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HIGHWAYS AND GLOBALIZATION

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ABSTRACT

This paper quantifies the value of US highways and their contribution in shaping regional specialization patterns and facilitating internal and external market integration. We develop a multisector general equilibrium model of interregional and international trade with many locations in the United States (i.e., counties) and many countries. In the model, producers choose shipping routes subject to domestic and international trade costs, endogenous congestion, and port efficiency at international transshipment points. We find that removing the Interstate Highway System reduces real GDP by $619.1 billion (or 3.9 percent) with one quarter due to reduced international market access. We also quantify the value of the twenty longest highway segments and find a range between $2.7 and $55.1 billion with I-5 being the most valuable. Our results highlight the role of domestic transportation infrastructure in shaping regional comparative advantage and gains from international trade.

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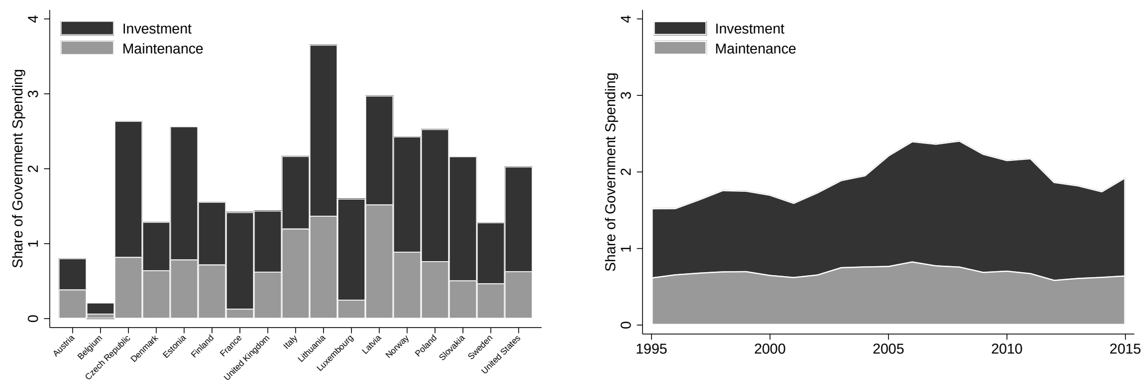
1 Introduction

A substantial portion of international trade makes use of the domestic transportation infrastructure of importing and exporting countries. This suggests that the fiscal efficacy of investment in transportation infrastructure depends in part on the access it provides to international markets. This is particularly important for quantifying the benefits of domestic road networks against substantial construction and maintenance costs. For example, Figure 1 shows that average spending on road investment and maintenance in the OECD countries between 1995 and 2015 was approximately 2% of total annual government spending. Quantifying economic benefits of such expenditures, however, is challenging because the quality of domestic road infrastructure affects the spatial pattern of specialization vis-à-vis domestic and foreign trading partners, generates spillovers across industries and locations, and alters domestic congestion levels.

Figure 1: Road Infrastructure Spending by Country and Year



A. Road Infrastructure Spending by Country   B. Road Infrastructure Spending by Year

Notes: The figure shows infrastructure spending on new investment and maintenance by country and year. Panel A shows average spending as a share of total government expenditure on road infrastructure by country between 1995 and 2015. Panel B shows the average spending as a share of total government expenditure in the same set of countries over time.
Source: The data are from OECD (2020a,b).

In this paper, we provide a novel framework to address these challenges and quantify the contribution of transportation infrastructure to regional economic development. The model allows for many sectors and locations, and locations in a country are integrated with each other and all foreign trading partners subject to industry-specific domestic or international trade costs. We inform the model using detailed data on the domestic highway network in the United States as well as consumption, production and trade data on nearly 3,000 US counties, 36 foreign countries, and 22 sectors. The model captures the fact that the available road network mediates the intensity of spatial and inter-sectoral spillover effects in the US economy. First, sectors and locations are connected via input-output linkages such that given spatial specialization patterns, better transportation networks reduce costs of sourcing intermediate and final goods and allows relatively remote regions to specialize in sectors where they have comparative advantage. Second, all sectors and locations use the same road network but with varying traffic intensity reflecting truck capacity of carrying sector-specific cargo. This means that transporting goods creates congestion externalities that are heterogeneous across locations and sectors.

The model in this paper captures these spillovers via endogenous trade costs. More specifically, producers in each location choose optimal routes to all destinations such that the domestic portion of trade costs reflect travel time via the US highway network that takes into account potential congestion. The international portion of trade costs reflect the costs of transshipment at US ports as well as international shipping between US ports and US foreign trading partners. Simultaneously, domestic and international trade in each sector generates traffic with sector-specific intensity, which ultimately affects trade costs in all sectors.

We use the model to produce three main sets of results. First, we quantify the total value of the entire Interstate Highway System (IHS) and find that in the absence of the IHS real GDP in the United States falls by \$619.1 billion in 2012 dollars (or 3.9 percent). These losses are concentrated in counties in the Northeast and West, and counties that are the most remote experience the largest relative losses. We also show that about one quarter of these losses can be attributed to the contribution of the IHS to reducing international trade costs. The intuition behind our results is that the IHS allows remote regions to exploit their comparative advantage and concentrate production in a few sectors with relatively high productivity.

This is confirmed in the second set of results that illustrate how removing the IHS affects a measure of revealed comparative advantage as in Balassa (1965). In particular, we show that removing the IHS leads states to alter their sectoral composition of total output. In addition, all states consume more of their own production and export less to other states and foreign countries. This suggests that the reduction in trade costs due to the IHS plays an important role in shaping the location of production, the pattern of specialization, and the distribution of the gains from trade across US locations.

Finally, we quantify the value of each of the twenty longest IHS segments by mileage (I-5, I-10, I-95, etc). From this exercise we find that I-5, I-10, I-80, I-95, and I-40 are the most valuable. Aggregate losses from removing these twenty segments range between

$2.7 and $55.1 billion and losses per mile range between $2.5 and $39.7 million. We also quantify the contribution of each segment to international trade costs and find this to be greater than 9 percent of the total effect for these segments. These results are broadly useful for understanding the value of any IHS segment and similar exercises can be used to quantify the value of other parts of the transportation network or proposed changes. Overall, our approach highlights the interaction between domestic transportation infrastructure and international trade, which may be useful for assessing the aggregate impact and distributional consequences of investment in transportation infrastructure.

This paper contributes to several areas of the literature. First, we contribute to research on the impact and value of the Interstate Highway System in the United States. One part of this literature estimates the effects of transportation access on economic activity (Isserman and Rephann, 1994; Coşar and Fajgelbaum, 2016; Michaels, 2008) and household location decisions (Baum-Snow, 2007).[1] Another part of this literature uses quantitative models to value the Interstate Highway System. Perhaps, most closely related to this paper is work by Allen and Arkolakis (2014, 2019). These authors quantify the value of the Interstate Highway System focusing on aggregate domestic trade and the welfare gains associated with improving shorter sections.[2] We contribute to this literature by highlighting the role of the IHS in shaping spatial comparative advantage and decomposing its total value in two components due to better domestic and international market access. Our approach is complementary to Allen and Arkolakis (2014). In fact, a version of our model without input-output linkages suggests that the gains from the IHS due to better domestic market access are roughly $185 billion (in 2012 dollars), which is in line with Allen and Arkolakis (2014).[3] This suggests that the two channels that we highlight, i.e., sectoral specialization with input-output linkages and better international market access, add and additional $370 billion and $160 billion, respectively.[4]

Second, the solution method used in this paper follows the *hat algebra* approach as in Dekle, Eaton and Kortum (2007, 2008), Caliendo and Parro (2015), and Caliendo, Dvorkin and Parro (2019). Relying on the observed allocations of domestic and international trade

[1]In addition, there is a growing literature that estimates the effects of transportation infrastructure in the context of developing countries (e.g., Faber, 2014; Baum-Snow, Brandt, Henderson, Turner and Zhang, 2017; Cosar, Demir, Ghose and Young, 2020).

[2]Also related is work on historical railroads (Fogel, 1964; Fishlow, 1965; Donaldson and Hornbeck, 2016; Donaldson, 2018) and highways more recently (Alder, 2017; Jaworski and Kitchens, 2019) as well research on optimal infrastructure investment in general equilibrium settings (Fajgelbaum and Schaal, 2020).

[3]Allen and Arkolakis (2014) estimate the value of the IHS to be between $150 billion and $200 billion in 2007 dollars or between $166 and $221 billion (in 2012 dollars).

[4]The intuition behind these results is consistent with Caliendo and Parro (2015) and Ossa (2015) who argue that including input-output structure magnifies the gains from trade.

shares, labor and traffic allows us to sidestep the challenge of solving for the unobservable fundamentals of the economies represented with the large number of interacting locations and sectors. This is particularly important for our setting in which we focus on the impact of changes in domestic trade costs for all US counties and all US foreign trading partners. We contribute to this literature by showing how to apply the hat algebra approach in models with two-tier spatial units where locations in the first tier are aggregated into larger units in the second tier. As it turns out, we can examine county-level outcomes in the US by relying on the observed state-level allocations together with the data on intra-state trade costs. We also show how to incorporate congestion frictions into the model and how to use spatial allocation of traffic together with trade flows to solve for counterfactual equilibria.

Finally, we contribute to recent work on the role of domestic trade costs in shaping trade and welfare (Agnosteva, Anderson and Yotov, 2019; Atkin and Donaldson, 2015; Coşar and Demir, 2016; Coşar and Fajgelbaum, 2016; Fajgelbaum and Redding, 2018; Redding, 2016; Ramondo, Rodríguez-Clare and Saborío-Rodríguez, 2016, 2019). Our results suggest that improvements in domestic transportation networks allow remote regions to concentrate production and exports in sectors where they have a comparative advantage. This leads to substantial welfare gains and has potentially important distributional consequences within and between countries. To measure domestic trade costs and parts of international trade costs that use US infrastructure, we use detailed data on travel time as a function of distance, posted speed and congestion on all county-to-county and county-to-port routes. This allows us to examine the interaction between domestic and international market access by quantifying the contribution of changes in domestic road infrastructure to all trade costs. Importantly, we also allow trade costs, port efficiency, and trade elasticity parameters to vary across sectors and estimate them using data on the internal trade flows within the United States.

The remainder of this paper is organized as follows. In the next section, we describe the key components of the US highway network and describe how to we use the data on traffic, distance, and posted speed to calculate travel time in a way that incorporates potential congestion. Section 3 presents the model of interregional and international trade, including the role of domestic and international trade costs, and the solution method used to carry out counterfactual experiments. In Section 4, we provide an overview of the data used to calibrate the model, which includes the construction of sector-specific trade costs and the estimation of sector-specific model parameters. Section 5 presents our counterfactual results and Section 6 concludes.

2 The US Highway Network with Congestion

In 2010 there were over four million miles of paved road in the United States. The Interstate Highway System (IHS) comprises nearly 50,000 miles with posted speeds typically set at 70 miles per hour. Although it accounts for roughly 1 percent of paved road mileage in the United States, the IHS facilitates one quarter of vehicle miles traveled annually. An additional 132,000 miles contribute the remainder of US federal-aid highways. US states have their own highways, which account for approximately 211,000 miles of paved roads. The complete US highway network used in this paper is shown in Panel A of Figure 2 and includes the IHS, US Highways, and state highways. The remaining roads (not shown) are primarily used for local travel, including county roads, city streets, and neighborhood streets.

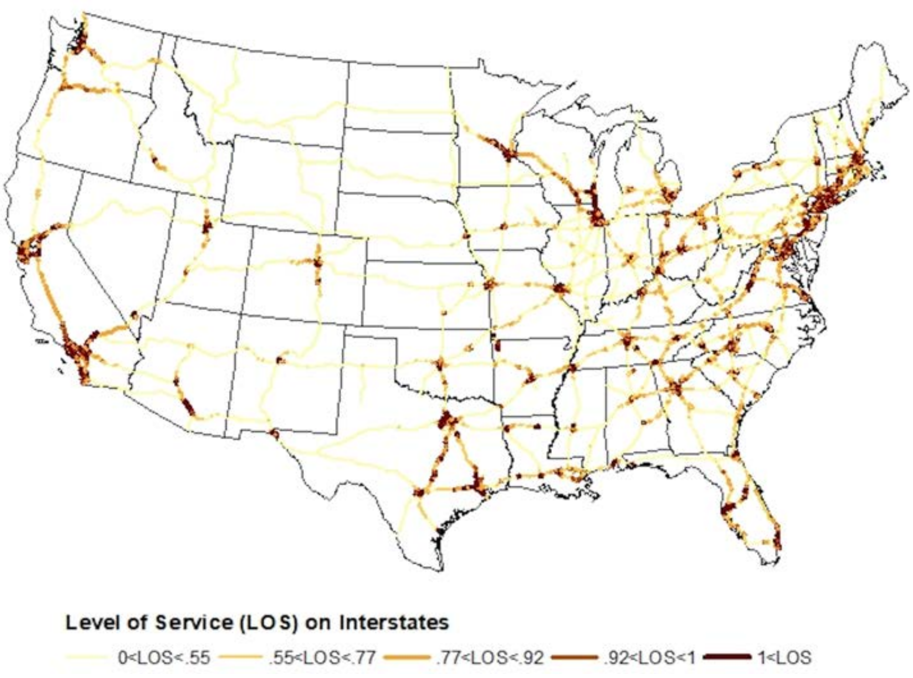
The highway network shown in Panel A of Figure 2 includes the major roads used for the movement of goods within the United States and constitutes the main focus of our analysis.[5] In 2010, trucking accounted for almost half of ton-miles nationally. The fraction of the value of domestic trade moved by truck was nearly 70 percent relative to 10 percent by rail and 5 percent by water. The highway network also provides important links for international trade. In general, 30 percent of all imports by weight used trucks exclusively to deliver goods domestically, while 34 percent used trucks for at least part of their journey. For exports, more than half of shipments by weight used trucks as a single mode to deliver goods to ports and 60 percent used trucks partially to ship goods to ports. For trade between Canada and Mexico, the highways play an even larger role: 70 percent of the value of trade between the United States, Canada, and Mexico is transported on US highways (Bureau of Transportation, 2017).

While highways in the United States are vital for facilitating domestic and international trade, movement of goods via highways is subject to congestion. For example, recent surveys suggest that congestion costs are as high as 100 hours per driver each year (INRIX Research, 2019). To measure the severity of congestion, the Federal Highway Administration collects average annual daily traffic conditions on highways from state-level agencies. The average annual daily traffic is then combined with the road capacity to create a measure that reflects how congestion affects travel speeds, this measure is known as the level of service (LOS). We illustrate observed values of the LOS on different segments of US highways in Panel B of Figure 2. Using LOS suggests that nearly 18,000 miles (or 40 percent) of the IHS experiences reduced travel speeds due to congestion. The figure also suggests that the levels of

[5] While portions of domestic trade are conducted via waterways, railroads and air transportation, trucking by far remains the most important mode of transportation.

Figure 2: US Highways and Congestion

A. Components of the US Highway Network



B. Congestion on US Highways

Notes: The figure depicts the US highway network and congestion in 2010. Panel A shows Interstate Highway System in black and the remaining national and state highways in gray. Panel B shows congestion on the Interstate Highway System congestions are highly heterogeneous across segments and concentrated in the Eastern and Western parts of the US. Importantly, for this paper, this suggests that incorporating congestion costs is important for quantifying the impact of highways on regional specialization and trade outcomes.

As mentioned above, Figure 2 includes the IHS, US Highways, and state highways. Shapefiles of this network are available that divide these key components into roughly 650,000 individual sections. We observe LOS, distance, and speed, which together determine the travel time on each section of the highway network, which we denote with subscript $\mathcal{S}$. We then use information for each $\mathcal{S}$ to calculate travel time according to (see National Research Council, 2000, Exhibit 23-2):

$$\text{time}_{\mathcal{S}} = \frac{\text{distance}_{\mathcal{S}}}{\mathcal{A}_{\mathcal{S}} \cdot \text{posted speed}_{\mathcal{S}}} \quad \text{, where} \quad \mathcal{A}_{\mathcal{S}} = \begin{cases} 1.000 & \text{for} \quad 0 \leq \text{LOS}_{\mathcal{S}} < 0.55 \\ 0.950 & \text{for} \quad 0.55 \leq \text{LOS}_{\mathcal{S}} < 0.77 \\ 0.825 & \text{for} \quad 0.77 \leq \text{LOS}_{\mathcal{S}} < 0.92 \\ 0.708 & \text{for} \quad 0.92 \leq \text{LOS}_{\mathcal{S}} < 1.00 \\ 0.600 & \text{for} \quad 1.00 < \text{LOS}_{\mathcal{S}} \end{cases} \tag{1}$$

We then can calculate total travel time between any pair of locations i and j using:

$$\text{time}_{ij} = \sum_{\mathcal{S}} \mathbb{1}_{\mathcal{S},ij} \text{time}_{\mathcal{S}} \tag{2}$$

where $\mathbb{1}_{\mathcal{S},ij}$ is an indicator function equal to one if $\mathcal{S}$ is used when travelling from i to j or zero otherwise. Note that time_{ij} is endogenous to the route between i and j as well as $\text{time}_{\mathcal{S}}$, which is a function of traffic–including trade-generated congestion–on segment $\mathcal{S}$. The theoretical model presented in the next section incorporates both of these sources of endogeneity.

3 Theoretical Framework

In this section, we present a theoretical model of interregional and international trade. The model can accommodate multiple countries each consisting of multiple regions. However, for the ease of exposition we will present the model using US states (and the District of Columbia) each with multiple counties and all other countries in the world with a single county each. The geographic structure of the model (i.e., counties specifically nested within states) allows us to accommodate rich internal geography within and across US states and reflects the constraints of available data described in Section 4. Each US county is integrated with all other US counties and all countries using county-to-county and county-to-country travel via US highways, ports, and international shipping lanes. We first present the model in levels and then show how the model can be expressed in relative changes for counterfactual exercises.

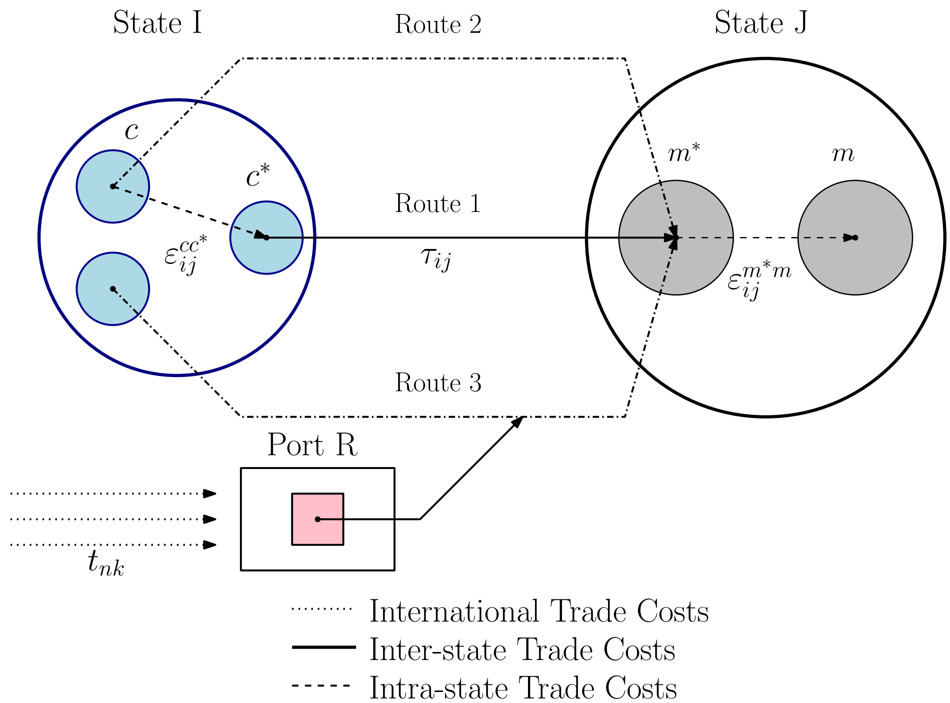
3.1 Illustration of Domestic and International Trade Costs Components

We first introduce different types of trade costs and their role in shaping domestic and international trade flows. Figure **3** provides a stylized example of trade between states i and j. To start, assume that state i consists of three counties and state j has two counties. There are three highway routes (i.e., Route 1, Route 2, and Route 3) that can potentially be used for transporting goods between the two states. Producers in all counties in state i simultaneously choose the least cost route from any county in i to any county in j, i.e., producers choose the least cost route from among Route 1, Route 2, and Route 3. Choosing Route 1 as the least costly route from i to j implies that the relevant interstate trade cost is now τ_{ij} and that the relevant exporting-importing counties are $c^* \in i$ and $m^* \in j$. These two counties will act as goods entry and exit points for both exporting and importing.

Now consider a producer located in county $c \in i$ that ships goods to county $m \in j$. We already know that the interstate trade cost component will be τ_{ij}; however, there are two additional intrastate components. On the exporting side, the producer pays intrastate trade cost, $\varepsilon_{ij}^{cc^*}$, for transporting goods from the production location $c \in i$ to the relevant aggregation point $c^* \in i$. On the importing side, there is an additional intrastate trade costs, $\varepsilon_{ij}^{m^*m}$, to transport goods from the entry point $m^* \in j$ to the final destination county $m \in j$. Hence, total trade costs from $c \in i$ to $m \in j$ consist of $\varepsilon_{ij}^{cc^*}$, τ_{ij}, and $\varepsilon_{ij}^{m^*m}$. We show how these three components are aggregated to total trade costs below where we describe the rest of the model.

We next consider how goods are transported from foreign countries to each county in the United States. First, a foreign exporter n must ship the goods to the relevant US port r located in state k and pay the associated international trade cost, t_{nk}, as illustrated in Figure **3**. Then, the goods are shipped via the US domestic transportation network to the import aggregation county in the destination state in the same way as for the interstate trade. Finally, there are also intrastate trade costs to transport the goods to the destination

Figure 3: Domestic and International Trade Costs



Notes: The figure illustrates the domestic and international trade cost components in the theoretical model. Intrastate trade costs are denoted $\varepsilon_{ij}^{cc^*}$ and $\varepsilon_{ij}^{m^*m}$, interstate trade costs are denoted τ_{ij}, and international trade costs are denoted t_{nk}.

county. Hence, international trade costs also consist of three components: t_{nk}, τ_{kj}, and $\varepsilon_{kj}^{m^*m}$.

3.2 A Model with Two-Tier Locations and Endogenous Trade Costs

The model of intranational and international trade in this section extends the multisector Ricardian model of trade in two ways. First, the model features two location tiers such that production, consumption, and trade of counties (first tier) can be consistently aggregated to corresponding state-level (second tier) variables. Ultimately, we formulate all county-level variables as functions of their state-level counterparts and intrastate trade costs. This allows us to examine economic outcomes at the county level, while keeping the solution of the model computationally feasible and matching the level of aggregation in available data. Second, the model accounts for two sources of endogeneity in trade costs: the choice of transportation routes and the effect of trade on congestion.

County-level Production and Consumption

We start by describing the supply and demand side in each county c in state i. Consumers in county $c \in i$ allocate their total income across goods from sectors $s \in S$ to maximize the following utility function:

$$U_i^c = \prod_{s \in S} Q_i^c(s)^{\alpha_i(s)} \quad \text{s.t.} \quad \sum_{s \in S} \alpha_i(s) = 1, \tag{3}$$

where $\alpha_i(s)$ is Cobb-Douglas consumption share and $Q_i^c(s)$ is the total quantity consumed of goods from sector s. Equation (3) leads to the following indirect utility function:

$$V_i^c(s) = \frac{I_i^c}{P_i^c}, \text{ where } P_i^c = \prod_{s \in S} \left(\frac{P_i^c(s)}{\alpha_i(s)} \right)^{\alpha_i(s)},$$

where I_i^c denotes total nominal income of consumers in $c \in i$ and $P_i^c(s)$ is the CES price index for goods from sector s.

Producers in county $c \in i$ and sector s face the following cost of an input bundle:

$$\kappa_i^c(s) = B_i(s) w_i^{\gamma_i(s)} \left(\prod_{\dot{s} \in S} P_i^c(\dot{s})^{\eta_i(\dot{s}s)} \right)^{1-\gamma_i(s)}, \tag{4}$$

where $B_i(s)$ is a constant, $\gamma_i(s)$ is the share of value added, and $\eta_i^{\dot{s}s}$ is the share of inputs that producers in sector s source from sector $\dot{s}$. These shares reflect input-output linkages across sectors. All producers in $c \in i$ in sector s face the same input bundle cost.

Recall from Section 3.1 that before shipping goods outside of state i, all varieties produced in each $c \in i$ are aggregated at the county $c^* \in i$ that offers the least cost route to ship to the desired destination. For example, consider shipping goods in sector s from $c \in i$ to state j and let $\varepsilon_{ij}^{cc^*}(s)$ denote the exporting intrastate component of trade costs. Since producers minimize trade costs, the intrastate components of trade costs for goods shipped from i to j are characterized by the optimal exporting and importing counties $c^*(s) \in i$ and $m^*(s) \in j$ as the outcome of the following minimization problem:

$$\{c^*(s), m^*(s)\} = \arg\min_{c,m} \left\{ \tau_{ij}^{cm}(s) \right\} \text{ for all } c \in i \text{ and } m \in j, \tag{5}$$

where $\tau_{ij}^{cm}(s)$ denotes the interstate trade cost when $c \in i$ and $m \in j$ are corresponding exporting and importing counties. Given that $c^*(s)$ is the optimal exporting county, producers in $c \in i$ and sector s ship goods to that county prior to exporting to j. All counties in i do the same and so all county-level varieties are aggregated in $c^*(s)$ such that the ijs-specific unit cost of production can be formulated as:

$$\kappa_{ij}(s) = \left(\sum_c \left(\kappa_i^c(s) \varepsilon_{ij}^{cc^*}(s) \right)^{-\theta(s)} \right)^{-\frac{1}{\theta(s)}}. \tag{6}$$

The functional form in equation (6) follows from the fact that producers in each county $c \in i$ draw productivity from the same is-specific Fréchet distribution with shape parameter $\theta(s)$. A CES-type aggregator in $c^* \in i$ then looks for the cheapest value of each county variety subject to intra-state trade costs.[6] Note that ij-specifc unit cost of production in each sector s arises due to endogenous intra-state trade costs and departs from neoclassical multi-sector models of international trade as in Eaton and Kortum (2002) and Caliendo and Parro (2015) where production costs only vary across export locations. With this specification we can express the share of exports from state i to state j that come from county c:

$$\mu_{ij}^c(s) = \frac{\left(\kappa_i^c(s) \varepsilon_{ij}^{cc^*}(s) \right)^{-\theta(s)}}{\sum_k \left(\kappa_i^k(s) \varepsilon_{ij}^{kc^*}(s) \right)^{-\theta(s)}}, \tag{7}$$

such that $\sum_c \mu_{ij}^c(s) = 1$.

State-level Production, Consumption, and Intra-US Trade

State-level producers in i take the unit cost of production for each destination j specified in equation (6) as given. Each state producer has a productivity $z(s)^{\frac{1}{\theta}}$, where $z(s)$ is drawn from a state-specific extreme value distribution with the location parameter $T_i(s)$ and shape parameter $\theta(s)$. As in Eaton and Kortum (2002), consumers and firms look for the cheapest price for each state variety given trade barriers such that the price of $z(s)$ in state j is given by:

$$p_j(z(s)) = \min_i \left\{ z_i(s)^{-\frac{1}{\theta(s)}} \kappa_{ij}(s) \tau_{ij}(s) \right\},$$

where $\tau_{ij}(s)$ denotes sector s-specific minimum state-to-state trade costs. The stochastic formulation of state-level productivity combined with the law of large numbers allows us to

[6] An alternative microfoundation for this expression would be to use an Armington CES-type aggregator as in Anderson and van Wincoop (2003) and assume each county produces a specific production input.

write the share of j's total income spent on goods from state i as:

$$\pi_{ij}(s) = \frac{T_i(s)\left(\kappa_{ij}(s)\tau_{ij}(s)\right)^{-\theta(s)}}{\sum_n T_n(s)(\kappa_{nj}(s)\tau_{nj}(s))^{-\theta(s)}}, \tag{8}$$

and the state-level price index can now be written as,

$$P_j(s) = A_j(s)\left(\sum_n T_n(s)(\kappa_{nj}(s)\tau_{nj}(s))^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}}, \tag{9}$$

where $A_j(s)$ is a constant.

County-level trade shares and prices can be written as state-level variables. First, similarly to equation (8) county-to-county trade shares from $c \in i$ to $m \in j$ in sector s can be expressed as:

$$\pi_{ij}^{cm}(s) = \frac{T_i(s)\left(\kappa_{ij}(s)\tau_{ij}(s)\right)^{-\theta(s)}\left(\varepsilon_{ij}^{m^*m}(s)\right)^{-\theta(s)}}{\sum_n T_n(s)(\kappa_{nj}(s)\tau_{nj}(s))^{-\theta(s)}(\varepsilon_{nj}^{m^{**}m}(s))^{-\theta(s)}}, \tag{10}$$

where $\varepsilon^{m^*m}(s)$ and $\varepsilon^{m^{**}m}(s)$ are intra-state trade costs in state j of transporting goods from the optimal importing counties to m relevant for exporters i and n, respectively. Second, the price index in $m \in j$ is as follows:

$$P_j^m(s) = \left(\sum_n T_n(s)(\kappa_{nj}(s)\tau_{nj}(s))^{-\theta(s)}(\varepsilon_{nj}^{m^{**}m}(s))^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}}. \tag{11}$$

Using the result in equation (8), we can rewrite the county-level prices and shares as:

$$P_j^m(s) = P_j(s)\left(\sum_n \pi_{nj}(s)(\varepsilon_{nj}^{m^{**}m}(s))^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}} \tag{12}$$

Similarly, the county-level expression for trade shares is as follows:

$$\pi_{ij}^{cm}(s) = \frac{\pi_{ij}(s)(\varepsilon_{ij}^{cm}(s))^{-\theta(s)}}{\sum_n \pi_{nj}(s)(\varepsilon_{nj}^{m^{**}m}(s))^{-\theta(s)}}. \tag{13}$$

Hence, our formulation allows us to express all county-level variables as functions of their state-level counterparts and intra-state trade costs. Importantly, this means we can examine county-level outcomes while using the data on state-level variables to overcome the absence of county-level data for trade flows and prices.

Equation (8) describes trade shares between US states. However, to describe trade shares between states and international partners, we have to consider trade costs beyond highways. To do this, we account for the fact that US exports and imports can be transported via ports and international sea freight.[7] We allow trade between states, Mexico and Canada to be conducted via inland ports.

We specify international trade costs between state i and foreign country n via port $r \in j$ in sector s in the following way:

$$\tau_{in}^{r}(s) = \tau_{ij}(s)\varepsilon_{ij}^{m^*r}(s)\xi_j^r(s)t_{jn}(s), \tag{14}$$

where $\tau_{ij}(s)\varepsilon_{ij}^{m^*r}(s)$ capture domestic trade costs incurred in moving goods from state i to county $r \in j$ where the port is located, $\xi_j^r(s)$ captures the efficiency of port r in handling and shipping goods in sector s, and $t_{jn}(s)$ captures international trade costs of shipping goods from port $r \in j$ to importer n.[8] Here, as stated before, we assume that each foreign country consists of a single county.

For each port $r \in \mathcal{R}$, producers in state i and sector s get a separate and independent efficiency draw $h_i(s)$ from a Frechét distribution with location parameter $\xi_r(s)T_i(s)$ and shape parameter θ^s. This allows us to write average international trade cost between i and j across all ports as:

$$\tau_{in}(s) = \left(\sum_{r=1}^{\mathcal{R}} \tau_{in}^{r}(s)^{-\theta(s)} \right)^{-\frac{1}{\theta(s)}}, \tag{15}$$

and the share of country j's total income spent on goods from state i via port r is given by

$$\lambda_{in}^{r}(s) = \frac{\tau_{in}^{r}(s)^{-\theta(s)}}{\tau_{in}(s)^{-\theta(s)}}, \tag{16}$$

such that the trade share shipped through port r is given by: $\pi_{in}^r(s) = \lambda_{in}^r(s)\pi_{in}(s)$. Hence, we can describe trade shares between states and foreign countries exactly as in equation (8) while taking into account the fact that international trade involves multiple ports and international trade costs.

[7] For example, 75 percent of all international freight tons weight traveled by water (US Department of Transportation, 2013).

[8] International trade costs for an importing state and exporting country are symmetric and can be rewritten in a form consistent with equation (14) after changing indices.

Trade Costs and Congestion

Transporting goods between counties in the United States as well as ports for international transshipment involves using segments of the available highway network. This gives rise to potential congestion, which reduces travel speeds and ultimately affects trade costs. Let total absorption of state j in sector s be denoted as $Y_j(s)$ such that total quantity of goods in sector s travelling from i to j is as follows:

$$Q_{ij}(s) = \frac{\pi_{ij}(s)Y_j(s)}{\kappa_{ij}(s)}, \tag{17}$$

Let $\mathcal{C}(s)$ denote one truck capacity of moving quantity of goods in sector s, then trade flows between i and j, including trade when i or j act as a port hub, generate the following traffic:

$$M_{ij}(s) = \frac{Q_{ij}(s)}{\mathcal{C}(s)} \tag{18}$$

Not every segment of the highway network will be affected by $M_{ij}(s)$ but only those that are actually used when transporting goods between i and j. This includes interstate trade as well as transportation of goods between states and ports for international trade. Let $\mathbb{1}_{\mathcal{S},ij}$ denote an indicator function which takes the value of one if piece $\mathcal{S}$ in the set $\boldsymbol{S}$ is used when transporting goods between i and j and zero otherwise. Then total traffic generated by trade in all sectors and across all locations that is relevant for segment $\mathcal{S}$ can be expressed as:

$$N_{\mathcal{S}} = \sum_s \sum_{\mathcal{S}} \mathbb{1}_{\mathcal{S},ij} M_{ij}(s). \tag{19}$$

On the other hand, total traffic on $\mathcal{S}$ affects trade costs in all sectors for all ij pairs for which $\mathcal{S}$ is relevant. Trade costs between i and j in sector s are specified as a product of trade costs on all relevant $\mathcal{S}$. As traffic on each piece affects congestion, the relationship between sectoral trade costs and trade-generated traffic is expressed as follows:

$$\tau_{ij}(s) = \prod_{\mathcal{S}} \mathbb{1}_{\mathcal{S},ij} \tau_{\mathcal{S},ij}(s) \rho_{\mathcal{S},ij}(s), \quad \text{where } \frac{\partial \rho_{\mathcal{S},ij}(s)}{\partial N_{\mathcal{S}}} > 0. \tag{20}$$

Equation (20) assumes that segment-specific component of interstate trade costs consists of $\tau_{\mathcal{S},ij}(s)$ and $\rho_{\mathcal{S},ij}(s)$. The former is determined by exogenous fundamentals of $\mathcal{S}$ such as distance and posted speed and how they translate to sector-specific trade costs. The latter captures endogenous effects related to congestion generated by total interstate and international trade on trade costs. We specify the exact functional form of $\dfrac{\partial \rho_{\mathcal{S},ij}(s)}{\partial N_{\mathcal{S}}}$ in the next section, where we parameterize trade costs and show how they relate to travel time and trade-generated traffic. Equation (20) suggests that there are trade cost spillover effects across sectors due to aggregate traffic: sectors where $M_{ij}(s)$ is relatively high generate congestion and impose higher trade costs on all other sectors.

We assume that the optimal routes between i and j cannot change due to trade-generated congestion effects for three reasons. First, we want to avoid the potential for multiple equilibria that would arise if optimal routes change in response to congestion related to higher or lower trade traffic. Second, given the dimensions of the underlying model and the components of the highway network, allowing exporters to switch routes in response to changes in trade-generated congestion would be computationally infeasible. Finally, for interstate and international trade the gains in travel time associated with having access to Interstate segments is typically substantial such that trade-related traffic reductions in speed are unlikely to affect the chosen route.

Labor Mobility

Labor is mobile within countries subject to migration costs. Workers choose their residence county by maximizing indirect utility, V_i^c, across all possible counties subject to migration costs. In particular, workers located in county $c \in i$ choose to migrate to $m \in j$ if the following holds:

$$\left(V_j^m \delta_{ij}^{cm}\right) \epsilon > V_i^c,$$

where $\delta_{ij}^{cm} \in (0,1)$ is the deterministic component of migration costs and and ϵ is a random component drawn from an extreme value distribution. The share of workers that migrate from $c \in i$ to $m \in j$ can then be written as follows:

$$\omega_{ij}^{cm} = \frac{V_j^m \delta_{ij}^{cm}}{\sum_{k,n} V_n^k \delta_{in}^{ck}} \tag{21}$$

Given migration flows, total labor in each county and state are given by:

$$L_i^c = \sum_{k,n} \omega_{ni}^{kc} L_n^k \text{ and } L_i = \sum_c L_i^c. \tag{22}$$

In this setup, which follows Anderson (2011), the elasticity of migration flows with respect to real income and migration costs is equal to one, which provides an upper bound relative to the case of perfectly immobile labor.[9] In the counterfactual exercises we consider robustness to the case of immobile labor.

TRADE BALANCE AND EQUILIBRIUM

Total expenditures of state i on goods produced in sector s is the combination of demand for final and intermediate goods. Nominal wages are determined at the state level and are equal across all counties $c \in i$ such that the total expenditure can be expressed as follows:

$$Y_i(s) = \sum_{\dot{s}} (1 - \gamma_i(s)) \eta_i(s\dot{s}) \sum_j \pi_{ij}(s) Y_j(s) + \alpha_i(s)(I_i + D_i), \tag{23}$$

where $I_i = \sum_c I_i^c \equiv \sum_c L_i^c w_i$ and D_i is an exogenous deficit constant. Given $Y_i(s)$, we can specify the trade balance condition:

$$\sum_s \sum_n \pi_{ni}(s) Y_i(s) - D_i = \sum_s \sum_n \pi_{in}(s) Y_n(s), \tag{24}$$

which given a numeraire determines wages in all states and countries. This completes the description of the model and allows us to formally define the equilibrium conditions.

Definition 1: *Given primitives $T_i(s)$, $\xi_i^r(s)$, L_i^c, D_i, δ_{ij}^{cm} and trade costs structure $\epsilon_{ij}^{cm}(s)$, $\mathbb{1}_{\mathcal{S},ij}$, $\tau_{\mathcal{S},ij}(s)$, an equilibrium is a vector of wages, $\boldsymbol{w} \in \mathbb{R}_+$, prices, $\{P_i^c(s)\}$ and $\{P_i(s)\}$, such that the conditions in* (4), (5), (6), (8), (9), (12), (15), (17), (18), (19), (20), (21), (22), (23), (24) *are satisfied for all c, i, j, s and $\mathcal{S}$.*

3.3 Counterfactual Equilibrium in Relative Changes

In our counterfactual exercises, we examine the effects of changes in domestic and international trade costs. To do this, it is useful to express the model in relative changes. For convenience, we define the following identity for an arbitrary variable a:

$$\widehat{a} = \frac{a'}{a},$$

[9] See Allen and Arkolakis (2014) for an alternative approach to modeling trade in the presence of labor or factor mobility.

where a' and $\widehat{a}$ denote the counterfactual value of a and the change relative to its benchmark value, respectively. To calculate counterfactual outcomes we use the *hat algebra* approach similar to Dekle, Eaton and Kortum (2007) and Caliendo and Parro (2015).

We start by calculating the counterfactual changes in trade costs relative to the benchmark equilibrium. In particular, we remove certain parts of the highway system in the United States, e.g., the entire Interstate Highway Sytem or individual segments (I-5, I-10, etc) so that producers and consumers are presented with a subset of segments available in the benchmark, $\boldsymbol{S}' \subset \boldsymbol{S}$. Given the new set $\boldsymbol{S}'$ and fundamental characteristics of each segment, producers choose optimal routes to minimize trade costs between states and between states and ports such that we observe counterfactual $\mathbb{1}'_{\mathcal{S},ij}$. This allows us to calculate counterfactual intrastate, interstate, and state-to-port trade costs as:

$$\widehat{\varepsilon}^{cm}_{ij}(s) = \frac{\varepsilon^{cm}_{ij}(s)'}{\varepsilon^{cm}_{ij}(s)}; \;\; \widehat{\tau}_{ij}(s) = \frac{\prod_{\mathcal{S}\in\boldsymbol{S'}} \mathbb{1}'_{\mathcal{S},ij}\tau_{\mathcal{S},ij}(s)'\rho_{\mathcal{S},ij}(s)\widehat{\rho}_{\mathcal{S},ij}(s)}{\tau_{ij}(s)}; \;\; \widehat{\tau}^{r}_{ij}(s) = \widehat{\tau}_{ij}(s)\widehat{\varepsilon}^{m^*r}(s),$$

where all a'- and a-type variables are observed. Given counterfactual values of $\boldsymbol{S}'$ and $\mathbb{1}'_{\mathcal{S},ij}$, a counterfactual equilibrium in changes is characterized by the following conditions:

(*i*) *Changes in county-level costs:* $\widehat{\kappa}^c_i(s) = \widehat{w}_i^{\gamma_i(s)} \left(\prod_{\dot{s}\in S} \widehat{P}^c_i(\dot{s})^{\eta_i(\dot{s}s)}\right)^{1-\gamma_i(s)}$.

(*ii*) *Changes in state-level costs:* $\widehat{\kappa}_{ij}(s) = \left(\sum_c \mu^c_{ij}\left(\widehat{\kappa}^c_i(s)\widehat{\varepsilon}^{cc^*}_{ij}(s)\right)^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}}$.

(*iii*) *Changes in state-level prices:* $\widehat{P}_j(s) = \left(\sum_n \pi_{nj}(s)(\widehat{\kappa}_{nj}(s)\widehat{\tau}_{nj}(s))^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}}$.

(*iv*) *Changes in trade shares:* $\widehat{\pi}_{ij}(s) = (\widehat{\kappa}_{ij}(s)\widehat{\tau}_{ij}(s))^{-\theta(s)}\,(\widehat{P}_j(s))^{\theta(s)}$.

(*v*) *Changes in county-level prices:* $\widehat{P}^m_j(s) = \widehat{P}_j(s)\left(\frac{\sum_n \widehat{\pi}_{nj}(s)\pi_{nj}(s)(\widehat{\varepsilon}^{km^*}_{nj}(s)\varepsilon^{km^*}_{nj}(s))^{-\theta(s)}}{\sum_n \pi_{nj}(s)(\varepsilon^{km^*}_{nj}(s))^{-\theta(s)}}\right)^{-\frac{1}{\theta(s)}}$.

(*vi*) *Changes in state-to-country trade costs:* $\widehat{\tau}_{ij}(s) = \left(\sum_{r=1}^{\mathcal{R}} \lambda^r_{ij}(s)\widehat{\tau}^r_{ij}(s)^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}}$.

(*vii*) *Changes in county-level real wages:* $\widehat{V}^c_i = \widehat{w}_i/\widehat{P}^c_i$.

(*viii*) *Counterfactual migration shares:* $\omega^{cm\prime}_{ij} = \frac{\widehat{V}^m_j\omega^{cm}_{ij}}{\sum_{k,n}\widehat{V}^k_n\omega^{ck}_{in}}$.

(*ix*) *Counterfactual labor force:* $L_i^{c\prime} = \sum_{k,n} \omega_{ni}^{kc\prime} L_n^{k\prime}$ and $L_i' = \sum_c L_i^{c\prime}$.

(*x*) *Counterfactual absorption:* $Y_i(s)' = \sum_{\dot{s}} (1-\gamma_i(s))\eta_i(s\dot{s}) \sum_j \pi_{ij}(s)' Y_j(s)' + \alpha_i(s)(I_i' + D_i)$.

(*xi*) *Counterfactual nominal income:* $I_i' = L_i \widehat{L}_i w_i \widehat{w}_i$.

(*xii*) *Counterfactual state wages:* $\sum_s \sum_n \pi_{ni}(s)' Y_i(s)' - D_i = \sum_s \sum_n \pi_{in}(s)' Y_n(s)'$.

(*xiii*) *Changes in sectoral trade-generated traffic:* $\widehat{Q}_{ij}(s) = \dfrac{\widehat{\pi}_{ij}(s)}{\widehat{\kappa}_{ij}(s)} \dfrac{Y_j(s)'}{Y_j(s)}$.

(*xiv*) *Changes in total trade-generated traffic:* $N_{\mathcal{S}}' = \sum_s \sum_{ij} \mathbb{1}_{\mathcal{S},ij}' M_{ij}(s) \widehat{Q}_{ij}(s)$.

(*xv*) *Changes in state-to-state congestion:* $\widehat{\rho}_{\mathcal{S},ij}(s) = \dfrac{g(N_{\mathcal{S}}')}{g(N_{\mathcal{S}})}$.

We specify the form of the increasing function $g(\cdot)$ in the next section together with information on data sources and the construction of the benchmark variables needed to solve the system in $(i) - (xv)$. Hence, given the structure of counterfactual trade costs, the counterfactual equilibrium is a vector of counterfactual wages and prices such that the system in $(i) - (xv)$ is satisfied for all c, i, j, s and $\mathcal{S}$.

4 Data and Estimation

Solving the model and conducting counterfactuals requires information on trade flows, value-added, employment, migration, consumption shares, and input-output linkages. Crucially, we also need information on trade costs among counties in the United States as well as between US counties and foreign countries. This section describes the underlying data and estimation. We provide additional information on data construction and sources in the Data Appendix. The benchmark year for all variables is 2012 unless noted otherwise.

4.1 Mapping the Model to the Data

We calibrate the model with data on 2,894 counties in the United States including the District of Columbia, but excluding Alaska and Hawaii. We also include 35 other countries and an aggregate that combines data for the rest of the world.[10] In terms of the sectoral coverage, we consider 22 sectors including 12 manufacturing sectors, 8 service sectors, construction, and combined wholesale and retail trade.[11]

Domestic and International Trade Flows

We require data on domestic trade flows between US states and international trade flows between US states and foreign countries. Domestic trade flows are taken from the 2012 Commodity Flow Survey and international trade flows for 2012 are downloaded from the Census Bureau's USA Trade Online tool. We then calculate the expenditure share for each state or country pair, which corresponds to $\pi_{ij}(s)$ in the model. In addition, we use information on trade flows between US states and foreign countries through US ports, which are also draw from the Commodity Flow Survey and USA Trade Online for 2012.

County Employment, Output, and Migration

Data on employment and payroll at the county level are drawn from the County Business Patterns in 2012. We match the initial value of the county-level employment to L_i^c. We use data on L_i^c together with the data on annual payroll to calculate the initial values of $\mu_{ij}^c(s)$ as county output relative to the state total weighted by inverse intra-state trade costs in a given sector. Migration flows between US counties are constructed from Internal Revenue Service data for 2011-2012. In particular, this data aggregates information on the county of residence in 2011 and 2012 from individual tax returns, which we use to calculate ω_{ij}^{cm} from the model.

State Production and Consumption Shares

To construct the value added shares, intermediate input shares, and Cobb-Douglas consumption shares, we use data from the County Business Patterns and World Input-Output Database in 2012. We calculate the value-added share in sector s as the ratio of value-added to output, which corresponds to $\gamma_i(s)$; we calculate the consumption share as the fraction of final consumption in sector s, which gives $\alpha_i(s)$; and we calculate the intermediate input

[10]The countries included are Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, Czech Republic, Germany, Denmark, Estonia, Finland, France, Great Britain, Greece, Hungary, Indonesia, India, Ireland, Italy, Japan, Korea, Lithuania, Mexico, the Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Turkey, and Taiwan.

[11]The Data Appendix describes the mapping from the sectors listed in the North American Industry Classification System (NAICS) or World Input-Output Database (WIOD) to the 22 sectors we consider in this paper.

shares as the fraction of the intermediate input usage of sector $\dot{s}$ sourced from sector s, which is $\eta_i(s\dot{s})$. In each case, the parameters are specific to a state or country i.

4.2 Constructing Trade Costs

The starting point for constructing trade costs is detailed information on the US highway network shown in Figure 2. We use the highway network, domestic navigable waterways, international shipping lanes, and trade flows to construct the domestic and international trade cost components used to calibrate the model.

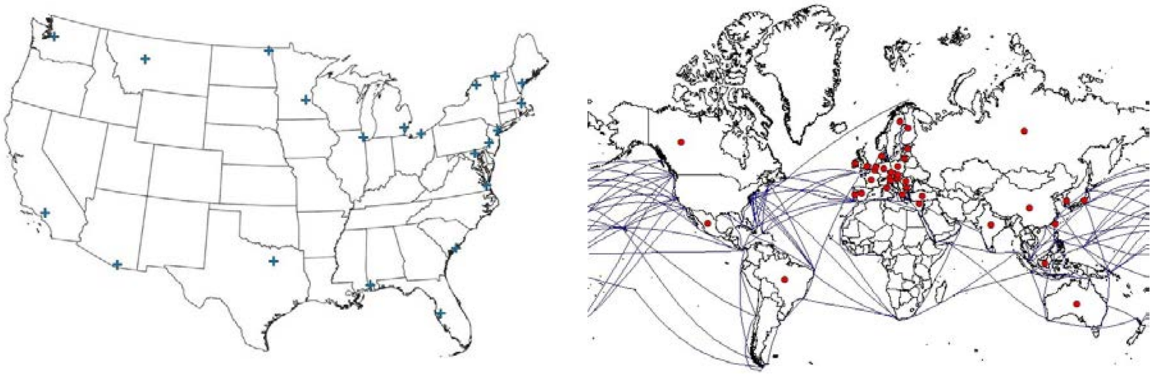
Data for Domestic and International Trade Costs

The key inputs into the domestic trade cost components are the travel time and distance between US county pairs as well as the travel time and distance between US counties and US ports. To construct these inputs we represent each location as the geographic county centroid or centroid of the county in which a port is located. Each county or port centroid is connected to the US highway network via an access road network. Each of the roughly 650,000 pieces of the highway network is assigned a speed based on its classification, specifically, we assign 70, 55, and 45 miles per hour to the components of the Interstate Highway System, US highways, and state highways, respectively, and 10 miles per hour to the access road network.[12] Next we use the highway network to identify the routes and corresponding travel time underlying the domestic trade costs components in Figure 3, including interstate (τ_{ij}) and intrastate ($\varepsilon_{ij}^{cc^*}$ and $\varepsilon_{ij}^{m^*m}$) trade costs.

To calculate the international trade cost component we use information on the location of 21 US ports, domestic navigable waterways, and international shipping lanes between US ports and 35 foreign trading partners. US ports are shown in Panel A of Figure 4 and shipping lanes are presented in Panel B of Figure 4. Using this data we calculate the minimum distance route between each port and country. This corresponds to the international trade cost component (t_{ik}) in Figure 3. The combined domestic and international trade cost components can be used to construct the trade costs between any pair of locations in the model.

[12]To find the county centroids we overlay shapefiles for county boundaries in 2012 using shapefiles from the US Census Bureau (2012) and identify the geographic centroid. Jaworski and Kitchens (2019) find that using population-weighted county centroids or assigning alternate speeds to the components of the highway network does not lead to substantially different results.

Figure 4: US Ports and International Sea Shipping Routes



A. US Ports B. Sea Shipping Routes

Notes: This figure shows the portions of the transportation network that contribute to international trade costs. Panel A shows the location of US ports. Panel B shows the international shipping lanes and country centroids.

Estimation of Trade Elasticity Parameter

A key input for constructing trade costs and performing quantitative analysis is the set of parameters governing the dispersion of productivity within sectors, $\theta(s)$. Importantly, values for these parameters determine the elasticity of trade flows with respect to trade costs. We use information on domestic trade flows between state i and state j to estimate the following equation using ordinary least squares:

$$\ln\left(\frac{\pi_{ij}(s)}{\pi_{ii}(s)}\frac{\pi_{ji}(s)}{\pi_{jj}(s)}\right) = \phi(s)\ln\left(\tau_{ij}(s)\right) + \epsilon_{ij} \tag{25}$$

Following Head and Ries (2001), the transformation of the dependent variable eliminates the challenge associated with estimating fixed effects for each state i and state j. To estimate equation (25), we assume that $\kappa_{ij}(s)$ can be approximated as a product of i-specific, j-specific components, and the residual term captured in ϵ_{ij}. The coefficient of interest, $\phi(s)$, is interpreted as $-2 \times \theta(s)$.

Estimating $\phi(s)$ requires observable information on trade costs rather than relying on a parameterization. To do this, we construct a measure of τ_{ij} that is valid in the benchmark equilibrium as in Combes and Lafourcade (2005). We combine information on the time and distance of moving goods between state i and state j. In particular, we use the labor cost determined by the average hourly wage of a truck driver and the fuel cost based on the price

Table 1: Estimates of $\phi(s)$ and $\theta(s)$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
$\phi(s)$	-21.7	-10.0	-15.2	-34.5	-28.1	-21.5	-8.7	-19.9	-20.3	-20.4	-39.9	-8.8
	(1.66)	(1.39)	(0.98)	(5.16)	(2.93)	(1.69)	(0.91)	(1.72)	(3.13)	(3.50)	(6.09)	(0.76)
$\theta(s)$	10.9	5.0	7.6	17.3	14.0	10.8	4.3	10.0	10.2	10.2	19.9	4.4
	(0.83)	(0.69)	(0.49)	(2.58)	(1.46)	(0.85)	(0.46)	(0.86)	(1.56)	(1.75)	(3.04)	(0.38)
Observations	1,824	1,502	1,898	768	1,912	1,870	1,252	1,984	1,806	1,708	1,340	1,882

Notes: The table shows estimates of $\phi(s)$ using equation (25) and implied estimates of $\theta(s)$ for each sector s. The dependent variable is the Head and Ries (2001) transformation of trade shares referred to in the text. Standard errors clustered on origin and destination state are reported in parentheses. Column 1 is Food, Beverage, and Tobacco, Column 2 is Textiles and Leather, Column 3 is Wood, Paper, and Printing, Column 4 is Petroleum and Coal, Column 5 is Chemicals, Column 6 is Plastics and Rubber, Column 7 is Nonmetallic Minerals, Column 8 is Primary and Fabricated Metals, Column 9 is Machinery, Column 10 is Computers, Electronics, and Electrical, Column 11 is Transportation Equipment, and Column 12 is Furniture and Miscellaneous. The number of observations in each column reflect the number of state origin-destination pairs with non-zero trade flows.

of fuel per gallon together with fuel usage per mile to calculate:

$$\tau_{ij}(s) = 1 + \frac{\text{hours}_{ij} \times \text{wage per hour} + \text{miles}_{ij} \times \text{cost per mile}}{\text{average value of shipment in sector } s} \tag{26}$$

where the denominator is the average value of a shipment in sector s taken from the Commodity Flow Survey in 2012. The hourly wage for a truck driver and fuel cost per mile, respectively, are calculated with data from the decennial census (Ruggles, Alexander, Genadek, Goeken, Schroeder, Sobek et al., 2010) and US Census Bureau (2010).

Table 1 shows the results of estimating $\phi(s)$ and the implied estimate of $\theta(s)$ for each of the 12 manufacturing sectors. Two-way clustered standard errors on states i and j are reported in parentheses. The results reveal substantial variation across sectors: the estimates of $\theta(s)$ range between 4.35 for *Nonmetallic Mineral Products* and 19.94 for *Transportation Equipment*, are statistically significant at the 1 percent level, and are consistent with existing estimates in the literature. Our approach is different from but complementary to alternative approaches used in the international trade literature. For example, Caliendo and Parro (2015) use data on international trade flows and exploit variation in tariffs to estimate $\theta(s)$.[13] Instead, we combine the Head and Ries (2001) approach with domestic trade flows and exploit variation in interstate trade costs. Finally, we assign the average value of these estimates to the sectors where trade flow data is not available.

[13] Caliendo and Parro (2015) report estimated values of $\theta(s)$ that range between 0.37 and 51.08 for manufacturing sectors.

Parameterizing Domestic Trade Costs and Congestion

We parameterize domestic trade costs as a function of shipping time via the highway network. In particular, we estimate the following equation using Poisson Pseudo Maximum Likelihood for each sector s:

$$\pi_{ij}(s) = \exp\left[\varphi(s)\text{time}_{ij} + exp_i(s) + imp_j(s)\right] + \epsilon_{ij} \tag{27}$$

where $\pi_{ij}(s)$ is the trade share, $exp_i(s)$ and $imp_j(s)$ are sector-specific fixed effects, and time_{ij} is the minimum travel time (in hours) between state i and state j. This captures transportation costs and other trade barriers associated with time (see Hummels and Schaur, 2013).

The results of estimating $\varphi(s)$ for each sector s are shown in Table 2, where standard errors clustered on states i and j are reported in parentheses. The results indicate substantial heterogeneity across sectors, with estimates of $\varphi(s)$ ranging from -0.051 for *Computer, Electronic Products, and Electrical Equipment* to -0.344 for *Petroleum and Coal Products*. This is consistent with intuition that trade flows for relatively high value and light weight goods will be less responsive to shipping time, while cheaper and heavier goods are more sensitive to shipping time.

Table 2: Estimates of $\varphi(s)$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
$\varphi(s)$	-0.169	-0.066	-0.184	-0.344	-0.108	-0.106	-0.273	-0.131	-0.073	-0.051	-0.099	-0.082
	(0.017)	(0.016)	(0.010)	(0.045)	(0.015)	(0.015)	(0.026)	(0.013)	(0.007)	(0.013)	(0.016)	(0.008)
Observations	2,401	2,401	2,401	2,401	2,401	2,401	2,401	2,401	2,401	2,401	2,401	2,401

Notes: The table shows estimates of $\varphi(s)$ using equation (27) for each sector s. The dependent variable is the trade shares between state i and state j. All specifications include state importer and exporter fixed effects. Standard errors clustered on origin and destination state are reported in parentheses. Column 1 is Food, Beverage, and Tobacco, Column 2 is Textiles and Leather, Column 3 is Wood, Paper, and Printing, Column 4 is Petroleum and Coal, Column 5 is Chemicals, Column 6 is Plastics and Rubber, Column 7 is Nonmetallic Minerals, Column 8 is Primary and Fabricated Metals, Column 9 is Machinery, Column 10 is Computers, Electronics, and Electrical, Column 11 is Transportation Equipment, and Column 12 is Furniture and Miscellaneous.

Combining the results from Tables 1 and 2 we use estimates of $\theta(s)$ and $\varphi(s)$ to construct trade costs between state i and state j according to:

$$\tau_{ij}(s) = \exp\left(-\frac{\hat{\varphi}(s)}{\hat{\theta}(s)}\text{time}_{ij}\right),$$

where time_{ij} is calculated as described in equation (2) in Section 2. This specification is consistent with our theoretical model in the sense that the following equation is satisfied,

$$\tau_{ij}(s) = \tau_{ik}(s)\tau_{kj}(s) = \exp\left(-\frac{\hat{\varphi}(s)}{\hat{\theta}(s)}(\text{time}_{ik} + \text{time}_{kj})\right).$$

We can now characterize the exact functional form for the relationship between trade-generated congestion and trade costs. Intuitively, higher trade-generated traffic increases the level of service (LOS), which decreases speed and increases travel time. To estimate this relationship, we calculate $N_{\mathcal{S}}$ following equations (17), (18), and (19), where we measure the benchmark value of M_{ij} using the Commodity Flow Survey in 2012. We then estimate the following regression:

$$\ln \text{LOS}_{i\mathcal{S}} = \zeta \ln N_{\mathcal{S}} + \nu \ln \text{distance}_{\mathcal{S}} + \text{state}_i + \epsilon_{i\mathcal{S}}, \tag{28}$$

where $\text{distance}_{\mathcal{S}}$ is the length $\mathcal{S}$ in miles and state_i is a set of indicators that equal one if $\mathcal{S}$ is used for transporting goods to or from state i and zero otherwise. We report the results in Table **3**.

Table 3: The Relationship Between LOS and Traffic

$\ln N_{\mathcal{S}}$	0.097
	(0.029)
$\ln \text{distance}_{\mathcal{S}}$	-0.034
	(0.006)
Observations	73,874

Notes: The table shows the results of estimating (28) on all highway segments with positive traffic. The dependent variable is the level of service (LOS) on segment $\mathcal{S}$ in state i. The log of $N_{\mathcal{S}}$ reflects the amount of trade-related traffic on $\mathcal{S}$ and the log of $\text{distance}_{\mathcal{S}}$ is the distance (in miles) of segment $\mathcal{S}$. The specification also includes state_i, which is a set of indicators equal to one if $\mathcal{S}$ is used for transporting goods to or from state i and zero otherwise. Standard errors are clustered on the combination of highway type (e.g., IHS, other federal, and state) and the associated numbered segment.

The estimated coefficient ζ is 0.097 with a standard error of 0.029 so that a 1 percent increase in trade-generated traffic increases the level of service by 0.097 percent. This allows us to construct the counterfactual level of service for each $\mathcal{S}$ according to:

$$\text{LOS}'_{\mathcal{S}} = (\widehat{N}_{\mathcal{S}})^{0.097}\text{LOS}_{\mathcal{S}}.$$

Using $\text{LOS}'_{\mathcal{S}}$ we can calculate the counterfactual congestion speed coefficient $\mathcal{A}'_{\mathcal{S}}$ following the step function in equation (1), the counterfactual value of $\rho_{\mathcal{S},ij}(s)$, and the functional form of $g(\cdot)$.

Calibrating State-Port Trade Shares

The remaining component required for the counterfactual analysis are state-port-country shares, $\lambda^r_{in}(s)$, which are not directly observed in the data. To overcome this limitation, we use the predictions of the theoretical model together with a parameterization of international trade costs to calibrate $\lambda^s_{in}(s)$ from the data at a higher aggregation level. In particular, we combine data on total sectoral shipments from each state to each of the 21 US ports with data on total sectoral shipments from each port to each foreign country.

The first data set describes shipments from each US state i to each US port $r \in j$ and corresponds to the following equation in the context of our theoretical framework:

$$\Lambda^r_i(s) = \sum_{n \neq i} \pi^r_{in}(s) Y_n(s) = \sum_{n \neq i} T_i(s) \left(\kappa_{ij}(s)\tau_{ij}(s)\varepsilon^{m^*r}_{ij}(s)\xi^r_j(s)t_{jn}(s)\right)^{-\theta(s)} P_n(s)^{\theta(s)} Y_n(s).$$

The second data set describes shipments from each US port to each foreign trading partner. In the context of our theoretical model, the following equation describes shipments between port $r \in j$ and country n (for $n \neq i$):

$$\text{V}^r_n(s) = \sum_{i \neq n} \pi^r_{in}(s) Y_n(s) = \sum_{i \neq j} T_i(s) \left(\kappa_{ij}(s)\tau_{ij}(s)\varepsilon^{m^*r}_{ij}(s)\xi^r_j(s)t_{jn}(s)\right)^{-\theta(s)} P_n(s)^{\theta(s)} Y_n(s)$$

To isolate the parameters of interest, we first pre-multiply $\Lambda^r_i(s)$ by $(\tau_{ij}(s)\varepsilon^{m^*r}_{ij}(s))^{\theta(s)}$ and then use Poisson Pseudo Maximum Likelihood to estimate the following equation using data on trade flows from each US state i to each US port j separately for each sector s:

$$\Lambda^r_i(\tau_{ij}(s)\varepsilon^{m^*r}_{ij}(s))^{\theta(s)} = \exp\left(\text{state}_i(s) + \text{iport}_r(s)\right) + \epsilon_{ir}(s), \tag{29}$$

where $\text{state}_i(s)$ and $\text{iport}_r(s)$ are sector-state-specific and sector-port-specific fixed effects. We then estimate the following equation (again, with Poisson Pseudo Maximum Likelihood) using data on trade flows between each US port r and each foreign trading partner j:

$$\text{V}^r_n(s) = \exp\left(\text{xport}_r(s) + \sum_{q=1}^{5} \psi_q(s)\mathcal{Q}_q \ln(\text{distance}_{rn}) + \text{country}_n(s)\right) + \epsilon_{rj}(s) \tag{30}$$

where $\text{xport}_r(s)$ and $\text{country}_n(s)$ are sector-port-specific and sector-country-specific fixed effects. We parameterize international trade costs via water using the (log) distance in miles between port r and country n and allow this to vary with indicators for each quintile $\mathcal{Q}_q$. The estimated coefficients on the indicator variables are reported in Figure A1 in the Appendix.

The estimates from equations (29) and (30) allow us to calibrate international trade costs, $t_{rj}(s)^{-\theta^s}$, and the sector-port-specific productivity level, $\xi_j^r(s)$, as follows:

$$t_{rj}(s)^{-\theta^s} = \sum_{q=1}^{5} \hat{\psi}_q \mathcal{Q}_q \ln(distance_{rj}) \text{ and } \xi_i^r(s)^{-\theta^s} = \frac{\exp\left(\widehat{\text{xport}_r}\right)}{\sum_i \exp\left(\widehat{\text{state}_i}\right)(\tau_{ij}(s)\varepsilon_{ij}^{m^*r}(s))^{-\theta(s)}}.$$

Note that for estimation purposes only, we assume that $\kappa_{ij}(s)$ can be approximated by an i-specific fixed effect plus an ij-specific term captured by the residual. Once we have recovered $t_{rj}(s)^{-\theta^s}$ and $\xi_j^r(s)$, we calculate exporter-port-importer shares by sector as follows:

$$\lambda_{in}^r(s) = \frac{(\tau_{ij}(s)\varepsilon_{ij}^{m^*r}(s)\xi_j^r(s)t_{jn}(s))^{-\theta(s)}}{\tau_{in}(s)^{-\theta(s)}}. \tag{31}$$

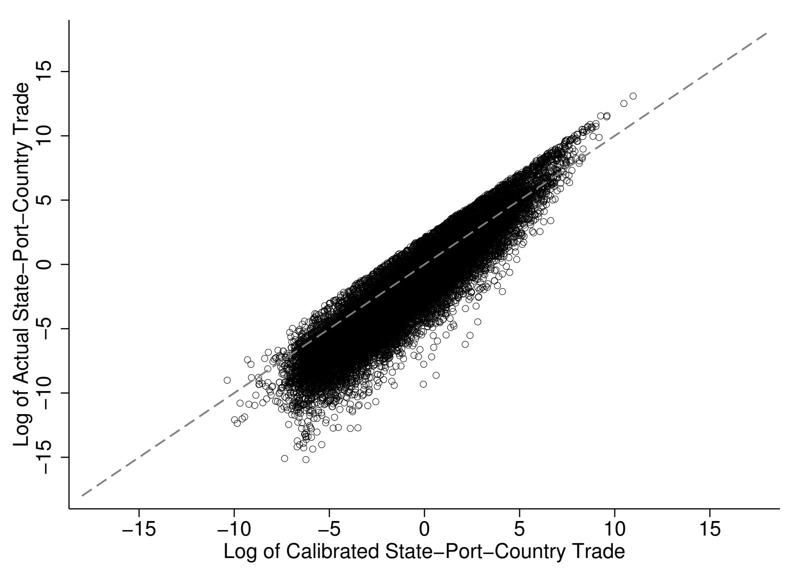
Since we do not directly observe $\lambda_{in}^r(s)$ in the data and must rely on the decomposition above, it is useful to validate how the calibrated values of $\lambda_{in}^r(s)$ align with the available aggregate data.

We compare the predictions of the model to other data available from USA Trade Online not used in the estimation or calibration. These data include information on total exports from each US state via each US port with each foreign country. We use the port share estimates, $\lambda_{ij}^r(s)$, multiplied by bilateral sectoral trade flows and aggregated over sectors to predict total exporter-port-importer trade flows. These predictions (in log) are then compared to the corresponding actual data (in log). The results in Figure 5 suggest that our calibration of $\lambda_{in}^r(s)$ matches the data well. The correlation between (log) predicted and (log) actual aggregate state-port-country trade flows is 0.92.

5 Results

The first set of counterfactual exercises quantify the losses from removing the entire Interstate Highway System. We eliminate segments that belong to the IHS from the available road network $\boldsymbol{S}' \subset \boldsymbol{S}$ such that producers are forced to re-optimize and face higher trade costs relative to the benchmark equilibrium. This holds for all domestic and portions of

Figure 5: Calibrated versus Actual State-Port-Country Shares



Notes: The figure shows the relationship between calibrated (x-axis) and actual (y-axis) exporter-port-importer trade shares together with the 45 degree line. The calibrated shares are constructed by summing $\lambda_{in}^{r}(s)$ from the model over s. The actual shares are aggregated data from USA Trade Online that were not used in calibration.

international trade costs that depend on the US transport network. The second set of counterfactual exercises quantify the losses from removing individual segments of the IHS (I-5, I-10, etc). For these counterfactuals we focus on the twenty longest segments (in miles).

Finally, for each counterfactual we also decompose the aggregate effect into the contribution of domestic versus international trade costs components. To do this, we quantify the losses associated with counterfactual changes in $\boldsymbol{S}$ applied only to interstate trade costs within the United States. The international component is then calculated as the difference between the total and domestic components, which we interpret as the marginal welfare effect of changes in international trade costs due to exogenous changes in US highway network.

5.1 Removing the Entire IHS

The baseline counterfactual results are shown in the first row of Table 4. Column 1 reports that in the absence of the IHS–including nearly 50,000 miles of limited-access roads graded for high travel speeds–real GDP losses are equal to \$619.1 billion in 2012 dollars (or 3.9 per-

Table 4: Total Losses from Removing the IHS

	Total (1)	Domestic (2)	International (3)
Baseline, No IHS	619.1	459.9	159.3
No Congestion	564.4	426.9	137.5
No Migration	614.9	456.1	158.8
No Input-Output	248.4	182.9	65.4

Notes: The table shows results from counterfactual exercises removing the Interstate Highway System. Column 1 shows the reduction in real GDP from removing the IHS for both the domestic and international components of trade costs. Column 2 shows the reduction in real GDP from removing the IHS domestic components of trade costs. Column 3 shows the difference between columns 1 and 2, which is he reduction in real GDP from removing the IHS foreign components of trade costs. The results in row 1 are for the baseline version of the model. The remaining rows show results for versions of the model with no congestion (row 2), no migration (row 3), and no input-output linkages (row 4).

cent).[14] The remaining columns decompose this aggregate effect from removing the IHS for routes associated with all US trade into the domestic (column 2) and international (column 3) components, respectively, \$459.9 and \$159.3 billion. It is noteworthy that the international component of trade costs accounts for roughly one quarter of the total losses from removing the IHS. The total and decomposed losses presented in row 1 indicate both that the value of the IHS is substantial and that the access it provides to international markets is quantitatively important.

To quantify the importance of different channels in driving the total welfare results, we conduct three additional experiments where we turn off migration, trade induced traffic congestion, and input-output linkages one at a time. The second and third rows of Table 4 show alternative versions of the baseline model without congestion and no labor mobility. As noted above, approximately 18,000 miles of the Interstate Highway System are considered to be congested. In row 2 we remove congestion as a mechanism in the model that reduces the speed of travel on roads with more traffic and also eliminate the potential for the reallocation of traffic in response to changes in the highway network. The results suggest that the effects of trade related congestion are nearly \$55 billion or 9 percent of total effect in row 1. This means that trade-generated congestion costs are \$175 per person. These costs are large, but smaller than those estimated from surveys (e.g., INRIX Research, 2019). The difference between our results and the implied congestion costs derived from surveys may reflect the

[14] These estimates are larger than existing estimates in the literature. For example, our estimates are about three times larger than the \$150 to \$200 billion reported by Allen and Arkolakis (2014). For international context, our estimates are up to twice as large as the impact of India's Golden Quadrilateral (Alder, 2017; Asturias, García-Santana and Ramos, 2019).

difference between our focus on trade-related congestion and the congestion faced by urban commuters. Integrating these two sources of congestion in a consistent theoretical framework and quantifying their effects is an important avenue for future research.

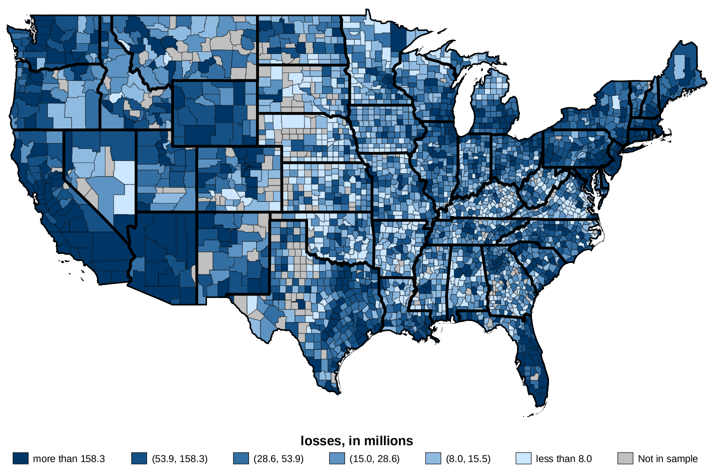
The results in row 3 do not allow for migration in response to the changes in the highway network from removing the IHS. The total and decomposed losses are similar to the baseline counterfactual with migration; the difference between the baseline and "no migration" scenarios is less than $5 billion or 1 percent of the total effect. This suggests that migration may be less important in the context of our counterfactuals where productivity and local amenities are fixed and migration is costly. If, alternatively, we allowed for changes of the fundamental characteristics of locations in response to counterfactual changes in the highway network we would expect the associated losses to be larger in the absence of migration.[15]

An important feature of our model is the presence of many sectors and linkages across sectors through input-output relationships. This may be particularly important in the context of transportation infrastructure as better road networks allow remote locations specialize in specific sectors, which improves overall efficiency. For example, Hornbeck and Rotemberg (2019) and Asturias, García-Santana and Ramos (2019), respectively, find substantial gains from allocative efficiency associated with improvements in railroads in the United States during the late nineteenth and early twentieth centuries and roads in India more recently. The fourth row of Table 4 presents results of removing the IHS without the input-output structure linking sectors in the full model. In this case the results differ substantially from the baseline results. Instead of $619.1 billion reported in row 1, the total losses in row 4 are $248.4 billion and the decomposed losses are $182.9 and $65.4 billion, respectively, for the domestic and international components of trade costs. This highlights the importance of sectoral heterogeneity, spatial specialization patterns, and the input-output linkages for understanding the effects changes in the US highway network. In addition, the results in row 4 more closely match the results obtained by Allen and Arkolakis (2014) for a similar counterfactual exercise. These authors estimate losses from removing the IHS between $150 and $200 billion in 2007 dollars. We obtain results that fall in this range when we eliminate intermediate inputs from the model and focus only on the effect of the domestic trade cost components.

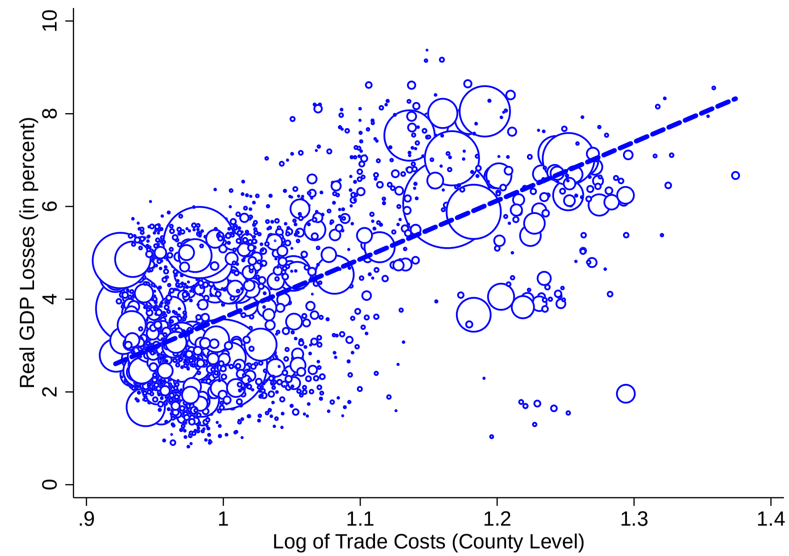
Panel A of Figure 6 illustrates the geographic distribution of the total effects from removing the IHS at the county level. The largest total losses are concentrated in the northeastern and western regions of the United States. Across the 2,894 counties in the sample, all expe-

[15]See recent work by Heblich, Redding and Sturm (2020) and Brinkman and Lin (2019) on the effects of transportation infrastructure on the fundamentals within cities.

Figure 6: Losses from Removing the IHS by County



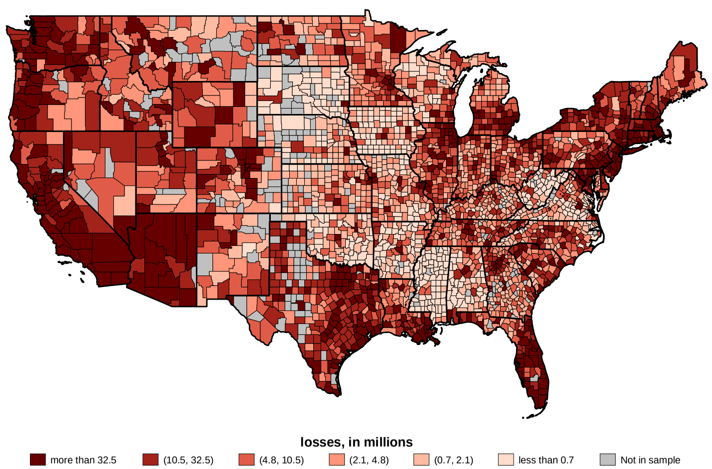
A. Contribution of All Trade Costs to the Reduction Real GDP



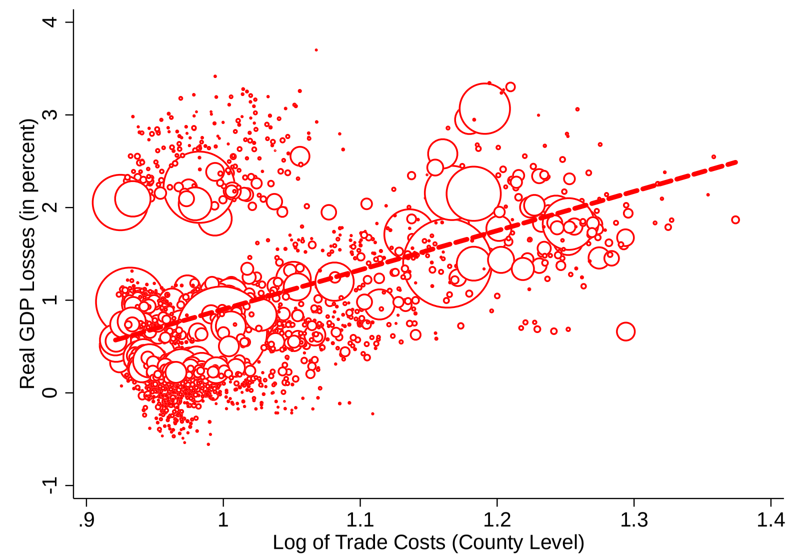
B. Reduction of Real GDP and All Trade Costs

Notes: The figure shows the results for removing the Interstate Highway System at the county level. Panel A shows the geographic distribution of the reduction in real GDP (in percent) from removing the IHS for both the domestic and international components of trade costs. Panel B shows the relationship between the reduction in real GDP from removing the IHS for all trade cost components and the level of actual trade costs in 2010.

Figure 7: Losses from Removing the International Trade Cost Component of the IHS by County



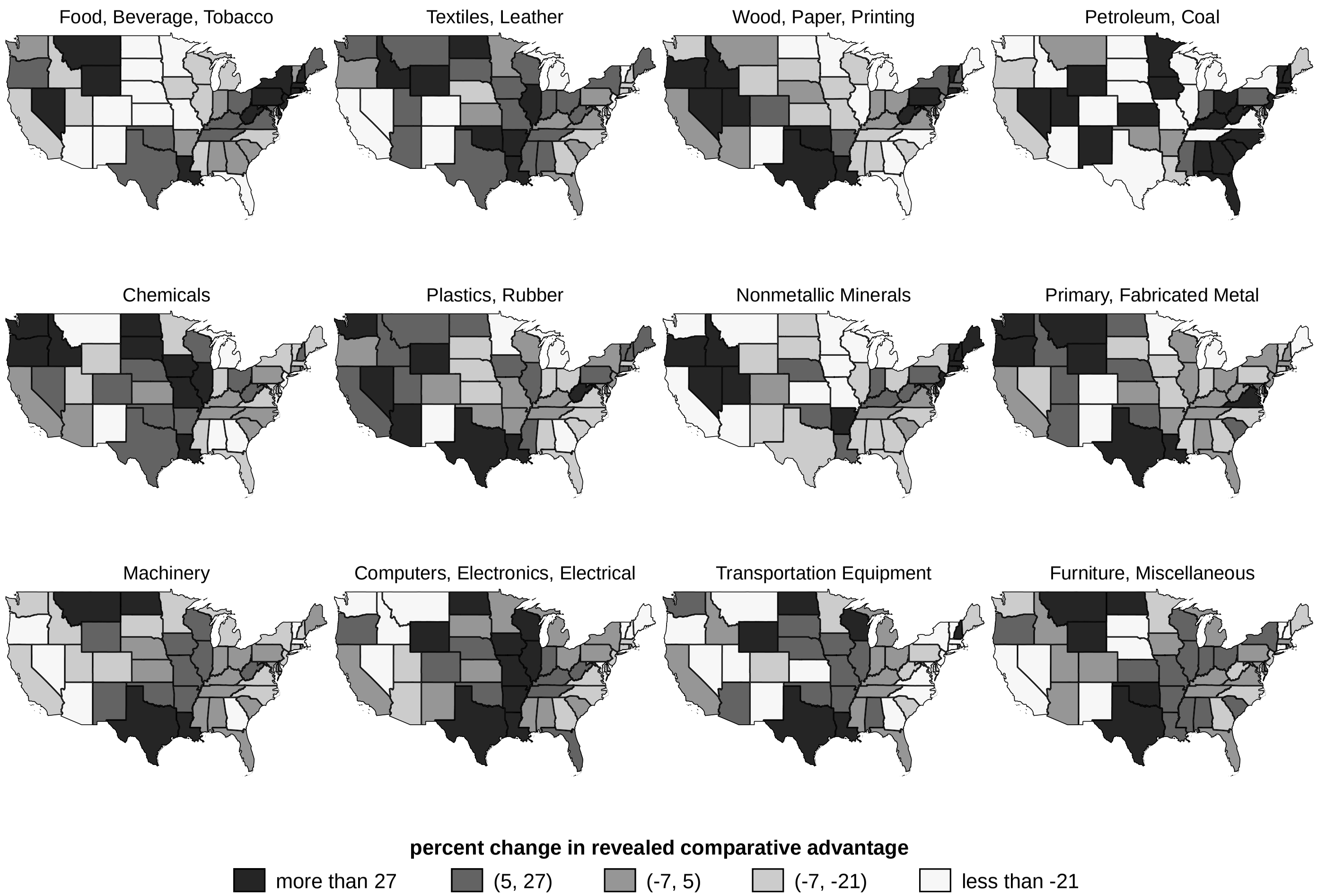
A. Contribution of Foreign Trade Costs to the Reduction Real GDP



B. Reduction of Real GDP and Foreign Trade Costs

Notes: The figure shows the decomposition results for removing the Interstate Highway System due to the contribution of the international trade cost components at the county level. Panel A shows the geographic distribution of the reduction in real GDP (in percent) from removing the IHS for the international components of trade costs. Panel B shows the relationship between the reduction in real GDP from removing the IHS for the international trade cost components and the level of actual trade costs in 2010.

Figure 8: The Effect of Removing the IHS on Revealed Comparative Advantage by State



Notes: The figure shows the change (in percent) in revealed comparative advantage from removing the IHS for both the domestic and international components of trade costs at the state level for twelve manufacturing sectors. Revealed comparative advantage is calculated as in Balassa (1965): $(E_i(s)/\sum_{s'} E_i(s'))/(\sum_{i'} E_{i'}(s)/\sum_{i',s'} E_{i'}(s'))$.

rience at least some loss, while the average loss is \$213.9 million. Panel B of Figure **6** shows the relationship between the log of actual trade costs in 2010 and the losses (in percent) from removing the IHS, which indicates that losses are concentrated in counties that are more remote from domestic and international markets. Figure **7** shows the losses attributed to removing the IHS for the international component of trade costs. These losses overlap in some counties, but other counties are affected differently by the changes in domestic versus international trade costs due to the IHS–the correlation between the domestic and foreign components (in percent) is 0.294. This suggests that the IHS plays different roles in facilitating trade across US counties and states. For example, total losses of \$71.4 billion for Texas are split more evenly between domestic and international trade costs (\$40.8 and \$30.6) than in smaller state economies, e.g., Alabama, where losses from the change in the domestic trade cost component are substantially more important.

Finally, Figure **8** shows the effect of removing the IHS on revealed comparative advantage (see Balassa, 1965) for the twelve manufacturing sectors across US states. In general, we expect to observe changes in revealed comparative advantage that reflect trade cost minimizing decisions on the part of producers that balance the access to input and output markets. For example, in some sectors (e.g., *Transportation Equipment*), states in the middle of the country export relatively more to other states and countries in the absence of the IHS. This change partially reflects proximity to final goods consumers as well as proximity to suppliers. For other sectors (e.g., *Food, Beverage, and Tobacco*), states on the coast export relatively more without access to the IHS. These findings complement work by Michaels (2008) and Duranton, Morrow and Turner (2014) that documents changes in industrial composition and exports in response to trade costs.

5.2 Removing Individual IHS Segments

The results in the previous subsection focus on removing the entire IHS. From the perspective of policymaking, it is also useful to address smaller changes in the highway network that quantify the value of individual segments and can thus serve as a guide for the allocation of funding for new construction, improvements, and maintenance. To do this, in this subsection, we consider counterfactual exercises that remove twenty longest highways of the IHS illustrated in Figure **9**. This will shed light on the aggregate benefits of improving individual segments, the distribution of those gains across US states, and variation in the importance of the access provided to domestic versus international markets.

In this exercise, we focus on the losses associated with the twenty longest Interstate

Figure 9: Location of the Twenty Longest IHS Segments by Length

A. I-10, I-15, I-25, I-40, I-70, I-75, I-80, I-90, I-94, I-95

B. I-5, I-20, I-29, I-35, I-44, I-55, I-64, I-65, I-81, I-85

Notes: This figure shows the twenty longest of Interstate Highway System in miles. Panel A shows the ten longest segments including I-10, I-15, I-25, I-40, I-70, I-75, I-80, I-90, I-94, and I-95. Panel B shows the remaining segments including I-5, I-20, I-29, I-35, I-44, I-55, I-64, I-65, I-81, and I-85.

Highway System segments by mileage in 2010. For these counterfactuals, we remove all sections of the corresponding numbered interstate and allow traffic to adjust endogenously to changes in trade costs. The results are presented in Table 5. Column 1 gives the total length in miles of each segment. Columns 2 and 3 report the total and per mile reduction in real GDP from removing each IHS segment, while fixing the rest of the highway network. For these twenty segments, the total losses range from $55.1 billion for I-5 to $2.7 billion for I-25. The four segments with the next largest losses after I-5 are I-10, I-40, I-80, and I-90.[16]

A few details are noteworthy. First, both I-5 and I-10 stand out with losses that are substantial relative to the other IHS segments. This reflects a combination of the lack of available alternate routes along the Pacific Coast or between the southwest and southeast United States, respectively. Looking at the losses by numbered interstate, either on an aggregate or per mile basis reveal few patterns, however, the four primary east-west routes (I-10, I-40, I-80, and I-90) and coastal routes (I-5) are clearly the most valuable.[17] Coming back to the substantial losses associated with the removal of I-5 or I-10, it is clear from Columns 4 and 5 that these interstates generate a significant portion of their value by facilitating international trade. The $11.2 billion in international trade generated by I-5 is larger than the total value generated by several of the segments considered in Table 5. These results suggest that segments linking US states to Canada, Mexico, and other ports of entry derive a large share of their gains from international market access and are more valuable in general.

Finally, in addition to these aggregate results, it is useful to highlight variation in the losses across US states. For example, removing I-5 generates $55.1 billion in total losses, but losses for California, Oregon, and Washington together are $58.9 billion and gains accrue to the remaining states as trade and economic activity are reallocated to other locations. We can also see that even among states that are directly affected by the removal a highway, there can be substantial differences in losses. For example, removing I-95 reduces real GDP in Maine by 2.5 percent and Massachussetts by less than 0.5 percent. These findings are important in the event that highway funding model in the United States is revised.

In general, the results in this subsection are useful for prioritizing spending on new

[16]There are two cases in Table 5 where the international losses (in column 5) are *negative*, i.e., for I-20 and I-55. These two cases in which removing highway segments for the international component of trade costs results in aggregate gains for the US economy suggest that the international component of trade costs associated with these highway segments leads to reallocation abroad that reduces real GDP. That said, it is important to emphasize these effects are small and this is not a pattern that emerges at all from the total losses (in column 2) or in the vast majority segment for international losses (in column 5).

[17]These numbered routes roughly correspond to the proposed system of interstate highways by Franklin D. Roosevelt in 1938 (Department of Transportation, 1967).

Table 5: Results for Removing IHS Segments

Interstate Highway Segment:	Total Miles (1)	Total, in billions (2)	Total Per Mile, in millions (3)	Domestic, in billions (4)	International, in billions (5)
I-5	1386.2	55.1	39.7	43.8	11.2
I-10	2452.2	42.7	17.4	33.7	9.0
I-15	1437.7	18.5	12.8	15.2	3.3
I-20	1507.0	5.1	3.4	5.7	-0.7
I-25	1065.1	2.7	2.5	2.4	0.3
I-29	751.0	2.8	3.7	1.9	0.8
I-35	1428.2	20.6	14.4	17.0	3.6
I-40	2528.3	30.6	12.1	27.5	3.1
I-44	628.7	6.9	10.9	6.2	0.6
I-55	932.6	4.3	4.6	6.0	-1.7
I-64	888.6	4.4	4.9	3.7	0.7
I-65	889.5	6.3	7.0	5.2	1.0
I-70	2066.0	15.3	7.4	13.5	1.9
I-75	1752.2	14.0	8.0	10.2	3.7
I-80	2875.1	30.5	10.6	25.5	5.0
I-81	815.5	7.5	9.2	6.2	1.3
I-85	631.3	4.0	6.4	2.6	1.4
I-90	2796.6	27.9	10.0	23.8	4.1
I-94	1479.5	5.3	3.6	4.4	1.0
I-95	1888.1	26.2	13.9	21.0	5.3

Notes: The table shows results from counterfactual exercises removing the twenty longest individual segments (in miles) of the Interstate Highway System. Column 1 shows the total number of miles. Columns 2 and 3 show the total and per-mile reduction in real GDP, respectively. Columns 4 and 5 show the portion of the total reduction attributed to the domestic and international components of trade costs, respectively.

construction, improvements, and maintenance, as well as understanding the distributional consequences of these decisions. For example, currently there are 18 high priority corridors designated as future interstates, and portions of four highways that will be upgraded and integrated into the IHS. The approach and results from this paper can serve as a guide for which segments will provide the largest gains, the sources of these gains, and can help understand the distributional consequences across regions and sectors.

6 Conclusion

Domestic transportation infrastructure facilitates trade within countries and international trade with the rest of the world. This suggests that the value of domestic transportation infrastructure reflects its contribution to both types of market access. For the United States, a key part of the domestic transportation infrastructure is the nearly 50,000 limited-access high-grade road miles that make up the Interstate Highway System. Despite the vital role that these highways play in both domestic *and* international trade, there is limited research quantifying the aggregate and relative importance of the dual functions performed by the IHS in US domestic and international trade.

In this paper, we build a multisector model of interregional and international trade of the United States. Importantly, the model accounts for the rich internal geography of the United States by integrating each US county with all other counties and foreign countries via the US highway network, US ports, and international shipping. In addition, the model accounts for the potential congestion of the US highway network that affects trade costs and may alter the associated pattern of both internal and external trade. In the first set of results, we use the model to quantify the losses associated with removing the entire IHS. We find losses equal to \$619.1 billion with about one quarter due to higher trade costs for accessing foreign markets and nearly 8 percent due to congestion. In the second set of results we focus on the twenty longest IHS segments and find a range of losses between \$55.1 billion for I-5 and \$2.7 billion for I-25.

Our results contribute to a growing literature in international trade and economic geography on the role of transportation infrastructure. We provide a framework that can be used to quantify the value of existing or proposed infrastructure. In addition, our approach also highlights the interaction between domestic transportation infrastructure and international trade. This is particularly important for understanding the implications of the changing patterns of globalization for the value and distributional consequences of future infrastructure spending (and trade policy).

References

Agnosteva, Delina E., James E. Anderson, and Yoto V. Yotov, "Intra-national Trade Costs: Measurement and Aggregation," *European Economic Review*, 2019.

Alder, Simon, "Chinese Roads in India: The Effect of Transport Infrastructure on Economic Development," 2017.

Allen, Treb and Costas Arkolakis, "Trade and Topography of the Spaital Economy," *Quarterly Journal of Economics*, 2014, *129* (3), 1085–1140.

_ and _ , "The Welfare Effects of Transportation Infrastructure Improvements," *Working Paper*, 2019.

Anderson, James E., "The Gravity Model," *Annual Review of Economics*, September 2011, *3* (1), 133–160.

_ and Eric van Wincoop, "Gravity with Gravitas: A Solution to the Border Puzzle," *American Economic Review*, March 2003, *93* (1), 170–192.

Asturias, Jose, Manuel García-Santana, and Roberto Ramos, "Competition and the Welfare Gains from Transportation Infrastructure: Evidence from the Golden Quadrilateral of India," *Journal of the European Economic Association*, 2019, *17* (6), 1881–1940.

Atkin, David and Dave Donaldson, "Who's Getting Globalized? The Size and Implications of Intra-National Trade Costs," Technical Report, National Bureau of Economic Research 2015.

Balassa, Bela, "Trade Liberalisation and "Revealed" Comparative Advantage," *The Manchester School*, 1965, *33* (2), 99–123.

Baum-Snow, Nathaniel, "Did Highways Cause Suburbanization?," *Quarterly Journal of Economics*, 2007, *122* (2), 775–805.

_ , Loren Brandt, J Vernon Henderson, Matthew A Turner, and Qinghua Zhang, "Roads, Railroads, and Decentralization of Chinese Cities," *Review of Economics and Statistics*, 2017, *99* (3), 435–448.

Brinkman, Jeffrey and Jeffrey Lin, "Freeway Revolts!," 2019.

Bureau of Transportation, "Border Crossing/Entry Data," 2017.

Caliendo, Lorenzo and Fernando Parro, "Estimates of the Trade and Welfare Effects of NAFTA," *Review of Economic Studies*, 2015, *82* (1), 1–44.

_ , Maximiliano Dvorkin, and Fernando Parro, "Trade and Labor Market Dynamics: General Equilibrium Analysis of the China Trade Shock," *Econometrica*, May 2019, *87* (3), 741–835.

Combes, Pierre-Philippe and Miren Lafourcade, "Transport Costs: Measures, Determinants, and Regional Policy Implications for France," *Journal of Economic Geography*, 2005, *5* (3), 319–349.

Coşar, A. Kerem and Banu Demir, "Domestic Road Infrastructure and International Trade: Evidence from Turkey," *Journal of Development Economics*, 2016, *118*, 232–244.

_ and Pablo D. Fajgelbaum, "Internal Geography, International Trade, and Regional Specialization," *American Economic Journal: Microeconomics*, 2016, *8* (1), 24–56.

Cosar, A. Kerem, Banu Demir, Devaki Ghose, and Nathaniel Young, "Road Capacity, Domestic Trade and Regional Outcomes," 2020.

Dekle, Robert, Jonathan Eaton, and Samuel Kortum, "Unbalanced Trade," *American Economic Review*, 2007, *97* (2), 351–355.

_ , _ , and _ , "Global Rebalancing with Gravity: Measuring the Burden of Adjustment," *IMF Staff Papers*, 2008, *55* (3), 511–540.

Department of Transportation, *United States System of Highways* 1967.

Donaldson, Dave, "Railroads of the Raj: Estimating the Impact of Transportation Infrastructure," *American Economic Review*, 2018, *108* (4-5), 899–934.

_ and Richard Hornbeck, "Railroads and American Economic Growth: 'A Market Access' Approach," *Quarterly Journal of Economics*, 2016, *131* (2), 799–858.

Duranton, Gilles, Peter M Morrow, and Matthew A Turner, "Roads and Trade: Evidence from the US," *Review of Economic Studies*, 2014, *81* (2), 681–724.

Eaton, Jonathan and Samuel Kortum, "Technology, Geography, and Trade," *Econometrica*, 2002, *70* (5), 1741–1779.

Faber, Benjamin, "Trade Integration, Market Size, and Industrialization: Evidence from China's National Trunk Highway System," *Review of Economic Studies*, 2014, *81* (3), 1046–1070.

Fajgelbaum, Pablo and Stephen J. Redding, "Trade, Structural Transformation and Development: Evidence from Argentina 1869-1914," 2018.

Fajgelbaum, Pablo D and Edouard Schaal, "Optimal Transport Networks in Spatial Equilibrium," *Econometrica*, 2020, *88* (4), 1411–1452.

Fishlow, Albert, *American Railroads and the Transformation of the Ante-bellum Economy*, Cambridge, MA: Harvard University Press, 1965.

Fogel, Robert W., *Railroads and American Economic Growth: Essays in Econometric History*, Baltimore, MD: Johns Hopkins University Press, 1964.

Head, Keith and John Ries, “Increasing Returns versus National Product Differentiation as an Explanation for the Pattern of U.S.-Canada Trade,” *American Economic Review*, September 2001, *91* (4), 858–876.

Heblich, Stephan, Stephen J. Redding, and Daniel M. Sturm, “The Making of the Modern Metropolis: Evidence from London,” *The Quarterly Journal of Economics*, 2020, *135* (4), 2059–2133.

Hornbeck, Richard and Martin Rotemberg, “Railroads, Reallocation, and the Rise of American Manufacturing,” Technical Report, National Bureau of Economic Research 2019.

Hummels, David L. and Georg Schaur, “Time as a Trade Barrier,” *American Economic Review*, 2013, *103* (7), 2935–2959.

INRIX Research, *Global Traffic Scorecard* 2019.

Isserman, Andrew and Terance Rephann, “New Highways as Economic Development Tools: An Evaluation using Quasi-Experimental Matching Methods,” *Regional Science and Urban Economics*, 1994, *24* (6), 723–751.

Jaworski, Taylor and Carl T. Kitchens, “National Policy for Regional Development: Historical Evidence from Appalachian Highways,” *Review of Economics & Statistics*, 2019, *101* (5), 777–790.

Michaels, Guy, “The Effect of Trade on the Demand for Skill: Evidence from the Interstate Highway System,” *Review of Economics and Statistics*, 2008, *90* (4), 683–701.

National Research Council, *Highway Capacity Manual* 2000.

OECD, “Infrastructure Investment,” 2020.

_ , “Infrastructure Maintenance,” 2020.

Ossa, Ralph, “Why trade matters after all,” *Journal of International Economics*, 2015, *97* (2), 266–277.

Ramondo, Natalia, Andrés Rodríguez-Clare, and Milagro Saborío-Rodríguez, “Trade, Domestic Frictions, and Scale Effects,” *American Economic Review*, 2016, *106* (10), 3159–84.

_ , _ , and _ , “Internal Geography, Labor Mobility, and the Distributional Impacts of Trade,” *American Economic Journal: Macroeconomics*, 2019, *11* (3), 252–288.

Redding, Stephen J., “Goods Trade, Factor Mobility and Welfare,” *Journal of International Economics*, 2016, *101*, 148–167.

Ruggles, Steven, J. Trent Alexander, Katie Genadek, Ronald Goeken, Matthew B Schroeder, Matthew Sobek et al., “Integrated public use microdata series: Version 5.0 [Machine-readable database],” *Minneapolis: University of Minnesota*, 2010, *42.*

Timmer, Marcel P., Erik Dietzenbacher, Bart Los, Robert Stehrer, and Gaaitzen J. De Vries, "An Illustrated User Guide to the World Input-Output Database: The Case of Global Automotive Production," *Review of International Economics*, 2015, *23* (3), 575–605.

US Census Bureau, *Highway Statistics Series* 2010.

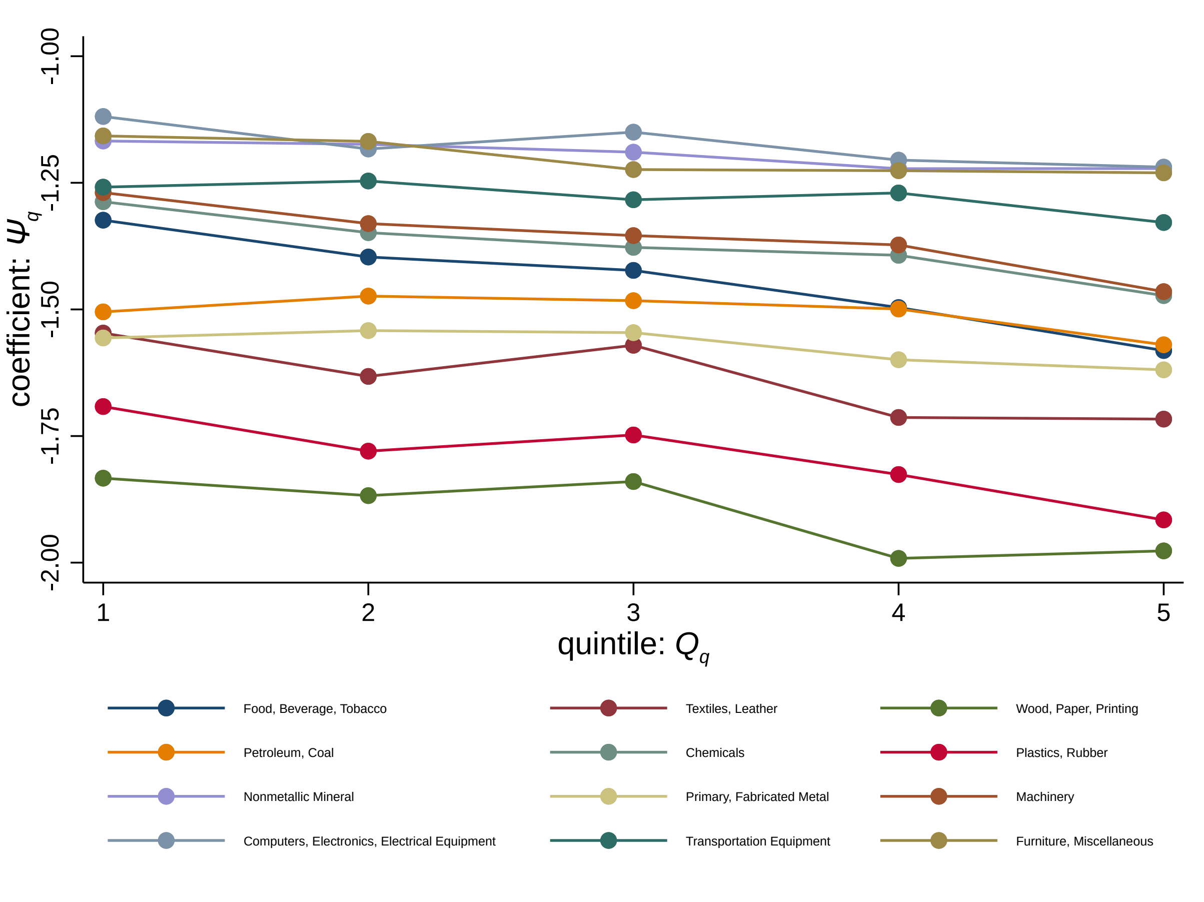
_ , *TIGER/Line shapefiles* 2012.

US Department of Transportation, *Freight Facts and Figures* 2013.

Appendix – For Online Publication

A Additional Tables and Figures

Figure A1: Results for International Distance Coefficients by Sector



Notes: This figure shows the results of estimating equation (30) for each sector s. The dependent variable are the trade flows between each US port r and each foreign trading partner j. Each line plots the coefficients associated with the quintiles of distance (in miles) for a given sector. All specifications include port and country fixed effects.

B Details for Data Sources and Variable Construction

Locations and Sectors: We calibrate the model to domestic locations in the Unites States including 2,894 counties in 48 states and Washington, DC, using data from 2012 as the benchmark year. We exclude Alaska and Hawaii. The foreign locations are 35 countries (Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, Czech Republic, Germany, Denmark, Estonia, Finland, France, Great Britain, Greece, Hungary, Indonesia, India, Ireland, Italy, Japan, Korea, Lithuania, Mexico, the Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Turkey, and Taiwan) and the rest of the world. Finally, we calibrate the model to 22 sectors, including 12 manufacturing sectors, 8 service sectors, construction, and combined wholesale and retail trade. Appendix Table B1 shows how we aggregate sectors from North American Industry Classification System (NAICS) to the sectors used in the empirical work.

Domestic and International Trade Flows: Data on domestic trade flows for the United States are drawn from the Commodity Flow Survey for 2012. We use this data construct trade flows between US states as well as the domestic flow of exports from US states to foreign countries via US ports. Data on international trade flows are drawn from USA Trade Online for 2012. We use this data to construct trade flows between US states and foreign countries as well as between US ports and foreign countries. For domestic trade flows, the public use file for the 2012 Commodity Flow Survey is available for download at `this link`. For international trade flows, data available for download or purchase from `USA Trade Online`.

Employment, Output, and Migration: Employment and annual payroll data are drawn from the County Business Patterns for 2012. Migration data are drawn from the Internal Revenue Service for 2011-2012. The employment and payroll data can be downloaded at `this link`. The migration data can be downloaded at `this link`.

State Production and Consumption Shares: Value added in gross output shares, intermediate input shares, and Cobb-Douglas consumption shares are constructed from data drawn from the County Business Patterns for 20102 and World Input-Output Database for 2012 (see Timmer, Dietzenbacher, Los, Stehrer and De Vries, 2015). The World Input-Output Database can be downloaded `here`.

Transportation Network Database and Trade Costs: The domestic and international transportation network is based on the US highway network–for routes between locations within the United States (i.e., counties and ports)–and international shipping–for routes between US ports and foreign countries.

Each location (i.e., counties, ports, countries) is represented as a centroid. Locations are connected via the transportation network which includes the US highway network from the US Department of Transportation (`download here`), navigable waterways providing access to inland ports from the National Transportation Atlas Database (`download here`), international shipping lanes digitized from the CIA World Factbook, and international transit between the United States and Canada or Mexico. The US highway network is comprised of all major roads including IHS segments, other federal-aid highways, and state highways. We assign travel speeds of 70, 55, and 45, respectively, to these portions of the US highway network. In addition, to ensure that all county and port centroids are connected to the highway network we build a network of "access roads" that provide direct connections. We assign a travel speed of 10 to the access road network.

To construct benchmark domestic and international trade costs we use ArcGIS to find the least cost route between centroids via the transportation network. In particular, for the domestic trade cost components, we use the network analyst tool to find the route between any pair of US counties or between US counties and US ports that minimizes *travel time*. These are used to the construct the interstate, intrastate, and state-to-port trade costs components. For the interstate trade cost component, for each state pair we identify the county pair that minimizes the travel time between states. For the intrastate trade cost component, we then find the route the minimizes travel time for all counties within a state and the county used as the aggregation point for interstate trade. This means that intrastate trade costs are specific to origin and destination states. Similarly, for the state-to-port trade cost component, we find the minimum travel between US states and US ports. For international trade costs, we use the network analyst tool to find the route between US ports and foreign trading partners that minimizes travel *distance*.

To construct counterfactual domestic trade costs we again use ArcGIS to find the least cost route corresponding to the interstate, intrastate, and state-to-port trade cost components, after removing the a segment or several segments of the US highway network. In some cases we include or exclude segments from particular counterfactuals. For example, for the counterfactual removing I-95 from the highway network, we exclude I-95 from the network. For each counterfactual we then find the route that minimizes the travel time and correspond to each of the domestic trade cost components.

To account for congestion in the benchmark and all counterfactual scenarios we use ArcPro to identify the which of the roughly 650,000 pieces of the US highway network (excluding the access road network) are used for particular interstate routes.[18] Each piece

[18] On a technical note, ArcPro is implemented in this step because the network route solver can identify the edges of the network used to construct the cost minimizing route with the `''returnRouteEdges=True''`

of the highway network has a tabulated annual daily traffic entry based on data collected by the Federal Highway Administration and used to construct level of service. We use this data for the benchmark scenario to quantify the relationship between the level of service and observed trade flows. For the counterfactuals, we then use the estimated relationship between level of service and observed trade flows in the benchmark scenario to assign trade-generated traffic and the corresponding level of service to the relevant pieces of the highway network for counterfactual routes.

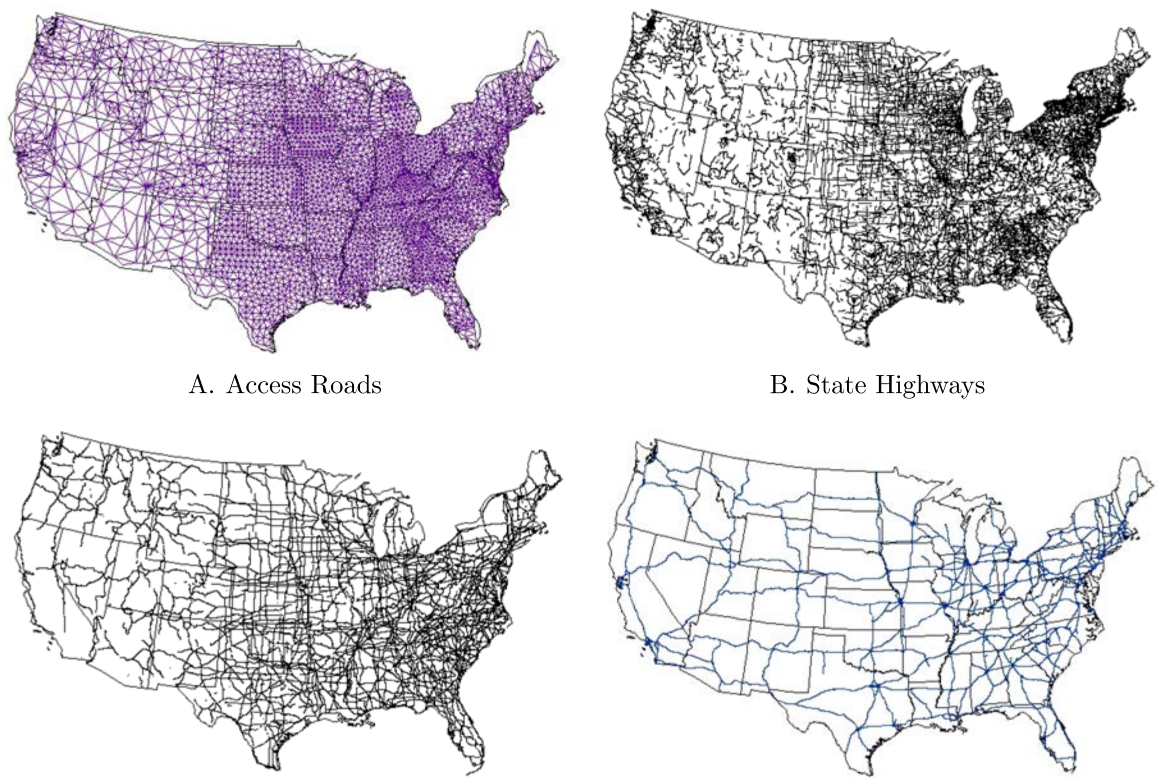
option, which is not available in ESRI ArcMAP.

Table B1: Aggregation of NAICS Sectors

Sector	Name	NAICS	WIOD
1	Food, Beverage, and Tobacco Products	311-312	5
2	Textile and Leather Products	313-316	6
3	Wood Products, Paper, Printing, and Related Products	321-323	8-9
4	Petroleum and Coal Products	324	10
5	Chemical Products	325	11-12
6	Plastics and Rubber Products	326	13
7	Nonmetallic Mineral Products	327	14
8	Primary Metal and Fabricated Metal Products	331-332	15-16
9	Machinery	333	19
10	Computer, Electronic Products, Electrical Equipment	334-335	18
11	Transportation Equipment	336	20-21
12	Furniture and Related Products, and Misc.	337-339	22
13	Transport Services	481-488	31-34
14	Information Services	511-518	37-40
15	Finance and Insurance Services	521-525	41-43
16	Real Estate Services	531-533	44
17	Education Services	61	52
18	Health Care Services	621-624	53
19	Accommodation and Food Services	721-722	36
20	Other Services	493, 541, 55, 561, 562, 711-713, 811-814	54-51
21	Wholesale and Retail Trade	42-45	28-30
22	Construction	236	27

Notes: This table shows the aggregation of the industries used in this paper based on the North American Industrial Classification and World Input-Output Database.

Figure B1: Components of the US Highway Network



A. Access Roads

B. State Highways

C. US Highways

D. Interstate Highway System

Notes: This figure shows the four components of the US highway network used to calculate travel time and trade costs. Panel A shows the access road network with assigned speed of 10 miles per hour, Panel B shows the state highway network with an assigned speed of 45 miles per hour, Panel C shows the US highway network with an assigned speed of 55 miles per hour, and Panel D shows the Interstate Highway System with an assigned speed of 70 miles per hour.