the data with this alternative calibration.

iceberg costs, the change in transportation productivity leads purchaser prices to vary in the same proportion regardless of the product's region of origin. The fourth row in the table investigates the correlation between output allocations and fundamental productivities, and fails to generate the intuitive specialization patterns obtained in the baseline model.

Finally, we show that the iceberg model, calibrated to match the same empirical targets, cannot rationalize the empirical result on the declining distance elasticity that we documented in the first column of Table 3. Since our comparison between the iceberg and baseline specifications in Tables 5-6 focused on the year 1947, we also estimate the gravity regression using that year as the counterfactual. While the model-implied time-varying distance elasticity, presented in the third column of Table 3, has the expected sign (a decrease in absolute value), its magnitude is much smaller compared to the estimate from the baseline model and is statistically insignificant. As we show in Appendix C.3, the distance elasticity in the iceberg model depends only on time-invariant parameters ζ_i and γ, and is thus fixed. Simply rescaling $\overline{\tau}$ changes the level of transport costs but not the slope with respect to distance. As a result, trade increases proportionally at all distances.

To sum up, our baseline model rationalizes the time-varying distance elasticity by varying only measured transportation productivity. To do so with the iceberg model would require an ad-hoc decrease either in the distance elasticity ζ_i itself, or in the Armington elasticity γ_i. We see the tight mapping from sectoral productivity to regional transportation costs in our approach as a major advantage over the iceberg model in conducting ex-ante analysis without overfitting the data.

8 Conclusion

We propose a model with sectoral and spatial linkages to study the effects of transportation productivity changes. Using the model, we quantify the aggregate welfare gains from higher transportation productivity observed in the US over 1947-2017 and we study the determinants of its regional and sectoral gross output effects. We find that the welfare gain is more than two times larger than what is implied by the transportation sector's share in the economy. Both the aggregate and the granular effects crucially depend on the structure of sectoral linkages. The findings point to the critical role of the transportation sector for the economy and suggest notable welfare losses should productivity growth in the transportation sector fall behind other sectors. The implications of such changes would be more pronounced for countries less far along their structural change path, with higher shares in agriculture, mining and manufacturing than the US.

They also be more pronounced starting from much higher levels of transportation costs.

We view our results as a lower bound on the contribution of the transportation sector to growth. Several factors could magnify its role: first, given its focus on transportation multifactor productivity, our analysis does not account for the improvement in energy efficiency and other innovations in transportation equipment. In addition, we have restricted our attention to freight and hence do not include the implications of lower costs of passenger transportation, which can contribute to growth by improving labor mobility, facilitating commuting and stimulating the tourism industry. Future research that assesses the contributions of improved equipment and higher passenger mobility would be of great interest.

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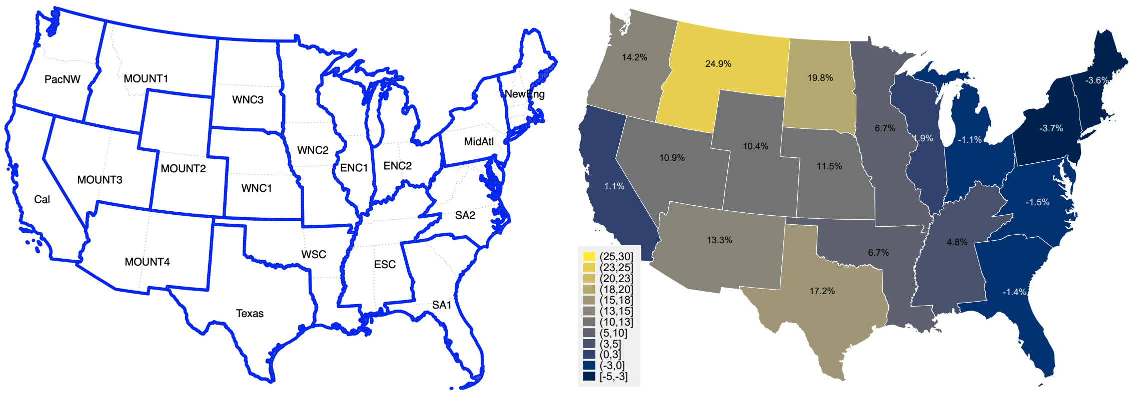
Figure 1: US Regions

(a) Regional Aggregation **(b) % Changes in Gross Output**



Notes: Left panel shows the aggregation of US states into 18 regions. Our regions can be aggregated to 9 US Census divisions which we follow for naming conventions: West South Central (WSC), West North Central (WNC), Mountain (Mount), East South Central (ESC), East North Central (ENC), New England (NewEng), South and Mid-Atlantic (SA, MidAtl). Right panel presents regional gross output changes in our main counterfactual exercise with the details explained in Section 6.

Figure 2: Regional Employment

(as a share of sectoral employment)

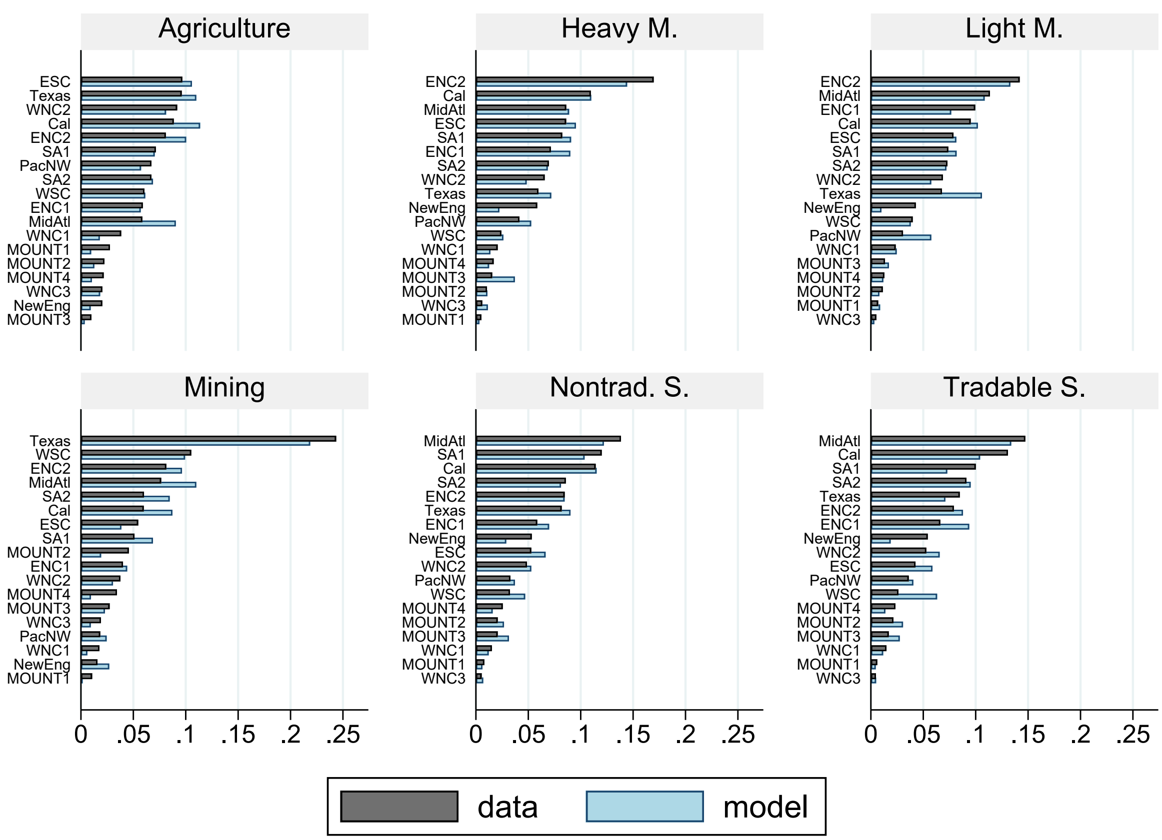


Figure 3: Baseline Model vs Hulten Benchmark

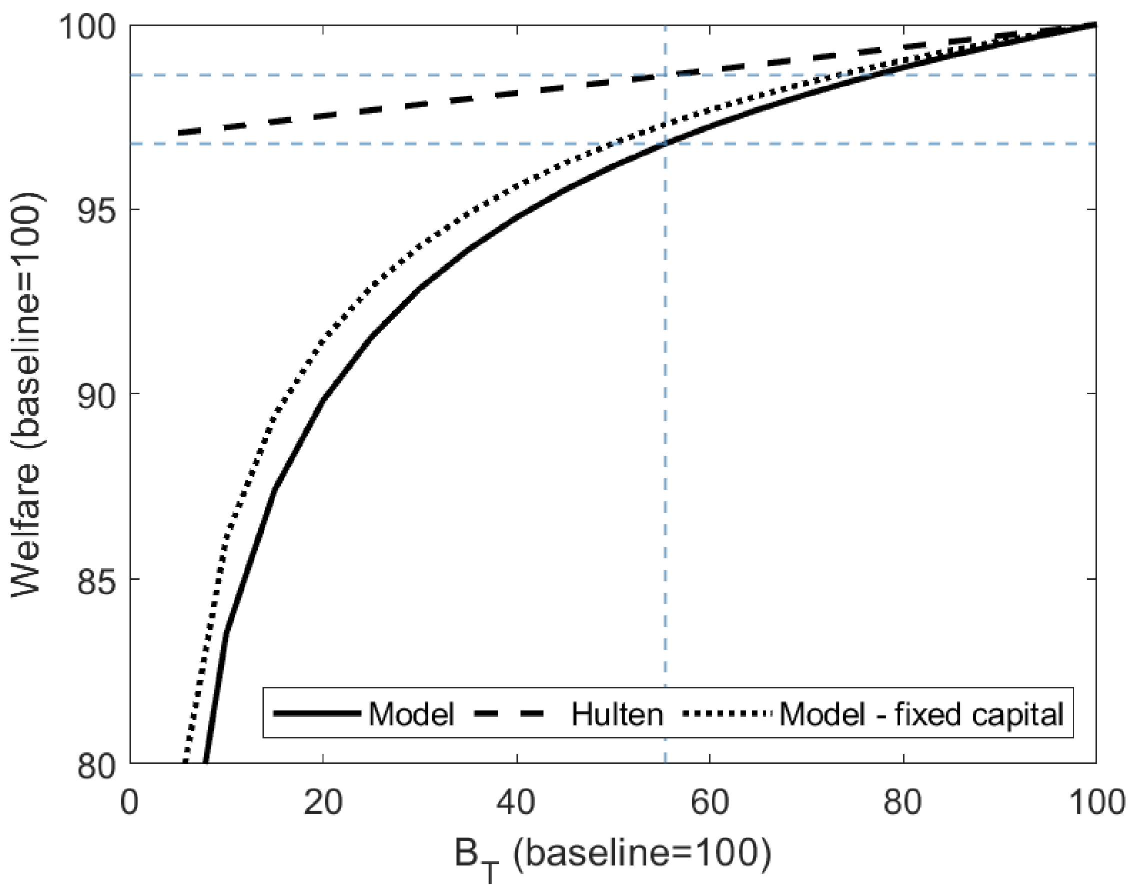
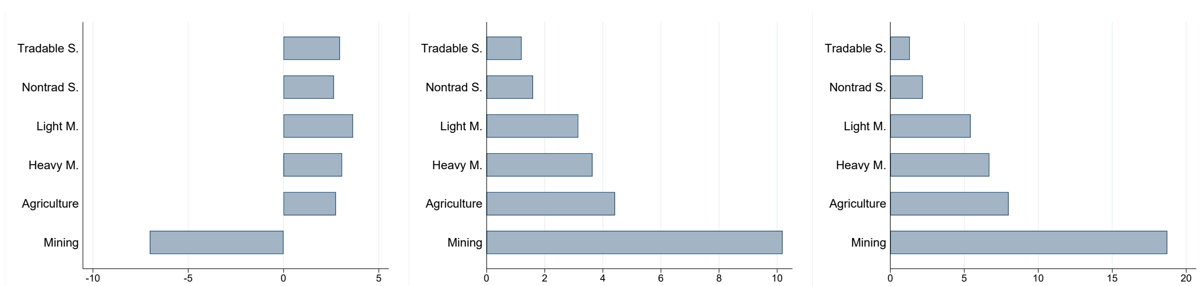


Figure 4: % Changes in Gross Output, Productivity and Supply Chain Efficiency



(a) Gross output (b) Labor productivity (c) Supply-chain efficiency