Regional and Aggregate Implications of Transportation Costs and Tradability of Services

Preliminary and incomplete. Please do not circulate.*

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February 6, 2019

1 Introduction

The feasibility and cost of separating the location of production from that of consumption (intermediate or final) are key aspects of economic activity. While *transportation technologies* determine the cost of shipping goods and the cost of traveling for workers to carry out transactions in person, *communication technologies* determine the cost of codifying and transmitting information. Regardless of whether they involve goods or services, these two technologies shape the linkages across space and across stages of production.

What are the aggregate, sectoral, and regional effects of major technological advances and productivity improvements in shipping goods and transmitting data? This paper aims to provide theoretical and quantitative answers to this question. The theory features a realistic and novel treatment of freight and tradability of services in a multi-sector, multi-region model: each intermediate input, be it a good or a tradable service, requires the complementary supply of hauling and communication, respectively. Their low substitutability bestows transport and

*We thank seminar participants at UQAM for useful comments.

communication a critical role in establishing the spatial links between other sectors in the input-output structure.

Existing work on modeling and quantifying trade costs, and the input-output structure of the economy typically follow separate tracks, without a unifying framework that treats freight and communication costs as determined by productivities of the sectors supplying these services. Workhorse models of economic geography investigating the effect of transportation technology and infrastructure feature a single-sector model of trade with iceberg trade costs (Allen and Arkolakis, 2014; Donaldson, 2018) but abstract from realistic input-output linkages in a multi-sector setting. General equilibrium models of the macroeconomy, on the other hand, typically feature a single region and thus abstract from spatial interactions across regions (Jones, 2011; Acemoglu et al., 2012). None of these models distinguish transportation and communication in terms of their substitutability. Our earlier research fits this categorization as well: (Coşar and Demir, 2016, 2018) estimate the magnitude and structure of intra-national road transportation costs and international maritime shipping costs, respectively, but do not model sectoral or regional effects in general equilibrium. Osotimehin and Popov (2017) analyze the propagation of distortions to input decisions through intersectoral linkages and quantify the aggregate productivity loss, but do not model the spatial dimension of these linkages. The proposed research brings together these two separate approaches in order to analyze the aggregate, sectoral and regional effects of reductions in the cost of overcoming distance.

To motivate the paper, we start by documenting a set of interrelated stylized facts from the U.S. economy. These facts pertain to the size and structure of the transportation sector over a long period of time, as well as spatial changes in sectoral activity. After showcasing the declining trend in the employment share of the transport sector throughout past decades, we provide novel evidence on qualitative changes in the modal distribution of manufacturing freight using the 2012 Commodity Flow Survey and 1963 Commodity Transportation Survey that we digitized. We then discuss how these facts could be related to a non-trivial reallocation of sectoral employment across aggregate U.S. regions over the same time period.

To speak to these stylized facts, we build a novel model in which transportation is modeled as an essential input in establishing spatial linkages between sectors: sourcing of intermediate goods requires freight services. Moreover, distance costs apply not only to the cost of shipping goods in the form of freight, but also to the tradability of services. In the model, each region produces a distinct variety in each sector. Given its sectoral total factor productivity, the representative firm in each region-sector combines labor and a composite intermediate of other region-sectors' varieties in a CES production function. Labor mobility across sectors and regions equalizes real wages in spatial general equilibrium. Each sector-region specific variety requires the complementary freight service in order to be delivered as an intermediate input to another sector-region. The cost of freight depends on the characteristics of the good being shipped as well as the distance between origin-destination regions. Freight services are produced by a distinct transportation sector using labor only.

The calibrated model helps to analyze the drivers of long-run sectoral and spatial structural changes. For instance, the decline of industrial concentration in the rust belt could be driven by changes in regional sector-specific productivities as well as in freight costs. Using our quantitative framework, we can decompose such shifts into their relevant components and provide predictions on the aggregate and regional effects of potential future improvements in transportation and communication technologies. In the current calibration of the model, we separate services into a tradable and non-tradable, setting the cost of selling outside of the region of production to zero for the former and to infinite for the latter. The object of interest in our preliminary quantitative application is the productivity of the transportation sector. In a simulation exercise, we mimic its change from 1960s to the present data used in calibration. This exercise suggests that, everything else being constant, lower freight costs have counteracted and moderated structural change from agriculture and manufacturing into services, since the former sectors are more transportation intensive. The model also qualitatively captures the population shift from northeastern U.S. regions toward the west of the country. It also suggests that documented long-run spatial changes in sectoral activity are primarily driven by forces other than transportation costs.

Our work is related to several strands of literature. A variety of quantitative spatial models, summarized by Redding and Rossi-Hansberg (2017), analyze interactions across locations, but in order to preserve analytical tractability, they typically restrict attention to a single sector or only feature aggregate sectors such as agriculture and manufacturing. An important exception is Caliendo et al. (2017), who build and quantify a multi-region, multi-sector model with spatial and input-output linkages. In their paper, distance-related trade costs between regions are modeled separately from wholesale trade and transportation sectors, which are treated as non-tradable. Our novel approach is to model explicitly the distance-related trade costs as the outcome of the production function of the wholesale and transportation sectors. We also generalize the treatment of trade costs by allowing tradability of services, and include transport-intensive agriculture and mining sectors in the analysis. Another notable difference is that we incorporate the low elasticity of substitution between intermediate inputs, which shapes the response of the economy to sector-specific productivity changes. Allowing the elasticity of substitution to be smaller than Cobb-Douglas is therefore crucial for the quantitative analysis. In terms of calibration strategy, instead of differencing out location- or sectoral-productivities, we quantify the levels of these parameters in different time periods in order to decompose observed long-run regional and sectoral shifts into their components.

Motivating our emphasis on not only transportation but also on communication costs is a nascent empirical literature analyzing its impact on fragmentation of production. Juhász and Steinwender (2018) identify the effect of reduced communication costs due to the extension of the global telegraph network in the 19th century on trade of intermediate inputs in the textile industry, which tend to be more differentiated than final goods. Using plant-level data from U.S. manufacturing, Fort (2017) finds that communication technologies enable firms to spatially fragment their production by outsourcing customized inputs. Given the challenge in directly measuring trade costs in services, Jensen et al. (2005) and Gervais and Jensen (2013) infer the tradability of services from observed patterns of concentration. Similarly, Michaels et al. (2013) measure the task specialization of U.S. cities from their occupational composition, and provide evidence on the effects of transport and communication technologies in long-run changes.

Finally, our research relates to the macroeconomic literature on inter-sectoral linkages that emphasizes the role of complementarities across inputs in production. Jones (2011), Atalay (2017) and Baqaee and Farhi (2017) analyze the propagation and aggregate impact of micro/sectoral shocks. Our research extends these frameworks to a spatial setting with a focus on long-run changes. In doing so, it also relates to the structural change literature, in particular to papers investigating the role of transportation costs (Herrendorf et al., 2012) and the spatial aspects of structural change (Eckert and Peters, 2018). In the context of the reallocation out of manufacturing, the structural change literature typically emphasizes the interaction between sectoral differences in productivity growth rates, and the low substitutability of goods and services in final consumption (Ngai and Pissarides, 2007). In contrast, we study the extent to which low substitution across intermediate inputs and the presence sectoral linkages can account for structural change.

2 Dataset Building

We utilize several datasets to motivate the research agenda and quantify the model. These include datasets that are downloadable from the websites of the U.S. Census Bureau and the Bureau of Economic Analysis (BEA), as well as data that are publicly available in print but had to be digitized by our research team. Since one of our main goals is to analyze the drivers of long-run changes in the spatial and sectoral composition of the U.S. economy, our data building effort aims at harmonizing datasets over the span of several decades. We now briefly describe this effort.

Data on intersectoral linkages, sectoral value-added and final consumption are obtained from the BEA Input-Output Accounts. We use IO data for 1963 and 2012, the latter being the most recent benchmark release year and the former being the earliest year for which data is available at a consistent industry classification. Data on regional employment by sector is obtained from the BEA Regional Economic Accounts. The 1969 data by SIC industry classification is concorded to the 2012 data by NAICS classification.

The second pillar of our dataset building is on transportation and tradability of services. We group service industries into tradable and non-tradable based on the classification of Jensen et al. (2005). Information on freight costs for goods and commodities comes from the Public Use Microdata File of the 2012 Commodity Flow Survey (CFS).

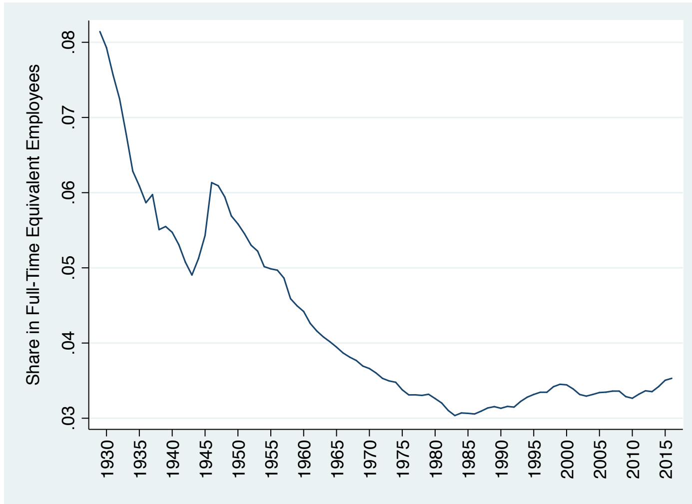
Since the earliest CFS year is 1993, we had to search elsewhere in order to assess long-run changes in transportation. To that end, we identified that the 1963 Economic Census was the first to collect detailed national transportation data. The predecessor to the CFS, the Commodity Transportation Survey (CTS) was conducted by the Census Bureau between 1963 and 1983. The 1963 survey covered shipments of beyond 25 miles by a sample of about 20,000 manufacturing establishments. Detailed mode-specific, regional and commodity-level statistics—resembling the information contained in the CFS Public Use Microdata files—were published in several volumes by the Department of Commerce in 1966. These volumes were digitized by Google and put into the public domain through the HathiTrust website. We employed a team of student research assistants to convert extensive data tables from images into a format that can be used with standard numerical software packages. Concording the 1963 Transport Commodity Codes (TCC) to the 2012 CFS Standard Classification of Transported Goods (SCTG), we linked the two transport surveys. In what follows, we use this novel dataset to provide motivating evidence on how freight logistics has changed in the U.S. over the past half a century.

3 Descriptive Evidence

We start by highlighting the fact that the employment share of the transportation sector has been in a declining trend in the U.S. Figure 1 plots this time-series between 1929-2016. A similar trend applies to its share in U.S. GDP (Redding and Turner, 2015). The average share, however, masks qualitative changes such as the rise of air transportation, and the modal shift from railroad and waterways to trucking.

To that effect, we document and analyze the change in the structure of freight logistics using the combined shipment surveys from 1963 and 2012. Left and right panels of Table 1 report the shares of shipping modes in total tons and ton-miles of manufacturing shipments,

Figure 1: U.S. Employment Share of the Transportation Sector



Notes: Data source is BEA. Transportation sector includes railroad transportation, local and interurban passenger transit, trucking and warehousing, water transportation, transportation by air, and transportation services.

respectively.[1] Initially, rail and waterways still constituted the dominant shipping modes. By 2012, trucks took over the leading role in freight. In unreported regression analysis, we verify that this shift is not driven by compositional effects due to the differences in modal preferences across commodities: controlling for commodity and mode fixed effects, trucking share displayed a significant increase over this time period.

The modal shift from rail/water to trucking was plausibly an essential component of the steep downward trend in the real cost of a ton-mile shipment throughout the 20th century, as shown by Glaeser and Kohlhase (2004). It was not only driven by increased efficiency of motor transportation equipment accompanied by the continuing construction and upgrading of the road network, exemplified by the interstate highway system, but also by the sustained growth

Table 1: Modal Distribution of Tons and Ton-Miles Shipped in U.S. Manufacturing

	1963	2012
Rail	0.326	0.140
Truck	0.423	0.711
Water	0.244	0.041

	1963	2012
Rail	0.372	0.248
Truck	0.191	0.606
Water	0.430	0.028

Notes: Left and right panels are percentages of tons and ton-miles manufacturing shipments by each mode, respectively. Data sources are 1963 Census of Transportation and 2012 Commodity Flow Survey, merged to be compatible in terms of sampling of establishments, commodities and shipment distances. Only domestic shipments are considered. In both panels, the shares add up to a number very close to 100 percent, with remaining marginal shares captured by air shipments.

[1]The analysis is confined to the manufacturing sector since the 1963 Census of Transportation covers manufacturing firms only. Therefore, we exclude pipe as a mode of transport. We do not report air shipping in the tables since it accounts for a marginal share of domestic manufacturing shipments in both years.

of multi-factor productivity in trucking during the same period (Gordon, 1992). We posit that the modal shift toward trucking contributed to increased productivity in the transportation sector by alleviating the first- and last-mile problems, that is, by enabling point-to-point delivery without the additional labor of discharging and loading cargo across modes, allowing reliable logistics for supply chains and time-sensitive goods (Hummels and Schaur, 2013). Since freight transportation is a key intermediate input, these facts motivate us to investigate whether dramatic increases in its productivity have an aggregate effect greater than its share in GDP by facilitating more intense and efficient sourcing of intermediate inputs.

Our next piece of motivating evidence is the long-run spatial change in U.S. industrial activity. By how much and in which directions did U.S. industries relocate throughout this time period? We address this question for 7 sectors at the regional level. The sectoral aggregation groups 3-digits NAICS industries into agriculture, mining (including oil and gas extraction), three groups of manufacturing in terms of their transportation intensity, as well as tradable and non-tradable services. The spatial aggregation groups continental states into 9 Census divisions, denoted as regions for simplicity.[2] The share of region ℓ in the employment of sector i is given by

$$\lambda_{i\ell} \;=\; \frac{L_{i\ell}/\sum_{\ell} L_{i\ell}}{\sum_{i} L_{i\ell}/\sum_{i}\sum_{\ell} L_{i\ell}},$$

where the numerator is the sectoral employment share of the region normalized by the share of the region in total U.S. population in the denominator.

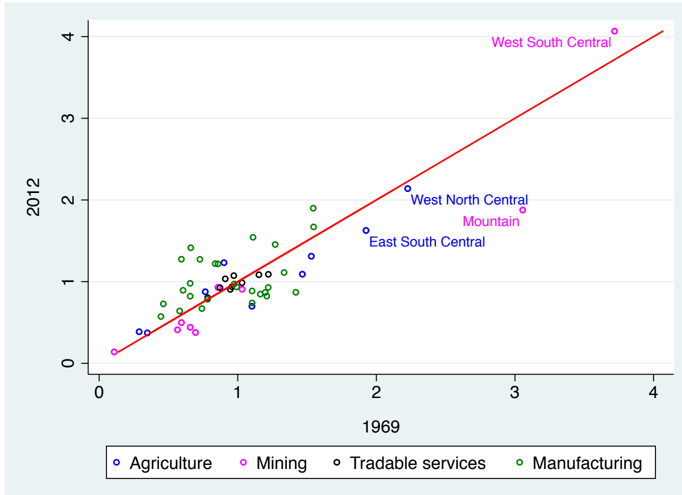
In Figure 2, we plot the normalized shares for 54 region-sector pairs in 1969 and 2012, excluding non-tradable services.[3] Unsurprisingly, and in line with previous work (Dumais et al., 2002), industry locations are quite persistent. There are, however, substantial changes even at this level of aggregation. Manufacturing, color-coded by green, displays a shift from the north-east toward the center and the west of the country, over and above the shift of the well-known population shift in the same direction. Similarly, agriculture displays a shift from the south-east toward the west and midwest. Mining, the most concentrated activity due to the distribution of natural endowments, displays a reallocation away from the Mountain region (encompassing eight states including Colorado and Utah), toward the West South Central region (encompassing Texas, Oklahoma, Arkansas and Louisiana).

The changes in regional composition of sectoral activity that we documented could be driven by two mechanisms: the effect of lower transportation costs on regional specialization conditional on regional-sectoral productivities, and changes in these

[2] Analyzing concentration patterns for U.S. manufacturing industries at various levels of aggregation, Ellison and Glaeser (1997) find that measured levels of state and regional concentration are quite similar.

[3] Displaying the lowest level of concentration, non-tradable services tend to follow the population distribution and thus persistently concentrate around 1 at the 45-degree line.

Figure 2: Long-run Change in Sectoral Employment Shares across U.S. Regions



Notes: Each observation is the normalized employment share (defined in the text) of a sector-region (U.S. Census division) pair in 1969 and 2012. Manufacturing encompasses 3 groups in terms of transportation intensity, which are not separately color-coded. Data is from the BEA.

productivities themselves. The two mechanisms can also interact through sectoral linkages. We now describe a model featuring these forces, and as a quantitative exercise, explore the role of transportation costs.

4 Model

4.1 Environment

Physical environment The economy consists of ℓ distinct locations where production and consumption take place. Other than transportation services, there are n sectors, and every location produces a distinct variety in every sector. While some of these sectors are services (other than transportation), we denote their output as commodities for brevity. Hence, there are $n \times \ell$ commodities, identified by the pair of indices i (denoting sector) and o (denoting origin). The output of different sectors are used as intermediate inputs or for final uses, which we denote as consumption.

Consumers and preferences There is an atomless mass of households with measure $\bar{L}$. Every household supplies one unit of labor inelastically. Households move freely and costlessly across locations, but must consume in the location where they supply labor. Preferences over consumption are given by the utility function

$$U_\ell \; = \; \prod_{i=1}^{n} \beta_i^{-\beta_i} \prod_{i=1}^{n} \tilde{C}_{i\ell}^{\beta_i}, \tag{1}$$

where $\tilde{C}_{i\ell}$ is the composite sector-i commodity in ℓ. We assume away consumption of transportation services.

Production A subset $\mathcal{P}_{\mathcal{NT}}$ of the sectors are nontradable. The remaining sectors in the set $\mathcal{P}_{\mathcal{T}}$ are tradable. For tradables, different local varieties are aggregated in a CES fashion. To economize on notation, define $\tilde{Q}_{id}$ as the composite commodity i, assembled in location d with the following production function:

$$\tilde{Q}_{id} = \begin{cases} \left(\sum_{o=1}^{\ell} \left(\frac{1}{\ell}\right)^{1-\gamma} Z_{io,d}^{\gamma} \right)^{\frac{1}{\gamma}} & i \in \mathcal{P}_{\mathcal{T}} \\ Z_{id,d} & i \in \mathcal{P}_{\mathcal{NT}}, \end{cases} \tag{2}$$

where $Z_{io,d}$ are shipments of commodity i from origin o to destination d. The elasticity of substitution between locational varieties is given by $\frac{1}{1-\gamma} > 1$. Even though the aggregation function is the same for all locations, asymmetric transportation costs will induce every location to combine local varieties in different proportions. The composite commodity can be used as an intermediate input or as consumption good $\tilde{C}_{id}$.

Commodities are produced as follows:

$$Q_{id} = A_{id} \left[(1-\alpha_i)^{1-\sigma} (B_{id} L_{id})^{\sigma} + \alpha_i^{1-\sigma} \left(\sum_{j=1}^{n} v_{ij}^{1-\rho} \tilde{X}_{id,jd}^{\rho} \right)^{\frac{\sigma}{\rho}} \right]^{\frac{1}{\sigma}}, \tag{3}$$

where L_{id} is the labor input and $\tilde{X}_{id,jd}$ is the composite j intermediate good assembled in location d and used by sector id. The parameters A_{id} and B_{id} are sector-location specific Hicksian and labor-augmenting productivities respectively. The parameter ρ governs the elasticity of substitution $\frac{1}{1-\rho}$ between locational varieties of intermediate inputs, and σ determines the elasticity of substitution between intermediate commodities and the primary input labor. The vector $\boldsymbol{\alpha}$ and the matrix $\boldsymbol{V}$ containing the v_{ij}'s are input-output parameters that are common across locations. In summary, while the production technology is uniform within the country, locations differ in their sectoral productivities. The same applies to transportation services, which we describe next.

Transportation We treat transport services as complementary to the delivery and use of origin-specific varieties in destination locations. In particular, when $Z_{io,d}$ units of commodity

io are used in location d, a total supply of transportation services $Z_{io,d} \cdot t_{io,d}$ is required. This specification captures the impossibility of substituting transportation services.[4] It is also consistent with the additive (rather than ad-valorem) nature of transportation costs. Moreover, $t_{io,d}$ depends on the characteristics of commodity i being supplied (such as its weight per value, or whether its shape and volume require specialized modes) as well as the distance between the origin and the destination.

We assume that transportation services are produced using only labor and must be purchased at the origin of the shipment. Using $L_{transp,o}$ units of labor with an aggregate transport productivity of A_{transp}, origin o supplies the following amount of transportation services to outgoing freight:

$$T_o = A_{transp} \cdot L_{transp,o} \tag{4}$$

Resource constraints The production possibility of the economy is described by the production functions (2) - (4) and the following resource constraints:

$$Q_{io} = \sum_d Z_{io,d} \tag{5}$$

$$\tilde{Q}_{io} = \sum_k \tilde{X}_{ko,io} + \tilde{C}_{io} \tag{6}$$

$$T_o = \sum_i \sum_d Z_{io,d} \cdot t_{io,d} \tag{7}$$

$$\bar{L} = \sum_o \sum_i L_{io} + \sum_o L_{transp,o} \tag{8}$$

The constraints are standard: the quantities $Z_{io,d}$ are the demands for io commodities in location d, so equation (5) is the market clearance for location-specific varieties. Equation (6) requires that producers (as intermediate input users) and consumers (as final users) situated in location o use up the supply of the composite commodity i assembled in location o. Equations (7) and (8) are the market clearance conditions for transportation services out of location o and the aggregate labor market, respectively.

4.2 Equilibrium

Market structure We assume that all markets are perfectly competitive. Together with the constant returns to scale (CRS) in all sectors, this implies that there are no profits in the economy and households have only labor income. We normalize the wage in location $\ell = 1$ to unity.

[4]There are other margins of substitution in the economy that are allowed by our model: higher transportation costs would induce producers to substitute away from out-of-region varieties toward local inputs.

Goods prices The CRS assumption implies that *conditional on wages*, all prices can be derived from cost minimization, without regard for market clearing conditions.

We will denote p_{io} to be the *producer* price of commodity io and $\tilde{p}_{id}$ to be the *user* price of the composite good i assembled in location d. Let $x_{io,d} \equiv t_{io,d}/A_{transp}$ denote the amount of labor required to deliver commodity io to location d. Then the cost of one unit of the shipment $Z_{io,d}$ is $p_{io} + x_{io,d}w_o$. With this in mind, cost minimization implies that the prices of composite commodities are given by:

$$\tilde{p}_{jd} = \begin{cases} \left[\sum_{o=1}^{\ell} \frac{1}{\ell}(p_{jo} + x_{jo,d}w_o)^{-\frac{\gamma}{1-\gamma}}\right]^{-\frac{1-\gamma}{\gamma}} & j \in \mathcal{P}_{\mathcal{T}} \\ p_{jd} + x_{jd,d}w_d & j \in \mathcal{P}_{\mathcal{NT}} \end{cases}. \tag{9}$$

In a similar fashion, cost minimization for io and perfect competition imply that

$$p_{io} = A_{io}^{-1}\left[(1-\alpha_i)w_o^{-\frac{\sigma}{1-\sigma}}B_{io}^{\frac{\sigma}{1-\sigma}} + \alpha_i\left[\sum_{j=1}^{n} v_{ij}\tilde{p}_{jo}^{-\frac{\rho}{1-\rho}}\right]^{\frac{1-\rho}{\rho}\frac{\sigma}{1-\sigma}}\right]^{-\frac{1-\sigma}{\sigma}}. \tag{10}$$

Equilibrium wages Recall that the composite commodity i is used for consumption and intermediate goods. The price index of consumption thus given by:

$$P_d = \prod_{j=1}^{n} (\tilde{p}_{jd})^{\beta_j}, \tag{11}$$

implying a real wage in location d equal to w_d/P_d. In a spatial equilibrium with free mobility of labor, real wages are equalized across locations:

$$\frac{w_d}{P_d} = \frac{w_{d'}}{P_{d'}}, \qquad \forall d, d' \in 1, \ldots, \ell. \tag{12}$$

The system (23) - (12) and the normalization assumption $p_1 = 1$ pin down all the prices in the economy. Real GDP is simply total real wages or $GDP = w_r\bar{L}$ with $w_r = w_d/P_d$ being the real wage.

Flow of goods There are $(2n+1) \times \ell$ goods in the economy: every location produces n commodities, assembles n composite commodities and provides transportation services for the commodities it ships out. We show that, conditional on prices, the whole vector of outputs can be efficiently computed by linear algebra.

We start by stacking all the goods in a vector. Let $\tilde{id}$ be the index for the composite commodity i assembled in location d. Transportation services are naturally indexed by their origin location o. Let $M_{x,y}$ denote the amount of commodity y that is optimally used for the production of one unit of commodity x. Note that M is a $(2n+1)\ell \times (2n+1)\ell$ matrix. Cost minimization implies the following:

$$
\begin{aligned}
M_{id,\tilde{j}d} &= A_{id}^{\frac{\sigma}{1-\sigma}} \alpha_i v_{ij} \left[\sum_{k=1}^{n} v_{ik} \tilde{p}_{kd}^{-\frac{\rho}{1-\rho}} \right]^{\frac{\sigma-\rho}{\rho(1-\sigma)}} \tilde{p}_{jd}^{-\frac{1}{1-\rho}} p_{id}^{\frac{1}{1-\sigma}} && (13) \\
M_{\tilde{id},io} &= \frac{1}{\ell} \tilde{p}_{id}^{\frac{1}{1-\gamma}} (p_{io} + x_{iod} w_o)^{-\frac{1}{1-\gamma}} \text{ if } i \in \mathcal{P}_{\mathcal{T}} && (14) \\
M_{\tilde{id},id} &= 1 \text{ if } i \in \mathcal{P}_{\mathcal{NT}} && (15)
\end{aligned}
$$

and all the other elements of the matrix are zeros. Let Q be the vector of all commodities and similarly C be the vector of all consumption demands by industry and location. Then the resource constraints (5) - (7) can be written more compactly as

$$Q = (I - M')^{-1} C. \tag{16}$$

Next, we turn to the determination of the vector of consumption. The consumers/workers in the various locations have the same preferences and real incomes, but face different relative prices. Thus, the geographic distribution of consumers will affect demand. Consumer optimization implies that

$$\tilde{C}_{id} = \beta_i \frac{w_r L_d}{\tilde{p}_{id}}. \tag{17}$$

Let c be a $\ell \times (2n+1)\ell$ matrix such that $c_{x,y}$ is the consumption demand for commodity y by a household in location d. The discussion above implies that $c_{d,\tilde{id}} = \beta_i \frac{w_r}{\tilde{p}_{id}}$ and all other elements of the matrix will be zero.[5] Then we have that

$$C = c' L,$$

where L is the vector of households by location. This in turn implies that $Q = (I - M')^{-1} c' L$, so the distribution of consumers across space affects the structure of the economy. We complete the model by the market clearing condition for labor for every location: household in various locations generate consumer demand, which gives rise to production of gross output, which in turn leads to demand for labor. Let $z_y \equiv L_y / Q_y$ be the amount of labor required to produce one unit of commodity y. It is straightforward to show that

$$z_{id} = (1 - \alpha_i)(A_{id} B_{id})^{\frac{\sigma}{1-\sigma}} \left(\frac{p_{id}}{w_d} \right)^{\frac{1}{1-\sigma}},$$

[5] Recall that households do not directly demand commodity io but purchase the composite good $\tilde{id}$.

$z_{\tilde{i}d} = 0$ and $z_o = A_{trans}^{-1}$.

If we denote $\hat{L}$ to be the demand for labor by all the good-location combinations, we have that

$$\text{diag}(z)Q = \hat{L}.$$

The allocation of labor within industry in a particular location does not affect the demand for consumption goods and hence gross output, so we need to sum the labor within the same location. Let F be $\ell \times (n+1)\ell$ matrix with $F_{d,id} = 1$ and $F_{d,id'} = 0$ if $d \neq d'$, so $F\hat{L} = L$. Then putting all the different components together, we obtain:

$$F\,\text{diag}(z)(I - M')^{-1}c'L = L. \tag{18}$$

Note that the matrices z, M and c are completely determined by the prices and F simply by the commodity ordering convention. As there are no scale effects in our economy, it can be arbitrarily scaled up and down. Hence the system above is underdetermined so far. Solving (18) is an eigenvalue problem: L is the eigenvector associated with the unitary eigenvalue, scaled up so that total labor supply equals $\bar{L}$.

This concludes the description of the structure and solution of the model. We now move on to describe its calibration and quantitative applications.

5 Calibration

We have three primary data sources for the calibration of model parameters: (1) The U.S. Input-Output tables from the BEA; (2) Employment and value added by industry and region from the BEA and (3) the CFS. We use the 2012 benchmark releases of the IO tables and CFS, and follow the spatial aggregation into 9 Census divisions and sectoral aggregation to 7 sectors described in Section 3.

Final demand The final use shares can be used to pin down the parameter β_i: $\beta_i = p_i C_i / (\sum_j p_j C_j)$, where C_i is the final use of product i.

Transportation requirements All non-service output is considered tradable. For agriculture, mining and manufacturing, we use data from the CFS to infer the transportation service intensities of corresponding commodities and origin-destination pairs. In particular, we use the ton-mile per dollar of products shipped as a proxy for $t_{io,d}$ for all tradable goods, and categorize manufacturing industries into heavy manufacturing, light manufacturing and manufacturing with medium transport intensity. Tradable services have zero cost of transport, that is $t_{i,od} = 0$ for all od pairs. For non-tradable services, we set it to a large number to implement the idea that $t_{io,d} = \infty$. This also implies a particular choice of units for the transportation services.

Production functions The parameters ρ and σ govern the elasticity of substitution between intermediate inputs and the primary input labor, and that between intermediate inputs, respectively. We set $\sigma = 0$ so as to render the intermediate input bundle Cobb-Douglas. We set ρ such that the elasticity of substitution between intermediate inputs and labor is $\frac{1}{1-\rho} = 0.3$. We set γ such that the elasticity of substitution across regional varieties is $\frac{1}{1-\gamma} = 3$.

The remaining parameters jointly determine the allocation of the primary input labor across sectors and locations and the flow of intermediate inputs. In the current version of the calibration, we shut down labor-augmenting productivities by setting $B_{io} = 1$ for all io. By a choice of units we can normalize $A_{i1} = 1$ for all i. We set the IO parameters $\boldsymbol{\alpha}$ and $\boldsymbol{V}$, and the productivity parameters A_{io} for $o = 2, \ldots \ell$ to match model-implied intermediate and employment shares to their empirical counterparts.[6] In particular, we construct the following moments from the model:

$$S_{ij} = \frac{\sum_{d=1}^{\ell} Q_{id} \left[\sum_{o=1}^{\ell} M_{id,\tilde{j}d} M_{\tilde{j}d,jo} p_{jo} \right]}{\sum_{d=1}^{\ell} p_{id} Q_{id}},$$

which corresponds to the share of sector j inputs in the value of industry i output and

$$e_{io} = \frac{\hat{L}_{io}}{\sum_{\ell} \hat{L}_{i\ell}},$$

which is the share of location o in the total sector i employment. The remaining 56 parameters of A_{io} (for 7 sectors in 9 regions after the normalization $A_{i1} = 1$ for all i), 7 parameters in $\boldsymbol{\alpha}$, the 49 parameters in $\boldsymbol{V}$ and transport sector productivity A_{transp} are calibrated to minimize the sum of squared errors between the empirical and model-implied values of 49 intermediate input shares S_{ij}, 63 sector-region employment shares e_{io}, and the value added share of the transportation sector. We now report the fit of the calibration and the results from an experiment that changes the productivity of transportation services.

[6] The limiting case of $\sigma \to 0$ and $\rho \to 0$ yields the Cobb-Douglas production function. In this case, $\boldsymbol{\alpha}$ and $\boldsymbol{V}$ can be directly read off the corresponding cost shares. In all other cases the IO flows depend on the whole matrix of IO parameters and on the productivity values.

6 Preliminary Results

6.1 Calibration results

The calibration fits the data remarkably well. The value added share of the transportation sector is 0.033 in the data and 0.034 in the model. Among the remaining moments, the model almost exactly replicates intermediate input shares, with a median gap of 0.38 percent from the empirical targets. The median gap between empirical and calibrated sector-region employment shares is 2 percent with a correlation of 0.99.

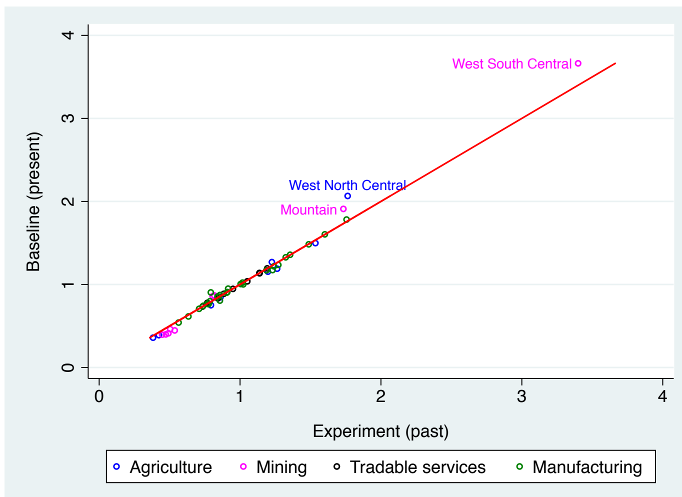
6.2 Determinants of long-run structural changes

To gauge the role of transportation costs in long-run structural changes in the economy, we simulate an increase in transportation costs so as to facilitate a comparison of the changes resulting from the model with the actual changes in the data. In 2012, the year of our baseline calibration, the share of the transportation sector in U.S. private employment is 3.3 percent. In early 1960s, this share was around 4.3 percent. In our experiment, we decrease A_{transp} by about 50 percent to capture this change. The thought experiment is that, after calibrating the model to the 2012 data, we reduce transportation productivity to its level five decades earlier while keeping everything else constant, and assess the model-implied aggregate, sectoral and spatial effects.

Starting with the aggregate impact, the experiment implies a GDP decrease of 2.8 percent. This is in contrast to the Hulten (1978) theorem, which posits that in a competitive economy with sectoral linkages, the first-order impact of a sectoral TFP shock on aggregate output is proportional to that industry's sales as a share of output. In our case, this would correspond to a drop in GDP by 1.7 percent ($= -0.5 \times 0.034$). The magnification effect is due to the complementary nature of transportation services, a result consistent with the analysis of Baqaee and Farhi (2017) who show the imprecise global performance of the first-order approximation proposed by Hulten, especially with strong nonlinearities in production.

As to the sectoral implications, the long-run structural change of the U.S. economy is well-known: the reallocation of employment out of agriculture in the 19th and early 20th centuries was followed by a further reallocation from manufacturing to services in the second half of the 20th century. To facilitate an intuitive interpretation and comparison with the latter episode, we report the sectoral results with respect to the past, i.e., what would have been the effect of increasing the productivity of transportation on sectoral shares from the simulated past period? In response to this question, the model mechanically predicts an increase in the employment of transport-intensive activities that benefit from cheaper transportation. In particular, the experiment implies an increase of 3.6 percent in the employment shares of agriculture and mining separately, and increases of 1 and 1.4 percent in the employment shares of heavy and medium-transport intensity manufacturing, respectively. Through input-output linkages that lower the cost of key intermediate inputs, the employment share of tradable services also increase by 0.8 percent, while that of non-tradable services contracts by about 1 percent. In short, while the magnitudes are small, productivity increases in transportation have qualitatively counteracted and moderated structural change. This is in contrast to Herrendorf et al. (2012) who posit that in the context of the 19th century, reductions in transportation costs due to railroads have contributed to structural change through income effects that are relevant for the reallocation out of agriculture.

Figure 3: Effect of Transportation Productivity on Sectoral Employment Shares across U.S. Regions



Notes: Each observation is the normalized employment share (defined in the text) of a sector-region (U.S. Census division) pair in the baseline calibration (y-axis) to 2012 data, and the simulated level corresponding to 1960s (x-axis). Manufacturing encompasses 3 groups in terms of transportation intensity, which are not separately color-coded.

In terms of regional effects, the model qualitatively captures the population shift out of north eastern regions (New England and Middle Atlantic) toward the center and the west (Pacific and Mountain regions), but fails to predict the increased population share of the South Atlantic region (encompassing Georgia, Carolinas and Florida). While the correlation between predicted and actual percentage population changes across 9 regions is 0.34, the model only captures about 10 percent of the absolute shift in population, suggesting that the distribution of U.S. population across aggregate regions is by and large driven by factors other than transport costs, such as housing costs and amenities. This conjecture is consistent with predicted persistence in the regional composition of sectoral activity in Figure 3, in contrast to its empirical counterpart in Figure 2.

7 Discussion

We laid out a database building effort and an innovative methodology to model and quantify transport costs and tradability of services in a spatial general equilibrium model with sectoral linkages. The quantitative application is a preliminary demonstration of how this structure can be utilized. We now describe planned theoretical and empirical extensions.

In terms of theory, the current version of the model abstracts from capital. In reality, shipping technologies are partially embedded in transportation equipment such as motor vehicles. To capture this sectoral linkage from manufacturing into transportation, we plan to incorporate capital in production, including in the supply of transportation services. A second line of extension is to allow region-sector specific productivities to endogenously respond to employment levels due to agglomeration economies, as well as include congestion forces in non-tradable services such as residential housing and commercial real estate.

In terms of quantitative applications, we have ignored the frictions involved in forming seller-buyer matches and contracting in tradable services by setting its trade costs equal to zero. Moreover, by keeping this zero trade cost unchanged in the experiment, we ignored potentially large decreases in communication and face-to-face meeting costs driven by telecommunication technologies and air transportation. Our first goal is to extend the quantitative exercise to allow for a more realistic treatment with positive and time-varying trade costs for tradable services. A related task is to incorporate different modes of transportation. Plausibly, sectors are heterogeneous in their modal intensities, such as tradable services being more intensive in air transport, manufacturing being more intensive in trucking and agriculture/mining being more intensive in railroads. This extension is not only likely to affect the backward-looking predictions of the model in terms of structural change, but would also be a better model to simulate forward-looking predictions on the potential impact of emerging mode-specific technologies. Yet another interesting and feasible application is a short-run analysis of the wage impact by keeping the distribution of labor across locations fixed.

We also plan to fully utilize all available data in order to calibrate the model to present as well as past empirical moments. This would enable us to capture changes in the relative productivities across sector-region pairs as well as in the technological parameters governing sectoral linkages. Similarly, we abstracted from region-sector specific labor augmenting productivity B_{io} in this version of the model. Region-sector level data on sales and wage bill can help us disentangle Hicksian and labor-augmenting productivities. We are exploring the feasibility of quantifying the model at spatially more disaggregated levels using present and past sectoral employment at the county level available from County Business Patterns datasets.

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A Extension: model with capital

In the baseline model we assume that the primary input of production is entirely composed of labor. In this extension we model the primary input of production as capital-labor composite with the labor share specific to industry. The basic model can replicate the shifts in value added across locations; since the wage bill to value added differs by industry, making a distinction between labor and primary input will allow us to better account for employment shifts.

A.1 Environment

The basic production structure is the same as before and here we will note only the added features of the model.

Consumers and preferences There is an atomless mass of households with measure $\bar{L}$. Every household supplies one unit of labor inelastically. Households move freely and costlessly across locations, but must consume in the location where they supply labor. Preferences over consumption are given by the utility function

$$U = \sum_{t=0}^{\infty} (1+r)^{-t} \, u(C_t), \tag{19}$$

where r denotes the rate of time preference, u is a utility function with standard properties (strictly concave and twice continuously differentiable). The aggregated consumption good is constructed as in the baseline model.

Production Production of the different commodities is carried out in the same way, but instead of labor L_{id}, industries use the capital-labor composite input H_{id} .

The primary input composite H_{id} is produced as follows

$$H_{id} = K_{id}^{\theta_i} L_{id}^{1-\theta_i}. \tag{20}$$

Investment and Capital formation The capital good is sector-specific. The capital stock of type i evolves as follows:

$$K_{id,s+1} = (1-\delta_i) K_{id,s} + D_{id,s} \tag{21}$$

where s is the date. Investment goods are produced as follows:

$$D_{id} = A_i^m \prod_{j=1}^{n} \eta_{ij}^{-\eta_{ij}} \prod_{k=1}^{n} \tilde{I}_{id,jd}^{\eta_{ij}}, \tag{22}$$

where $\tilde{I}_{id,kd}$ is a composite of sector k commodities and is used to assemble investment good i in location d, with the usual production function.

A.2 Equilibrium

We focus on the steady state of the model, so the net rate of return of all assets is r. This also implies that we can treat all the prices as constant. We drop the time subscripts on consumption from now on.

Goods prices The CRS assumption implies that *conditional on wages*, all prices can be derived from cost minimization, without regard for market clearing conditions.

We will denote p_{io} to be the *producer* price of commodity io and $\tilde{p}_{id}$ to be the *user* price of the composite good i assembled in location d. The price of transportation services (which are purchased at the origin of the shipment) are denoted p^t_{mo}. Then the cost of one unit of the shipment $Z_{io,d}$ is $p_{io} + \sum_m t^m_{iod} p^t_{mo}$. With this in mind, cost minimization implies that the prices of composite commodities are given by:

$$\tilde{p}_{jd} = \begin{cases} \left[\sum_{o=1}^{\ell} \frac{1}{\ell}(p_{jo} + \sum_m t^m_{iod} p^t_{mo})^{-\frac{\gamma}{1-\gamma}}\right]^{-\frac{1-\gamma}{\gamma}} & j \in \mathcal{P}_{\mathcal{T}} \\ p_{jd} + \sum_m t^m_{id,d} p^t_{md} & j \in \mathcal{P}_{\mathcal{NT}} \end{cases}. \tag{23}$$

Given this, cost minimization for io and perfect competition imply that

$$p_{io} = A_{io}^{-1} \left[(1-\alpha_i) q_{io}^{-\frac{\sigma}{1-\sigma}} B_{io}^{\frac{\sigma}{1-\sigma}} + \alpha_i \left[\sum_{j=1}^{n} v_{ij} \tilde{p}_{jo}^{-\frac{\rho}{1-\rho}} \right]^{\frac{1-\rho}{\rho} \frac{\sigma}{1-\sigma}} \right]^{-\frac{1-\sigma}{\sigma}}, \tag{24}$$

where q_{io} is the cost of the capital-labor composite. It is easy to determine that

$$q_{io} = [(r+\delta_i) p^k_{io}]^{\theta_i} w_o^{1-\theta_i}. \tag{25}$$

The term $(r+\delta_i)p^k_{io}$ is the price of the capital services of type i in location o. It is given by the required gross rate of return $r+\delta_i$ and the price of the capital good. (This assumes that there are no valuation effects on the capital stock, which will be true at the steady state.)

At the steady state the price of the specific kind of capital and the corresponding investment good will be the same and are given by:

$$p_{io}^{k} = \prod_{j=1}^{n} \tilde{p}_{jo}^{\eta_{ij}} \tag{26}$$

Conditional on local wages $\{w_o\}$, the system of equations (23) - (26) can be solved easily by iteration.

Consumer optimization We assume that consumers can move freely at the beginning of the period, but consumption must take place before the consumers can move again (so consumption takes place in the same location that the consumers earn labor income). Given consumption expenditure X_t, the aggregated consumption for an agent in location d is X_t/P_d with P_d being the ideal consumption index:

$$P_d = \prod_{j=1}^{n} \left(\tilde{p}_{jd}\right)^{\beta_j}, \tag{27}$$

At the steady state consumption expenditure would be simply labor income and the net return on assets. So, for a resident of location d, per period consumption is $(rW_d + w_d)/P_d$, where W_d is the value of the assets (wealth) owned by the residents. Free movement of households then implies that for any d, a:

$$\frac{rW_d + w_d}{P_d} \geq \frac{rW_d + w_a}{P_a}.$$

(We assume that a resident of d can take her portfolio with her and move. The same is true for residents of a

$$\frac{rW_a + w_a}{P_a} \geq \frac{rW_a + w_d}{P_d}.$$

Summing these implies:

$$W_d \left[\frac{1}{P_d} - \frac{1}{P_a}\right] \geq W_a \left[\frac{1}{P_d} - \frac{1}{P_a}\right].$$

Then we have that $P_d < P_a$ implies that $W_d > W_a$. Locations with higher prices can attract people by the higher wages they offer; people with higher share of nonlabor income will choose cheaper locations. We assume K is common across locations.

Setting $K_a = K_d, \forall a, d$ implies that for all occupied locations,

$$\frac{rK + w_a}{P_a} = \frac{rK + w_d}{P_d} \tag{28}$$

In the equation above, K is also an equilibrium object that will have to be found together with the vector of wages.

Flow of goods There are $(2n+f)\times\ell$ goods in the economy: every location produces n commodities, assembles n composite commodities and provides f modes of transportation services for the commodities it ships out.

Also, there are $(n+f)\ell$ capital stocks and labor demands, which we need to solve for in equilibrium.

Let's define the M matrix as before. The resource constraints can be written as:

$$Q = M'Q + C + I,$$

where I is the vector of demands of the particular commodity for investment purposes.

First, we are working on the investment term. In steady state, $D_{id} = \delta_i K_{id}$. Cost minimization in the production of D_{id} implies that the induced demand for $\tilde{jd}$ commodity is given by $\eta_{ij} p^k_{id}/\tilde{p}_{jd} D_{id}$. Let F^1 be a $(2n+f)\ell \times (2n+f)\ell$ matrix with $F^1_{id,\tilde{j}d} = \delta_i \eta_{ij} p^k_{id}/\tilde{p}_{jd}$ and zero elsewhere. Then $I = F^{1\prime} K$.

Next, we need to find the vector K. Cost minimization implies $K_{id}/H_{id} = \theta_i q_i / p^k_{id}$ and $H_{id}/Q_{id} = (1-\alpha_i)(A_{id}B_{id})^{\frac{\sigma}{1-\sigma}} (p_{id}/q_{id})^{\frac{1}{1-\sigma}}$. Let F^2 be $(2n+f)\ell \times (2n+f)\ell$ matrix with $F^2_{id,id} = (1-\alpha_i)(A_{id}B_{id})^{\frac{\sigma}{1-\sigma}} (p_{id}/q_{id})^{\frac{1}{1-\sigma}} \theta_i q_i / p^k_{id}$ and zero everywhere else. Then $K = F^{2\prime} Q$. So combining what we have, $I = F^{1\prime} F^{2\prime} Q \equiv F' Q$. Then the resource constraint is

$$Q = M'Q + F'Q + C \Rightarrow Q = (I - M' - F')^{-1} C.$$

The result above is not surprising, since intermediate goods can be thought as capital goods with depreciation rate 1.

Consumption demand Consumption by all the agents employed in industry i in location d follows directly from

$$C_{id,\tilde{j}d} = \beta_i \frac{(rW + w_d) L_{id}}{\tilde{p}_{jd}}$$

The rest of the model is exactly the same as in the proposal.

Finally, we need to pin down the value of the aggregate wealth. It is given simply by

$$W = \sum_i \sum_d p^k_{id} K_{id} \tag{29}$$

with $K = F^{2\prime} Q$.