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HIGHWAYS AND GLOBALIZATION

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ABSTRACT

This paper quantifies the value of US highways. We develop a multisector general equilibrium model 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. Applying the model, we find that removing the Interstate Highway System reduces real GDP by $421-$578 billion. The results highlight the gains from intersectoral and international trade as well as the role of domestic transportation infrastructure in shaping regional comparative advantage.

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1 Introduction

Countries around the world devote substantial resources to new road infrastructure and maintenance. Given the size of these expenditures, it is crucial to understand the mechanisms behind the aggregate and distributional effects of transportation infrastructure as a guide for ongoing and future investments. Quantifying these benefits is challenging since the quality of domestic infrastructure shapes the pattern of specialization vis-à-vis domestic and foreign trading partners, determines congestion, and generates spillovers across industries and locations. In addition, calculating benefits at a refined geographic scale, e.g., for counties in the United States, is subject to constraints due to data limitations.

In this paper, we aim to address these challenges and ultimately quantify the value of transportation infrastructure in the United States. In particular, focusing on highways, our approach captures the role of the transportation system in mediating the intensity of spatial and sectoral linkages along two margins. First, producers choose optimal routes to domestic and international markets such that the domestic portion of industry-specific trade costs reflect travel time via the US highway network or using alternative modes (e.g., rail, water, or air). Second, producers' decisions take into account congestion endogenously generated by industry-specific trade.

Our theoretical framework integrates each US county with all other counties and all foreign trading partners. To do this, we use a two-tier spatial structure that combines state- and county-level data with measures of industry-specific domestic and international trade costs. The framework also incorporates more standard features of economic geography models, including input-output linkages, imperfect labor mobility, and agglomeration. We apply the model to data for the entire contiguous United States made of more than 3,000 counties, 22 sectors, and 36 international trading partners (including the rest of the world).

In counterfactual exercises, we use the model to produce three main results. First, we quantify the value of the Interstate Highway System (IHS). Removing the entire IHS decreases real GDP between \$421 and \$578 billion in 2012 dollars. Both intersectoral trade via input-output linkages and international trade play an important role in determining the aggregate effects. Regionally, losses are concentrated in the Northeast and West of the United States and more remote counties experience the largest relative losses.

Second, underlying the intuition for these results is that the IHS allows remote regions to exploit their comparative advantage and concentrate production in a few sectors with relatively high productivity. We confirm this by showing how removing the IHS affects a measure of revealed comparative advantage (see Balassa, 1965). In particular, we show that removing the IHS alters the sectoral composition of output across US states. In addition, states consume more of their own production and export less to other states and foreign countries. This suggests the reduction in trade costs from the IHS plays an important role in shaping the location of production, pattern of specialization, and distribution of the gains from trade across US regions.

Finally, we quantify the value of the ten of the largest IHS interstates (e.g., I-10) and consider the value created by proposed upgrades to the highway network. Aggregate losses from removing these ten segments range between \$13 and \$92 billion and losses per mile range between \$9 and \$32 million. These results suggest that the contribution of highway to international trade costs constitutes approximately one-third of the total effect. These results are useful for allocating funds for maintenance and repair of existing highways, evaluating proposed changes, as well as better understanding the connection between transportation infrastructure policy and, for example, trade policy. We also calculate gains associated with proposal to improve four existing highways to be between \$507 and \$897 million.

In the end, we provide a framework that highlights the interaction between domestic transportation infrastructure and international trade while accounting for congestion, input-output linkages, and other salient features of economic geography environments. This paper builds on the literature in two ways. First, we contribute to research on the impact and value of the IHS in the United States. One strand of this literature estimates the effects of transportation infrastructure on economic activity (Isserman and Rephann, 1994; Fernald, 1999; Chandra and Thompson, 2000; Michaels, 2008) and household location decisions (Baum-Snow, 2007).[1] For example, Herzog (2021) examines the impact of domestic market access due to the construction of the Interstate Highway System on employment and wages at the county level.

Another strand of this literature uses quantitative models to value the Interstate Highway System. Most closely related to this paper is work by Allen and Arkolakis (2014, 2022). 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] Our contribution is to consider the impact of the IHS in the presence of input-output linkages and international

[1] In addition, there is a growing literature that estimates the effects of transportation infrastructure in the context of developing countries and various scenarios (e.g., Faber, 2014; Baum-Snow, Brandt, Henderson, Turner and Zhang, 2017; Cosar, Demir, Ghose and Young, 2020). For example, Balboni (2021) looks at how coastal flooding affects the value of transportation infrastructure in Vietnam.

[2] Also related is work on historical railroads (Fogel, 1964; Fishlow, 1965; Donaldson and Hornbeck, 2016; Donaldson, 2018; Nagy, 2020) and highways more recently (Alder, 2017; Bartelme, 2018; Jaworski and Kitchens, 2019; Santamaria, 2022) as well research on optimal infrastructure investment in general equilibrium settings (Fajgelbaum and Schaal, 2020).

as well as domestic trade. As in Allen and Arkolakis (2022), we account for the role of endogenous congestion levels and route choice. Our results suggest that accounting for input-output linkages and international trade are crucially important for the quantifying the value of infrastructure: the estimated value of the IHS increases threefold relative to previous estimates in the literature.[3]

Second, 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; Bartelme, 2018; Ramondo, Rodríguez-Clare and Saborío-Rodríguez, 2019). We show that improvements in domestic transportation allows remote regions to concentrate output and exports in comparatively advantaged sectors. This leads to large welfare gains and has important distributional consequences within and between countries. In addition, our approach to measuring trade costs (and the related congestion) is novel. We use detailed information on travel time as a function of distance, speed, and traffic on county-to-county and county-to-port routes. This provides a tractable way to incorporate congestion and yields a straightforward approach for decomposing the contribution of highways (or any other portion of the transportation system) to domestic versus international market access.

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 we use data on distance, speed, and traffic to calculate travel time to incorporate congestion. Section 3 presents the model of interregional and international trade, including the role of domestic and international trade costs, and the solution method for carrying out counterfactuals. 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 main results and Section 6 concludes.

2 The US Highway Network with Congestion

There are 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

[3]This result is consistent with Costinot and Rodriguez-Clare (2014), Caliendo and Parro (2015), and Ossa (2015) that shows including input-output linkages magnifies the gains from trade. To the best of our knowledge, our paper is the first to emphasize this mechanism in the context of domestic transportation infrastructure.

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, while most of the remainder of the system is made up of a combination of federal-aid and state highways. The US highway network used in this paper is shown in Panel A of Figure 1 and includes the Interstate, other federal-aid, and state highways. The remaining roads (not shown) are primarily used for local travel including county roads as well as city and neighborhood streets.

The highway network shown in Panel A of Figure 1 includes the major roads used for the movement of goods within the United States and constitutes the main focus of our analysis.[4] 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 use trucks exclusively to deliver goods domestically, while 34 percent use trucks for at least part of their journey. For exports, more than half of shipments by weight use trucks as a single mode to deliver goods to ports and 60 percent used trucks partially to ship goods to ports.[5]

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). Observed values of the LOS on segments of US highway network are shown in Panel B of Figure 1. 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 congestion are highly heterogeneous across segments. For the purposes of quantifying the value of highways, this suggests that incoporating congestion costs is important for understanding how highways shape trade outcomes, regional specialization, and the spatial distribution of economic activity.

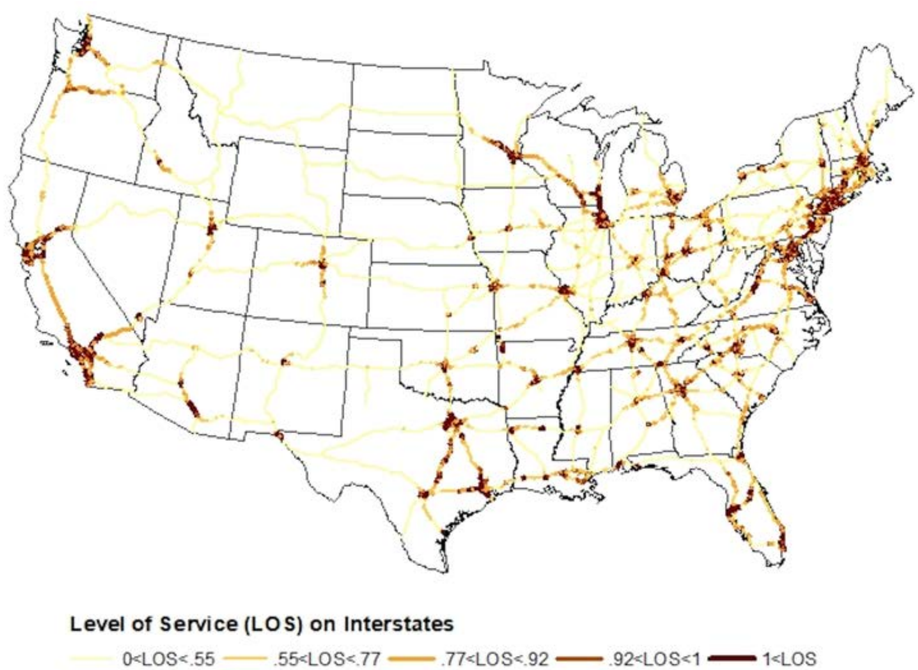
As mentioned above, Figure 1 includes all of the major highways in the United States. For this paper, we draw on shapefiles of the network that divide these key components into

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

[5] Specifically for trade with Canada and Mexico, highways also play a significant role. If we consider truck, rail, air, and vessel trade as classified by the Bureau of Transportation Statistics more than 60 percent of US exports to Canada and Mexico were moved by truck in 2012 (Bureau of Transportation Statistics).

Figure 1: 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 based on the level of service.

roughly 330,000 individual segments. We observe LOS, distance, and speed, which together determine the travel time on each segment 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 a piecewise function derived from the Highway Capacity Manual (see National Research Council, 2000, Exhibit 23-2):[6]

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

The travel time function in equation (1) captures the positive relationship between travel time and LOS. Whenever a segment, $\mathcal{S}$, is characterized by high congestion (or low $\mathcal{A}_{\mathcal{S}}$), it takes longer to complete $\mathcal{S}$.

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

$$\mathrm{T}_{ij} = \sum_{\mathcal{S} \in \boldsymbol{S}} \mathbb{1}_{\mathcal{S} \in \boldsymbol{S}_{ij}} \mathcal{T}_{\mathcal{S}} \tag{2}$$

where $\boldsymbol{S}$ is a set of all road segments in the network and $\boldsymbol{S}_{ij} \subseteq \boldsymbol{S}$ is a subset that consists of segments used to transport goods from i to j; $\mathbb{1}_{\mathcal{S} \in \boldsymbol{S}_{ij}}$ is an indicator function equal to one if $\mathcal{S}$ is in subset $\boldsymbol{S}_{ij}$ or zero otherwise. Note that T_{ij} is endogenous to the route choice $\boldsymbol{S}_{ij}$ between i and j as well as to $\mathcal{T}_{\mathcal{S}}$, 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 accommodates multiple countries with potentially many regions. The spatial structure of the model together with the assumption on the movement of goods allows us to use state-level economic outcomes together with intrastate measures of trade costs to calculate the

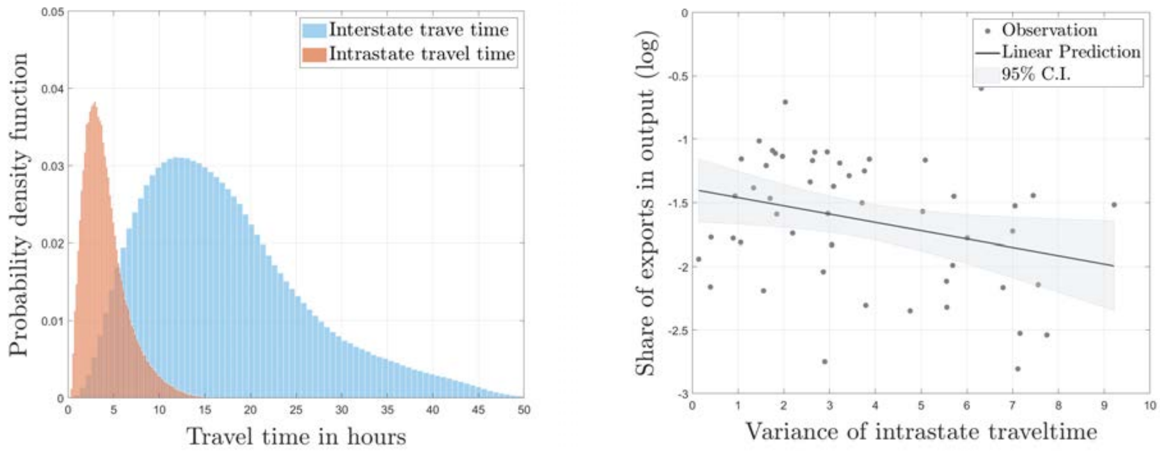
[6] The piecewise function we implement directly corresponds to the Bureau of Public Roads function developed in the 1950s. Specifically, the steps in our function are based on the ratio of observed traffic to the theoretical capacity of a given road segment (see National Research Council, 2000, Exhibit 21-3).

impact on county-level outcomes. This is important for overcoming data limitations. For ease of exposition we 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 counties and all countries using county-to-county, county-to-state, and county-to-country travel via US highways, ports, and international shipping lanes.

It is necessary to formulate a model that explicitly looks at counties rather than larger spatial units such as states for two reasons. First and foremost, intrastate trade costs are substantial relative to their interstate counterparts. In Panel A of Figure **2**, we plot the distributions of county-to-county travel times of the fastest routes in hours when they are located between states and within states. Though average intrastate travel times are lower than their interstate counterparts, they are substantial. For example, the 90^{th} percentile of intrastate travel times is higher than the 10^{th} percentile of interstate travel times. Choosing counties as our spatial units of analysis allows us to account for the importance of intrastate travel times. Second, trade costs between counties within each state also contribute the cost of moving goods between states or between states and foreign countries. In Panel B of Figure **2**, we plot variances of within state travel times against the share of exports in total output. Counties characterized by higher variance tend to have smaller export shares. As a result, ignoring intrastate trade costs would also affect interstate and international linkages. For these reasons, the model below is formulated at the county level.

We first present the model in levels and then show how to express the model in relative changes to conduct counterfactuals. The model extends the standard multisector Ricardian model and features two location tiers such that production, consumption, and trade of counties (first tier) can be consistently aggregated to the corresponding state-level variables (second tier). Ultimately, we formulate all county-level variables as functions of their state-level counterparts and trade costs. This allows us to examine economic outcomes at the county level, while matching the most detailed level of aggregation in the available data and keeping the solution of the model computationally feasible. As in Allen and Arkolakis (2022), the model accounts for two sources of endogeneity in trade costs: the choice of transportation routes (including modes) and the effect of trade-generated traffic on congestion.

Figure 2: Travel Times and Trade



A. Interstate and intrastate travel time

B. Intrastate travel time and exports

Notes: Panel A plots probability density function of interstate and intrastate travel time on the fastest available route. Panel B plots the relationship between the variance of intrastate travel time and state share of exports in total output.

County-level Consumption, Production, and Trade

We start by describing supply and demand in each county c in state i. On the demand side, 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 price of one unit of $Q_i^c(s)$.

On the supply side, the model features two distinct production levels in each sector s as in Costinot, Donaldson and Komunjer (2012) and Caliendo and Parro (2015). Varieties in sector s, $z(s)$, are produced by individual producers and aggregated into sectoral goods $Q(s)$ using a CES function prior to intermediate and final consumption. Varieties can be traded across counties (and states) and countries subject to trade costs.

The cost minimizing outcome for producers of varieties in county $c \in i$ and sector s is an input bundle given by:

$$\kappa_i^c(s) = B_i(s) w_i^{\gamma_i(s)} \mathbb{P}_i^c(s)^{1-\gamma_i(s)}, \tag{4}$$

where $B_i(s)$ is a constant, $\gamma_i(s)$ is the share of value added, and $\mathbb{P}_i^c(s)$ is the price of the aggregate intermediate input. Producers in sector s source intermediate goods from other sectors $\dot{s}$ according to a CES function with share parameters $\eta_i(\dot{s}s)$ and substitution parameter χ. The aggregate price can be calculated as:

$$\mathbb{P}_i^c(s) = \left(\sum_{\dot{s} \in S} \eta_i(\dot{s}s) P_i^c(\dot{s})^{1-\chi} \right)^{\frac{1}{1-\chi}}, \text{ where } \sum_{\dot{s} \in S} \eta_i(\dot{s}s) = 1. \tag{5}$$

This specification of input-output linkages is flexible and allows us to consider several alternative substitution patterns: (i) as χ approaches zero the structure becomes Leontief, (ii) $\chi \to 1$ corresponds to a Cobb-Douglas function with weights $\eta(\dot{s}s)$, and (iii) at $\chi \to \infty$ all intermediate inputs become perfect substitutes. The share of inputs that producers in sector s source from $\dot{s}$ is specified as:

$$\xi_i(\dot{s}s) = \eta_i(\dot{s}s) \left(\frac{P_i^c(\dot{s})}{\mathbb{P}_i^c(s)} \right)^{1-\chi}.$$

There is a continuum of varieties $z(s) \in [0, 1]$ produced in each sector s. Given the cost of the input bundle in equation (4), a producer located in county $c \in i$ offers variety $z(s)$ to state j at the following price:

$$p_{ij}^{cm^*}(z(s)) = \frac{\kappa_i^c(s) \tau_{ij}^{cm^*}(s)}{z_i^c(s)},$$

where $\tau_{ij}^{cm^*}(s)$ are total iceberg trade costs between county $c \in i$ and the aggregation location m^* in state j and $z_i^c(s)$ is the efficiency parameter drawn from a county-sector-specific productivity distribution. As in Eaton and Kortum (2002), efficiency is distributed Fréchet with location and shape parameters $T_i(s) K_i^c(s)$ and $\theta(s)$, respectively. This formulation of the location parameter implies that the average productivity of producers located in county $c \in i$ can be specified as a product of the relative county productivity within a state, $K_i^c(s)$, and a state-level shifter $T_i(s)$. Without loss of generality, the mean of $K_i^c(s)$ across counties within a state and sector is normalized to one.

In each state j there is a single and unique aggregation county $m^* \in j$, which searches for the minimum price for each variety across all potential supplier counties $c \in i$. Below we explain how we identify m^* for each state j. The minimum price of variety $z(s)$ in that aggregation location is as follows:

$$p_j^{m^*}(z(s)) = \min_{\{i,c\}} \left\{ \frac{\kappa_i^c(s)\tau_{ij}^{cm^*}(s)}{z_i^c(s)} \right\}. \tag{6}$$

As in Eaton and Kortum (2002), varieties $z(s)$ are aggregated into $Q(s)$ according to a standard CES aggregator prior to consumption. The probabilistic representation of technologies allows us to specify the price index of $Q(s)$ in the aggregation county $m^* \in j$ as:

$$P_j(s) = B_p(s) \left(\sum_i \sum_c T_i(s) K_i^c(s) \left(\kappa_i^c(s) \tau_{ij}^{cm^*}(s) \right)^{-\theta(s)} \right)^{-\frac{1}{\theta(s)}}, \tag{7}$$

where $B_p(s)$ is a constant. Since there is a unique m^* in each state, the CES price index in equation (7) reflects state prices that are available to consumers in $m^* \in j$. This implies that the share of $m^* \in j$ expenditure in sector s spent on varieties from $c \in i$ also reflects the aggregate trade share of state j:

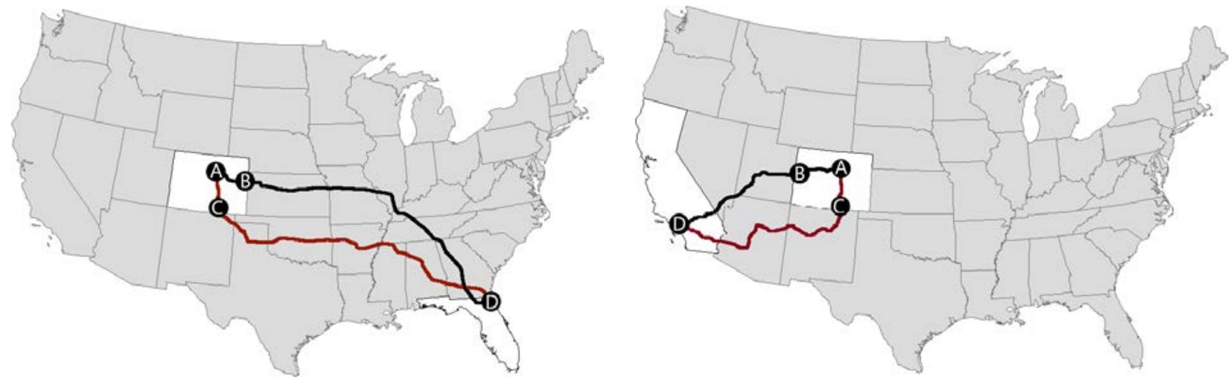
$$\pi_{ij}^c(s) = \frac{T_i(s) K_i^c(s) \left(\kappa_i^c(s) \tau_{ij}^{cm^*}(s) \right)^{-\theta(s)}}{\sum_n \sum_k T_n(s) K_n^k(s) \left(\kappa_n^k(s) \tau_{nj}^{km^*}(s) \right)^{-\theta(s)}}. \tag{8}$$

Representing county-level outcomes as a function of state-level variables is possible using a consistent aggregation procedure which relies on two assumptions. First, there is a single aggregation county $m^* \in i$ in each state that aggregates $z(s)$ into $Q(s)$. This CES aggregate can then be consumed in all other counties $m \in i$ subject to intrastate trade costs. Second, total trade costs between $c \in i$ and $m^* \in j$ can be specified as a multiplicative function:

$$\tau_{ij}^{cm^*}(s) = \varepsilon_i^{cc(ij)}(s) \cdot \overline{\tau}_{ij}(s) \cdot \varepsilon_j^{m(ij)m^*}(s), \tag{9}$$

where $\varepsilon_i^{cc(ij)}(s)$ is the intrastate trade cost for exporters transporting goods from county c to the "exporting" county $c(ij)$, which is ij-pair-specific; $\varepsilon_i^{m(ij)m^*}(s)$ is the importer intrastate trade cost of transporting goods from the "importing" county $m(ij)$ to the aggregation county m^*; $\overline{\tau}_{ij}(s)$ denotes the average interstate trade cost of transporting goods from i to j across all available transportation modes specified below.

Figure 3: Illustration of Intrastate and Interstate Routes



A. Route Colorado-Florida

B. Route Colorado-California

Notes: This figure illustrates the implementation for the multiple routes between locations in the model using two examples. For trade between Colorado and Florida, Panel A depicts trade that begins in Denver County (point A) in Colorado and first moves to either point B or point C depending on the route chosen and ends in Duval County (point D) in Florida. Similarly, for trade between Colorado and California, Panel B shows trade that begins in Denver County (point A) in Colorado and first moves to either point B or point C depending on the route chosen and ends in Los Angeles County (point D) in California.

Within each state, we assume goods can only be transported via roads.[7] For each ij state pair and route R, there are unique exporting and importing counties $c(ij) \in i$ and $m(ij) \in j$ that are determined endogenously by producers who choose optimal routes to transport goods from i to j. Route choices are subject to idiosyncratic shocks such that different producers may potentially choose different routes from the available set $\boldsymbol{R}_{ij}$.[8] For a given route between i and j, we identify $c(ij) \in i$ and $m(ij) \in j$ by allowing producers choose routes between the core area $c^* \in i$ and core area $m^* \in j$. These core counties are the largest population centers.[9] We show core counties in each state in Appendix Figure B1. When producers in $c^* \in i$ choose the optimal route to $m^* \in j$, they automatically determine $c(ij) \in i$ and $m(ij) \in j$ that then apply to all counties in i and j. Hence, we do not impose any assumptions about trade routes between the largest economic areas.

For example, consider transporting goods from Colorado to Florida as illustrated in Panel A of Figure **3**. The core counties in these two states are Denver County, CO (point A) and Duval County, FL (point D), respectively. In this example, for illustration we consider two potential routes from A to D. However, in our quantitative analysis we consider six

[7]This assumption is in line with the available data. According to the Commodity Flow Survey in 2012, road transportation accounted for a vast majority of within-state trade.

[8]We provide more detail for how we identify $\boldsymbol{R}_{ij}$ in Section 4.

[9]The core counties are typically part of the largest agglomerations within each state, which account for the vast majority of production and trade. For example, Core-Based Statistical Areas accounted for 57-64 percent of total domestic export and imports transported by truck in 2012 (US Bureau of the Census, 2012).

routes that may potentially overlap with each other on certain segments to avoid localized congestion. First, the least cost route between A and D (A-B-D) is chosen without imposing any restrictions.[10] Second, the optimal route determines the relevant export county (point B) in Colorado and import county in Florida. Export and import counties are not fixed and change depending on what route is chosen. For example, an alternative route (A-C-D) would use point C as an exit county in Colorado. Export and import counties are separately determined for each ij pair and route. Panel B in Figure **3** illustrates two potential routes of transporting goods from Denver County, CO to Los Angeles County, CA. Note that relative to the previous example, the exit county on the fastest route from Colorado to California (A-B-D) is now different. This approach allows us to flexibly model state-to-state trade costs, while preserving model tractability and convenient aggregation properties. We demonstrate how our approach matches the available county-level data in Section 4.2.

The examples in Figure **3** illustrate two routes for each ij pair. However, in reality producers may choose (partially) different routes to avoid traffic on certain segments. To account for this, we consider $\boldsymbol{R}_{ij}$ possible routes that may partially overlap when travelling between $c(ij) \in i$ and $m(ij) \in j$. This setup is in the spirit of Allen and Arkolakis (2022); however, given the detail of the road network and the number of locations considered in our analysis, we consider a number $\boldsymbol{R}_{ij}$ that is less than the number of all possible routes between i and j as the latter would quickly converge to a computationally infeasible problem.

Although producers always choose an optimal route to ship from $c(ij) \in i$ and $m(ij) \in j$, their choices are subject to exogenous producer-route-specific shocks drawn from an extreme value distribution. As in Allen and Arkolakis (2022) this leads to a discrete choice model across routes. This allows us to calculate the average cost of transporting goods from i to j by road as:

$$\tau_{ij}(s) = B_R(s) \left(\sum_{R \in \boldsymbol{R}_{ij}} \tau_{ij}^R(s)^{-\sigma} \right)^{-\frac{1}{\sigma}}, \tag{10}$$

where $\tau_{ij}^R(s)$ is the cost of transporting goods on route $R \in \boldsymbol{R}_{ij}$, σ governs the elasticity of substitution between routes, and $B_R(s)$ is a constant. Then the share of total road trade in

[10] For concreteness, in the figure, trade between Denver County, CO and Duval County, FL begins by following I-70 East, exiting CO through Kit Carson County (B) and continuing to I-57 South to I-24 East to I-75 South. The route enters Florida in Hamilton County (C) via I-75 South and terminated in Duval County, FL via I-10 East.

sector s transported from i to j by route R is given by:

$$\varsigma_{ij}^{R}(s) = \frac{\tau_{ij}^{R}(s)^{-\sigma}}{\tau_{ij}(s)^{-\sigma}}. \tag{11}$$

We also account for the fact that there are several transportation modes available to move goods between states. In equation (9), $\overline{\tau}_{ij}(s)$ denotes the average interstate trade cost between states i and j across different transportation modes. Let v_{ij}^{rail}, v_{ij}^{water} and v_{ij}^{air} denote trade costs between i and j when goods are transported via rail, water, and air, respectively. We follow Allen and Arkolakis (2014) and use a discrete choice model across modes to specify average trade costs between i and j:

$$\overline{\tau}_{ij}(s) = B_t(s)\left(\tau_{ij}(s)^{-\sigma} + \sum_{\ell} v_{ij}^{\ell}(s)^{-\sigma}\right)^{-\frac{1}{\sigma}} \quad \text{for} \quad \ell = \{\text{rail}, \text{water}, \text{air}\}, \tag{12}$$

where $B_t(s)$ is a constant. The share of total trade in sector s shipped from i to j by road is given by:

$$\varsigma_{ij}(s) = \frac{\tau_{ij}(s)^{-\sigma}}{\overline{\tau}_{ij}(s)^{-\sigma}}. \tag{13}$$

Since our main interest is on valuing highway infrastructure, we focus on changes in $\overline{\tau}_{ij}$ due to changes in τ_{ij}. Hence, while we do account for the possibility of transporting goods between i and j via multiple modes, we treat trade costs v_{ij}^{rail}, v_{ij}^{water}, and v_{ij}^{air} as constant in the model. However, this does not imply that the shares across different transportation modes remain constant, as these shares change in response to shocks to trade costs via the highway network.

Next, we aggregate county-level exports to state-to-state and state-to-country trade flows so that county-level variables are expressed as functions of their state-level counterparts and intrastate trade costs. We start by defining two variables:

$$\mu_{ij}^{c}(s) = \frac{K_i^c(s)\left(\kappa_i^c(s)\varepsilon_i^{cc(ij)}(s)\right)^{-\theta(s)}}{\sum_{c'} K_i^{c'}(s)\left(\kappa_i^{c'}(s)\varepsilon_i^{c'c(ij)}(s)\right)^{-\theta(s)}} \quad \text{and} \quad \kappa_{ij}(s) = \left(\sum_{c'} K_i^{c'}(s)\left(\kappa_i^{c'}(s)\varepsilon_i^{c'c(ij)}(s)\right)^{-\theta}\right)^{-\frac{1}{\theta(s)}},$$

where $\mu_{ij}^{c}(s)$ is the share of total exports in sector s from state i to j that comes from county $c \in i$ and $\kappa_{ij}(s)$ is the average relative cost of the input bundle faced by producers exporting to state j. We use the expression for trade shares in equation (8) together with the expressions for $\mu_{ij}^c(s)$ and $\kappa_{ij}(s)$ to express total nominal exports from $c \in i$ to j as:

$$X_{ij}^c(s) = \mu_{ij}^c(s) \cdot \frac{T_i(s)\left(\kappa_{ij}(s)\overline{\tau}_{ij}(s)\varepsilon_j^{m(ij)m^*}(s)\right)^{-\theta(s)}}{\sum_{i'} T_{i'}(s)\left(\kappa_{i'j}(s)\overline{\tau}_{i'j}(s)\varepsilon_j^{m(i'j)m^*}(s)\right)^{-\theta(s)}} \cdot Y_j(s). \tag{14}$$

Summing $X_{ij}^c(s)$ over all exporting counties c and dividing by total absorption of state j in sector s gives the following expression for state-to-state trade shares:

$$\pi_{ij}(s) = \frac{T_i(s)\left(\kappa_{ij}(s)\overline{\tau}_{ij}(s)\varepsilon_j^{m(ij)m^*}(s)\right)^{-\theta(s)}}{\sum_{i'} T_{i'}(s)\left(\kappa_{i'j}(s)\overline{\tau}_{i'j}(s)\varepsilon_j^{m(i'j)m^*}(s)\right)^{-\theta(s)}}. \tag{15}$$

Finally, we derive the expression for the CES price indices in county $m \in j$ taking into account that all varieties are first aggregated in m^* and then transported to m subject to intrastate trade costs $\varepsilon_j^{m^*m}(s)$:

$$P_j^m(s) = \varepsilon_j^{m^*m}(s)B(s)\left(\sum_i T_i(s)\left(\kappa_{ij}(s)\overline{\tau}_{ij}(s)\varepsilon_j^{m(ij)m^*}(s)\right)^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}},$$

where $B(s)$ is a constant. This aggregation allows us to express all county-level variables as functions of state-level counterparts and intrastate trade costs. Importantly, this means we can examine county-level outcomes while using state-level data to overcome the absence of county-level data for trade flows and prices. We next turn to describing trade between states and foreign countries.

International Trade

To describe trade shares between states and countries, we introduce international trade costs. To do this, we account for the fact that US exports and imports can be transported via ports and international sea freight.[11] In addition, we allow trade between US states, Mexico and Canada to be conducted via inland ports along the US-Canada and US-Mexico borders.

Consider international trade between county $c \in i$ with a foreign country n via port r that is located in state j. With a slight abuse of notation let r denote the port as well as state and county where it is located. The deterministic part of total trade costs between

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

county $c \in i$ and country n via port r is as follows:

$$\tau_{in}^{c,r}(s) = \underbrace{\varepsilon_i^{cc(ir)}(s)\overline{\tau}_{ir}(s)\varepsilon_r^{m(ir)r}(s)}_{\text{Domestic Component}} \cdot \underbrace{\xi_r^r(s)}_{\text{Port Component}} \cdot \underbrace{t_{rn}^r(s)}_{\text{International Component}},$$

where the domestic component measures the cost of transporting goods via US domestic infrastructure from the production county $c \in i$ to port r. The second component, $\xi_r^r(s)$, measures port r efficiency in transporting goods in sector s. Lastly, $t_{rn}^r(s)$ measures the cost of transporting goods from port r to country n. There is also a random component of trade costs drawn from an extreme value distribution such that the choice of ports can be modeled as a discrete choice. Then, the share of goods in sector s that n consumes from county $c \in i$ transported via port r is:

$$\pi_{in}^{c,r}(s) = \frac{T_i(s)K_i^c(s)\left(\kappa_i^c(s)\varepsilon_i^{cc(ir)}(s)\overline{\tau}_{ir}(s)\varepsilon_r^{m(ir)r}(s)\xi_r^r(s)t_{rn}^r(s)\right)^{-\theta(s)}}{\sum_{i'} T_{i'}(s)\left(\kappa_{i'n}(s)\overline{\tau}_{i'n}(s)\varepsilon_n^{m(i'n)m^*}(s)\right)^{-\theta(s)}}.$$

Summing across all counties $c \in i$ allows us to derive the share of varieties in sector s that n imports from state i via port r in n's total expenditure on s-goods:

$$\pi_{in}^r(s) = \lambda_{in}^r(s) \cdot \frac{T_i(s)\left(\kappa_{in}(s)\overline{\tau}_{in}(s)\right)^{-\theta(s)}}{\sum_{i'} T_{i'}(s)\left(\kappa_{i'n}(s)\overline{\tau}_{i'n}(s)\varepsilon_n^{m(i'n)m^*}(s)\right)^{-\theta(s)}}, \tag{16}$$

where $\left(\kappa_{in}(s)\overline{\tau}_{in}(s)\right)^{-\theta(s)} = \sum_r \left(\kappa_{ir}(s)\overline{\tau}_{ir}(s)\varepsilon_r^{m(ir)r}(s)\xi_r^r(s)t_{rn}^r(s)\right)^{-\theta(s)}$ and $\lambda_{in}^r(s)$ is the share of goods exported from i to n via port r, which is given by:

$$\lambda_{in}^r(s) = \frac{\left(\kappa_{ir}(s)\overline{\tau}_{ir}(s)\varepsilon_r^{m(ir)r}(s)\xi_r^r(s)t_{rn}^r(s)\right)^{-\theta(s)}}{\sum_{r'}\left(\kappa_{ir'}(s)\overline{\tau}_{ir'}(s)\varepsilon_{r'}^{m(ir')r'}(s)\xi_{r'}^{r'}(s)t_{r'n}^{r'}(s)\right)^{-\theta(s)}}.$$

Next, we derive port shares for imports from foreign countries to state j. Consider exports from a foreign country n to state j such that the share of goods transported via port r can be written as:

$$\lambda_{nj}^r(s) = \frac{\left(t_{nr}^r(s)\xi_r^r(s)\varepsilon_r^{rc(rj)}(s)\overline{\tau}_{rj}(s)\varepsilon_j^{m(rj)m^*}(s)\right)^{-\theta(s)}}{\sum_{r'}\left(t_{nr'}^{r'}(s)\xi_{r'}^{r'}(s)\varepsilon_{r'}^{r'c(r'j)}(s)\overline{\tau}_{r'j}(s)\varepsilon_j^{m(r'j)m^*}(s)\right)^{-\theta(s)}}.$$

Then the share of j's total expenditure on s imported from n via port r can be specified as:

$$\pi_{nj}^{r}(s)=\lambda_{nj}^{r}(s)\cdot\frac{T_{n}(s)\left(\kappa_{nj}(s)\overline{\tau}_{nj}(s)\right)^{-\theta(s)}}{\sum_{i'}T_{i'}(s)\left(\kappa_{i'n}(s)\overline{\tau}_{i'n}(s)\varepsilon_{n}^{m(i'n)m^{*}}(s)\right)^{-\theta(s)}},\tag{17}$$

where $\left(\kappa_{nj}(s)\overline{\tau}_{nj}(s)\right)^{-\theta(s)}=\sum_{r}(\kappa_{n}(s)\varepsilon_{j}^{m(rj)m^{*}}\overline{\tau}_{rj}(s)\varepsilon_{r}^{rc(rj)}(s)\xi_{r}^{r}(s)t_{nr}^{r}(s))^{-\theta(s)}$. Hence, state-to-country and country-to-state trade shares can be expressed in the same way as state-to-state shares in equation (15).

Congestion and Endogenous Route Choice

Transporting goods between states within the United States as well as to ports for international transshipment by road involves using segments of the available highway network. In the model, producers choose optimal highway routes to domestic and international destinations such that the domestic portion of trade costs reflects travel time via the highway network and takes into account congestion on each road segment. Congestion on each segment, in turn, depends on trade-generated traffic. Thus, we allow trade costs to endogenously depend on traffic generated by domestic and international trade.

Let $\mathcal{C}(s)$ denote a single shipment of goods in sector s so that trade flows between i and j–including trade when i or j act as a port hub–generate the following interstate traffic:

$$M_{ij}(s)=\frac{\pi_{ij}(s)Y_{j}(s)}{\kappa_{ij}(s)\mathcal{C}(s)}+\sum_{n}\mathbb{1}_{r=i}\lambda_{nj}^{r}(s)\frac{\pi_{nj}(s)Y_{j}(s)}{\kappa_{nj}(s)\mathcal{C}(s)},\tag{18}$$

where $\mathbb{1}_{r\in j}$ is an indicator function that takes value of one whenever port r is located in state i and zero otherwise.

Using the results in equation (11), we can derive total traffic on route R due to trade between locations i and j as:

$$M_{ij}^{R}=\sum_{R\in\boldsymbol{R}_{ij}}\varsigma_{ij}^{R}(s)M_{ij}(s).\tag{19}$$

Not every segment of the highway network will be affected by total trade-generated traffic M_{ij} but only those 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. Recall that $\boldsymbol{S}$ denotes the set of all available segments $\mathcal{S}\in\boldsymbol{S}$ in the road network.

Different routes $R \in \boldsymbol{R}_{ij}$ may overlap and total traffic on segment $\mathcal{S}$ is then:

$$N_{\mathcal{S}} = \sum_{R \in \boldsymbol{R}_{ij}} \mathbb{1}_{\mathcal{S} \in R} M_{ij}^{R}, \tag{20}$$

where $\mathbb{1}_{\mathcal{S} \in R}$ is an indicator function which is equal to one whenever segment $\mathcal{S}$ belongs to route R and zero otherwise.

Further, we parameterize travel time, $\mathcal{T}_{\mathcal{S}}$, introduced in Section 2 as $\mathcal{T}(N_{\mathcal{S}}, F_{\mathcal{S}})$ which measures travel time on segment $\mathcal{S}$ and depends on trade-generated congestion, $N_{\mathcal{S}}$, conditional on the segment fundamentals, $F_{\mathcal{S}}$. The latter includes distance, speed, and traffic generated by sources other than trade. Then total travel time on route R can be specified as:

$$\mathrm{T}_{ij}^{R} = \sum_{\mathcal{S} \in R} \mathcal{T}(N_{\mathcal{S}}, F_{\mathcal{S}}). \tag{21}$$

The expression for travel time in equation (21) accounts for two channels of how trade-generated traffic affects trade costs between i and j. First, M_{ij} increases congestion levels $N_{\mathcal{S}}$ on the relevant segments. Second, depending on the traffic patterns related to trade and road capacity, the allocation of traffic across different routes $R \in \boldsymbol{R}_{ij}$ is a function of travel time on each route.

Labor Mobility

Our specification of labor mobility in the model is standard and largely follows Anderson (2011).[12] Labor is mobile across counties in the United States subject to migration costs. Workers choose where to live to maximize indirect utility, V_i^c, across all possible counties subject to migration costs. Each county has an initial stock of labor L_i^c and workers 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

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

from $c \in i$ to $m \in j$ can then be written as follows:

$$\omega_{ij}^{cm} = \frac{\left(V_j^m \delta_{ij}^{cm}\right)^{\frac{\varrho+1}{\varrho}}}{\sum_{k,n} \left(V_n^k \delta_{in}^{ck}\right)^{\frac{\varrho+1}{\varrho}}}. \tag{22}$$

Note that ϱ governs the degree of labor mobility across counties. When $\varrho \to 0$, labor is completely immobile with $\omega_{ii}^{cc} = 1$ for all c and i. On the other hand, when $\varrho \to \infty$, 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 former case. Given migration flows, total labor in each county and state is given by:

$$L_i^c = \sum_{k,n} \omega_{ni}^{kc} L_n^k \text{ and } L_i = \sum_c L_i^c. \tag{23}$$

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:

$$Y_i(s) = \sum_{\dot{s}} (1 - \gamma_i(s)) \xi_i(s\dot{s}) \sum_j \pi_{ij}(s) Y_j(s) + \alpha_i(s)(I_i + D_i), \tag{24}$$

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 specify the trade balance condition:

$$\sum_s \sum_n \pi_{ni}(s) Y_i(s) - D_i = \sum_s \sum_n \pi_{in}(s) Y_n(s), \tag{25}$$

which given a numeraire determines wages in all states and countries. In the United States, labor markets clear at the state level such that there is a single nominal wage per state. However, prices and production may adjust at the county level such that the model is able to calculate county-level outcomes. This completes the description of the model and allows us to formally define the equilibrium conditions. Let us use $\mathbb{V}$ to denote the following parameters $\{\alpha_i(s), \gamma_i(s), \eta_i(\dot{s}s), \theta(s), \sigma, \varrho\}$.

Definition 1: *Given primitives $\mathbb{V}$, K_i^c, $T_i(s)$, $\xi_i^r(s)$, L_i^c, D_i, δ_{ij}^{cm} and trade costs structure $\boldsymbol{S}$, $\varepsilon_{ij}^{cc(ij)}(s)$, $F_{\mathcal{S}}$, $\tau_{ij}(s)$, and $v_{ij}^{\ell}(s)$, an equilibrium is a vector of wages, $\boldsymbol{w} \in \mathbb{R}_+$, and prices, $\{P_i^c(s)\}$, such that the conditions in (4), (7), (8), (11), (12), (14), (15), (16), (17), (18),* (20), (21), (22), (23), (24), (25) *are satisfied for all* c, i, s *and* $\mathcal{S}$.

3.1 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:

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

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. This approach has been used for counterfactual analysis in the context of international trade, e.g., Dekle, Eaton and Kortum (2007) and Caliendo and Parro (2015). More recently, Allen and Arkolakis (2022) show how to apply this approach in models featuring endogenous congestion and route choice. Our solution method is consistent with their approach and uses the observed allocations of domestic and international trade shares, labor and traffic as a way 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 foreign trading partners. As it turns out, we can examine county-level outcomes using the observed state-level allocations together with data on intrastate trade costs.

We start by calculating the counterfactual changes in trade costs relative to the benchmark equilibrium. In particular, we remove portions of the highway system in the United States, e.g., the entire Interstate Highway System or individual highways (e.g., I-5, I-10) so that producers and consumers are presented with a subset of segments available in the benchmark, $\boldsymbol{S}' \subseteq \boldsymbol{S}$. We then calculate counterfactual outcomes with a specific focus on the county and aggregate welfare changes generated by the exogenous changes in the available road network. Note that even after removing the entire IHS, the remaining federal-aid (approximately 133,00 miles) and state (approximately 213,00 miles) highways are available to move between any i and j, although subject to higher trade costs. Hence, our counterfactuals quantify the value of the IHS or individual highways conditional on the remaining highway network (and other modes).

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. They can choose among $R = 6$ new possible routes that may partially overlap on certain segments. Let $\rho_s(\mathrm{T}_{ij}^R)$ be a sector-specific function that translates travel time from i to j in sector s trade costs such that $\tau_{ij}^R(s) = \rho_s(\mathrm{T}_{ij}^R)$. We specify the exact functional form of $\rho_s(\cdot)$ in the next section. Then, given the new set of counterfactual $\boldsymbol{S}'$, we can specify changes in trade costs via the highway network as:

$$(i)\ \widehat{\tau}_{ij}(s) = \sum_R \left(\varsigma_{ij}^R(s) \left[\frac{\rho_s(\mathrm{T}'^R_{ij})}{\rho_s(\mathrm{T}_{ij}^R)} \right]^{-\sigma} \right)^{-\frac{1}{\sigma}}.$$

Next, conditional on costs of transporting goods via rail, water and air staying constant, we can specify changes in the average trade costs between i and j as follows:

$$(ii)\ \widehat{\overline{\tau}}_{ij}(s) = \left(\varsigma_{ij}(s) \widehat{\tau}_{ij}(s)^{-\sigma} + [1 - \varsigma_{ij}(s)] \right)^{-\frac{1}{\sigma}},$$

where $\varsigma_{ij}(s)$ are observed in the data. We keep sea trade costs from each port r to each country n as well as port efficiency constant such that $\widehat{t}_{jn}(s) = 1$ and $\widehat{\xi}_j^r(s) = 1$. This allows us to calculate counterfactual changes in sectoral average production costs gross of trade costs between states and foreign countries and vice versa as:

$$\begin{aligned}
(iii)\ \left(\widehat{\kappa}_{in}(s)\widehat{\overline{\tau}}_{in}(s)\right)^{-\theta(s)} &= \sum_r \lambda_{in}^r(s) \left(\widehat{\kappa}_{ir}(s) \widehat{\overline{\tau}}_{ir}(s) \widehat{\varepsilon}_r^{m(ir)r}(s) \right)^{-\theta(s)}, \\
(iv)\ \left(\widehat{\kappa}_{nj}(s)\widehat{\overline{\tau}}_{nj}(s)\right)^{-\theta(s)} &= \sum_r \lambda_{nj}^r \left(\widehat{\kappa}_n(s) \widehat{\varepsilon}_j^{m(rj)m^*} \widehat{\overline{\tau}}_{rj}(s) \widehat{\varepsilon}_r^{rc(rj)}(s) \right)^{-\theta(s)}.
\end{aligned}$$

Hence, given the counterfactual road network $\boldsymbol{S}' \subseteq \boldsymbol{S}$, the corresponding counterfactual changes in intrastate, inter-state and international trade costs are given by conditions (i) to (iv). Changes in trade costs together with the observations on $\{\mu_{ij}^c(s), \pi_{ij}(s), \lambda_{ij}^r(s), \omega_{ij}^{cm}, L_i^c, M_{ij}(s)\}$ in the initial equilibrium allow us to characterize the counterfactual equilibrium by the following conditions:

(v) *Changes in county-level costs:* $\widehat{\kappa}_i^c(s) = \widehat{w}_i^{\gamma_i(s)} \widehat{\mathbb{P}}_i^c(s)^{1-\gamma_i(s)}$.

(vi) *Changes in county-level price of intermediate input:* $\widehat{\mathbb{P}}_i^c(s) = \sum_{\dot{s}} \left(\xi_i(\dot{s}s) \widehat{P}_i^c(\dot{s})^{1-\chi} \right)^{\frac{1}{1-\chi}}$

(vii) *Changes in state-level costs:* $\widehat{\kappa}_{ij}(s) = \left(\sum_c \mu_{ij}^c \left(\widehat{\kappa}_i^c(s) \widehat{\varepsilon}_i^{cc(ij)}(s) \right)^{-\theta(s)} \right)^{-\frac{1}{\theta(s)}}$.

(*viii*) *Counterfactual trade shares:* $\pi_{ij}(s)' = \dfrac{\pi_{ij}(s)\left(\widehat{\kappa}_{ij}(s)\widehat{\overline{\tau}}_{ij}(s)\widehat{\varepsilon}_j^{m(ij)m^*}(s)\right)^{-\theta(s)}}{\sum_{i'}\pi_{i'j}(s)\left(\widehat{\kappa}_{i'j}(s)\widehat{\overline{\tau}}_{i'j}(s)\widehat{\varepsilon}_j^{m(i'j)m^*}(s)\right)^{-\theta(s)}}$.

(*ix*) *Changes in state-level prices:* $\widehat{P}_j(s) = \left(\sum_{i'}\pi_{i'j}(s)\left(\widehat{\kappa}_{i'j}(s)\widehat{\overline{\tau}}_{i'j}(s)\widehat{\varepsilon}_j^{m(i'j)m^*}(s)\right)^{-\theta(s)}\right)^{-\frac{1}{\theta(s)}}$.

(*x*) *Changes in county-level prices and real wages:* $\widehat{P}_i^c(s) = \widehat{\varepsilon}_i^{m^*c}(s)\widehat{P}_i(s)$ and $\widehat{V}_i^c = \widehat{w}_i/\widehat{P}_i^c$.

(*xi*) *Counterfactual migration shares:* $\omega_{ij}^{cm\prime} = \dfrac{\omega_{ij}^{cm}(\widehat{V}_j^m)^{\frac{\varrho+1}{\varrho}}}{\sum_{k,n}\omega_{in}^{ck}(\widehat{V}_n^k)^{\frac{\varrho+1}{\varrho}}}$.

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

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

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

(*xv*) *Counterfactual input shares:* $\xi_i'(\dot{s}s) = \xi_i(\dot{s}s)\widehat{P}_i(s)^{1-\chi}\widehat{\mathbb{P}}_i(s)^{\chi-1}$.

(*xvi*) *Counterfactual port shares:* $\lambda_{in}^r(s)' = \dfrac{\lambda_{in}^r(s)\left(\widehat{\kappa}_{ir}(s)\widehat{\overline{\tau}}_{ir}(s)\widehat{\varepsilon}_r^{m(ir)r}(s)\right)^{-\theta(s)}}{\sum_{r'}\lambda_{in}^{r'}(s)\left(\widehat{\kappa}_{ir'}(s)\widehat{\overline{\tau}}_{ir'}(s)\widehat{\varepsilon}_{r'}^{m(ir')r'}(s)\right)^{-\theta(s)}}$..

(*xvii*) *Counterfactual state wages:* $\sum_s\sum_j \pi_{ji}(s)'Y_i(s)' - D_i = \sum_s\sum_j \pi_{ij}(s)'Y_j(s)'$.

(*xviii*) *Counterfactual traffic:* $M_{ij}(s)' = \dfrac{\widehat{\pi}_{ij}(s)\widehat{Y}_j(s)}{\widehat{\kappa}_{ij}(s)}M_{ij}(s) + \sum_n \mathbb{1}_{r=i}\lambda_{nj}^r(s)'\dfrac{\widehat{\pi}_{nj}(s)\widehat{Y}_j(s)}{\widehat{\kappa}_{nj}(s)}M_{nj}(s)$.

Lastly, we determine traffic allocation shares and congestion:

$$(xix)\ \ M_{ij}^{R\prime} = \sum_{R\in\boldsymbol{R}_{ij}}\varsigma_{ij}^{R\prime}(s)M_{ij}(s)' \text{ and } N_{\mathcal{S}}' = \sum_{R\in\boldsymbol{R}_{ij}}\mathbb{1}_{\mathcal{S}\in R}M_{ij}^{R\prime}.$$

and counterfactual travel time that accounts for endogenous route choice:

$$(xx)\ \ \mathrm{T}_{ij}^{R\prime} = \sum_{\mathcal{S}\in R}\mathcal{T}(N_{\mathcal{S}}', F_{\mathcal{S}}).$$

Given the interstate traffic shares we can also calculate counterfactual changes in the intrastate trade costs. Hence, given the structure of counterfactual trade costs, the counterfactual equilibrium is a vector of counterfactual wages and prices such that the system defined by the conditions above is satisfied for all c, i, 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 in the benchmark equilibrium. 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.

We calibrate the model with data on US counties including the District of Columbia, but excluding Alaska and Hawaii. For computational purposes, we group counties into states according to conventional US states boundaries except for California and Texas. Due to their size and geographic shapes, we group counties in California into North and South agglomerations and counties in Texas into East, West, and North agglomerations. Splitting California and Texas is not necessary but it helps to improve the accuracy of our quantitative results as it allows us to account for the fact that there are multiple important economic agglomerations within these two states and producers in different agglomerations may choose different trade routes. Treating these agglomerations separately helps take this into account. This means that counties are grouped into 52 state areas.

We also include 35 other countries and an aggregate that combines data for the rest of the world.[13] In terms of the sectoral coverage, we consider 22 sectors including 12 manufacturing sectors, 8 service sectors, construction, and combined wholesale and retail trade.[14] The list of sectors is available in the Appendix. To solve for counterfactual equilibria, we need parameters in $\mathbb{V}$ and the values of $\{\varsigma_{ij}(s), \mu^c_{ij}(s), \pi_{ij}(s), \lambda^r_{ij}(s), \omega^{cm}_{ij}, L^c_i, M_{ij}(s)\}$ in the

[13]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.

[14]We follow the number and definition of sectors used in Caliendo, Dvorkin and Parro (2019). The Data Appendix provides more details, including 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.

benchmark equilibrium. We next describe how we obtain the benchmark values of these parameters and variables.

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 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. Due to data availability, $\gamma_i(s)$ vary by state but $\alpha_i(s)$ and $\eta_i(s\dot{s})$ are homogeneous for all states in the United States.

Transportation Mode Shares

To account for substitution across different transportation modes in counterfactual equilibria, we need initial transportation mode shares, $\varsigma_{ij}(s)$, and the elasticity parameter σ. We adopt the value of $\sigma = 14.2$ from Allen and Arkolakis (2014). To calculate transportation mode shares across states, we use data from the 2012 Commodity Flow Survey. We aggregate sectoral trade flows to state level by summing flows transported via a single mode in four categories: truck (*for-hire truck* and *private truck*), rail, water (*inland water, Grate Lakes, deep sea,* and *multiple waterways*), and air, which together allow us to calculate $\varsigma_{ij}(s)$.[15]

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 state-to-country and country-to-state trade flows for 2012 are downloaded from the Census Bureau's USA Trade online portal.[16] Domestic trade flows are

[15]Single mode transportation accounts for roughly 85 percent of domestic trade (US Bureau of the Census, 2012).

[16]For the data taken from the Commodity Flow Survey, we focus on single-mode shipments, which account for roughly 85 percent of domestic trade in 2012 (US Bureau of the Census, 2012). The data from USA Trade for country-state trade flows aggregate across all modes. However, a significant fraction of international trade by the United States involves a least some portion of the journey taking place via truck. For example, data from the Bureau of Transportation Statistics (Bureau of Transportation Statistics, 2015) indicate that up to 85 percent of international trade includes a truck as either the only mode of tranposrt or in combination with other modes.

observed at the level of Core Based Statistical Areas, which allows us to calculate domestic export and import flows for two agglomeration areas in California and three agglomeration areas in Texas. In addition, we combine foreign export and import flows from USA Trade at the district level with the data on international trade flows from the World Input Output Database to calculate foreign trade for California and Texas. In addition, we use information on trade flows between US states and foreign countries through US ports, which are also drawn from the Commodity Flow Survey and USA Trade for 2012. Data on international trade flows between foreign countries comes from the World Input Output Database. To calculate the initial values of μ^c_{ij}, we combine Commodity Flow Survey data which reports sectoral trade flows at the level of Core Based Statistical Areas and data on annual payroll at the county level as follows:

$$\mu^c_{ij}(s) = \mu^{CBS}_{ij}(s) \cdot \mu^{c,CBS}(s),$$

where $\mu^{CBS}_{ij}(s)$ is the share of CBS area in state i's total exports to j and $\mu^{c,CBS}(s)$ is the share of county c in CBS area's total value added in sector s.[17]

County Employment, Output, and Migration

Data on employment and wages 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^c_i. Migration flows between US counties are constructed from Internal Revenue Service data for 2011-2012.[18] 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^{cm}_{ij} from the model. Hence, the stock of labor in $c \in i$ is the sum of all workers across all destinations $m \in j$ that resided in c prior to 2012.

4.1 Constructing Trade Costs

The starting point for constructing trade costs is detailed information on the US highway network shown in Figure **1**. We use the highway network, domestic navigable waterways, international shipping lanes, and trade flows to construct the domestic and international

[17] The concordance between Core Based Statistical Areas and counties is available at https://www.nber.org/research/data/census-core-based-statistical-area-cbsa-federal-information-processing-series-fips-county-crosswalk.

[18] Census data from the Integrated Public Use Microdata (IPUMS) samples provide an alternative source of information on migration, but only for migration between metropolitan areas. We use the information from the IRS, since these data are available at the county level.

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 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 331,074 segments 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.[19] Next we use the highway network to identify the routes and corresponding travel time underlying the domestic trade costs by road, including interstate, $\tau_{ij}^{R}(s)$, and intrastate, ε_{ij}^{cm}, trade costs. To calculate the first-best route, we consider the fastest travel time route between two locations i and j taking into account the actual traffic on each segment from i to j. In addition, we consider up to five additional alternative routes between i and j in the event that endogenous congestion is high enough. In particular, to calculate the these alternative routes, we decrease the travel speed on the segments of the fastest route to account for potential congestion. The practical implications of this approach is that these alternative routes allow for circumventing high-traffic urban areas in the event that traffic is endogenously increased when we calculate our counterfactuals. Appendix Figure B2 provides an illustration of the six alternative routes used in the case of travel between Colorado and Florida.

To calculate the international trade costs 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 Appendix Figure B3 and shipping lanes are presented in Panel B of Appendix Figure B3. Using this data we calculate the minimum distance route between each port and country. This corresponds to the international trade cost component t_{ik}. The combined domestic and international trade cost components can be used to construct the trade costs between any pair of locations in the model.

[19]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.

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. Following Head and Ries (2001), let us establish the following identify for an arbitrary variable a_{ij} that varies by exporter i and importer j:

$$\widetilde{a}_{ij} = \frac{a_{ij}}{a_{ii}}\frac{a_{ji}}{a_{jj}}.$$

This Head-Ries decomposition allows us to eliminate i-specific and j-specific components in a_{ij} such that the structural gravity equation in equation (15) can be reformulated as:

$$\ln\left(\widetilde{\pi}_{ij}(s)\right) = -\theta(s)\ln\left(\widetilde{\tau\varepsilon}_{ij}(s)\right) + \widetilde{Z}_{ij}(s)\Theta^s + \epsilon_{ij}, \tag{26}$$

where $\widetilde{\tau\varepsilon}_{ij}(s)$ is a measure of total trade costs between i and j, which we describe below, and $\widetilde{Z}_{ij}(s)$ includes $\widetilde{\kappa}_{ij}(s)$ and $\widetilde{\varsigma}_{ij}(s)$; [20] ϵ_{ij} is a stochastic error term. To estimate $\theta(s)$ in equation (26), we need observable proxy measures of trade costs. We construct such measures of $\tau\varepsilon_{ij}(s)$ for the purpose of estimating $\theta(s)$ following the approach suggested by Combes and Lafourcade (2005). We combine information on the time and distance of moving goods between state i and the core county in state j.[21] In particular, we use the labor cost determined by the hourly wage of a truck driver averaged between origin i and destination j and the fuel cost based on the price of fuel per gallon together with fuel usage per mile to calculate:

$$\tau\varepsilon_{ij}(s) = 1 + \frac{\text{hours}_{ij}\cdot\text{wage per hour}_{ij} + \text{miles}_{ij}\cdot\text{cost per mile}}{\text{average value of shipment in sector } s} \tag{27}$$

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

Panel A of Table **1** shows the results of estimating $\theta(s)$ for each of the 12 manufacturing sectors. Two-way clustered standard errors on states i and j are reported in parentheses. The

[20] We obtain the estimates of $\kappa_{ij}(s)^{\theta(s)}$ as fitted values of ij-specific fixed effects, $f_{ij}(s)$, in:

$$\ln\big(\mu^c_{ij}(s)\big) = f_c(s) + f_{ij}(s) + \text{error}_{ij},$$

Table 1: Estimates of Trade Cost and Travel Time Elasticities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Panel A: Estimates of Trade Cost Elasticity												
$\theta(s)$	7.8	4.4	5.5	14.2	10.5	7.8	3.3	7.4	6.6	6.3	11.5	3.6
	(0.77)	(0.72)	(0.44)	(2.15)	(1.46)	(0.59)	(0.43)	(0.75)	(1.31)	(1.36)	(2.26)	(0.44)
Observations	1,818	1,502	1,898	768	1,912	1,870	1,248	1,980	1,806	1,708	1,340	1,878
Panel B: Estimates of Travel Time Elasticity												
$\varphi(s)$	-0.177	-0.071	-0.184	-0.327	-0.113	-0.111	-0.267	-0.137	-0.076	-0.055	-0.101	-0.082
	(0.016)	(0.015)	(0.009)	(0.027)	(0.014)	(0.015)	(0.019)	(0.013)	(0.008)	(0.011)	(0.016)	(0.008)
Observations	2,343	2,343	2,333	2,226	2,333	2,349	2,311	2,341	2,337	2,295	2,303	2,337

Notes: The table shows estimates of trade cost elasticity, $\theta(s)$, and travel time elasticity, $\varphi(s)$, for each sector s in panels A and B, respectively. The dependent variable in Panel A is the Head and Ries (2001) transformation of trade shares referred to in the text. The dependent variable in Panel B is the trade share between state i and state j. 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 reflect the number of state origin-destination pairs with non-zero trade flows. Standard errors clustered on origin and destination state are reported in parentheses.

results indicate substantial variation across sectors: the estimates of $\theta(s)$ range between 3.3 for 14.2 and are statistically significant at the 1 percent level. The magnitudes are consistent with the existing estimates in the literature, e.g., Eaton and Kortum (2002) and Caliendo and Parro (2015) who estimate average manufacturing θ to be 8.3 and 6.5, respectively. Our approach is complementary to 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 $\theta(s)$.[22] Finally, we assign the average value of these estimates to the sectors where trade flow data are not available.

Parameterizing Domestic Trade Costs and Congestion

We parameterize intrastate and interstate domestic trade costs as a function of shipping time via the available highway network. We start with estimating the effects of travel time on trade via the gravity equation in (15) using Poisson Pseudo Maximum Likelihood for each

which is a stochastic version of the structural equation for $\mu_{ij}^{c}(s)$.

[21] For estimation of $\theta(s)$ and $\varphi(s)$ (below), we do not impute trade flows for separate agglomerations in California and Texas but rather rely on aggregate flows for these two states.

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

sector s:

$$\pi_{ij}(s) = \exp\left[\varphi(s)\mathrm{T}_{ij} + Z_{ij}(s)\Xi^s + exp_i(s) + imp_j(s)\right] + \epsilon_{ij}, \tag{28}$$

where T_{ij} is the travel time between state i and state j, and $\varphi(s)$ is the elasticity of trade flows with respect to travel time;[23] $exp_i(s)$ and $imp_j(s)$ are exporter-sector- and importer-sector-specific fixed effects, and $Z_{ij}(s)$ is a vector of controls (i.e., for $\kappa_{ij}(s)$ and $\varsigma_{ij}(s)$) and Ξ^s are the associated coefficients. Note that in terms of the underlying theory, the interpretation of $\varphi(s)$ comes from the following relationship:

$$\varphi(s)\mathrm{T}_{ij} = -\theta(s)\ln\tau_{ij}(s)$$

Hence, the empirical relationship in equation (28) leads to the following parameterization of trade costs as a function of T_{ij}:

$$\tau_{ij}(s) \equiv \rho_s(\mathrm{T}_{ij}) = \exp\left(-\frac{\varphi(s)}{\theta(s)}\,\mathrm{T}_{ij}\right).$$

This parameterization is consistent with Hummels and Schaur (2013) and Allen and Arkolakis (2022). It also obeys the multiplicative structure of total trade costs in equation (9). The results of estimating $\varphi(s)$ for each sector s are shown in Panel B in Table **1**, where standard errors clustered on states i and j are reported in parentheses. Hence, to specify trade costs we need travel time, estimates of $\theta(s)$ and $\varphi(s)$. The results indicate substantial heterogeneity across sectors, with estimates of $\varphi(s)$ ranging from -0.055 for *Computer, Electronic Products, and Electrical Equipment* to -0.327 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.

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. We directly observe $\mathrm{LOS}_{\mathcal{S}}$ as this measure is recorded by the Federal Highway Administration. Next, we use equations (18), (19), and (20) to calculate the implied measure of $N_{\mathcal{S}}$. First, from the Commodity Flow Survey we observe total number of shipments in each industry, which allows us to calculate the average value of one shipment in each industry. We then use data

[23]For estimating $\theta(s)$ and $\varphi(s)$ we rely on the first best route to calculate T_{ij}.

on sectoral trade flows together with the average value per shipment to calculate the measure of traffic $M_{ij}(s)$. Then we use equation (19) to obtain traffic allocation across different routes $M_{ij}^R(s)$. Finally, we use our highway network data to generate indicators $\mathbb{1}_{\mathcal{S}\in R}$ and calculate $N_{\mathcal{S}}$ as in equation (20). We then estimate the following regression:

$$\text{LOS}_{\mathcal{S}} = \zeta N_{\mathcal{S}} + Z_{\mathcal{S}}\Gamma + \epsilon_{\mathcal{S}}, \tag{29}$$

where $Z_{\mathcal{S}}$ is a vector of controls, which includes (log) distance of segment $\mathcal{S}$ and frequency of use of this segment for trade and $\epsilon_{\mathcal{S}}$ is a stochastic error term. The frequency of use is calculated by summing $\mathbb{1}_{\mathcal{S}\in \boldsymbol{R}_{ij}}$ for all i, j and across all routes and indicates the number of pairs that use segment $\mathcal{S}$ for transporting goods. We first estimate equation (29) using ordinary least squares (OLS) and report the results in the first column of Table **2**. The OLS coefficient ζ is positive and precisely estimated.

In addition to estimating equation (29) using OLS, we also address potential bias and measurement error by using an instrumental variable approach. For example, LOS affects travel time, which may lead to lower trade and associated traffic and may lead to a biased estimate of ζ. To circumvent this problem we develop two instruments for $N_{\mathcal{S}}$. The intuition behind both instruments is that they predict bilateral trade generated traffic but are plausibly exogenous to the observed levels of trade traffic on segment $\mathcal{S}$.

The first instrument is based on historical distribution of population across US states in 1900. The second instrument is based on geographic areas of US states. We calculate two instruments for $N_{\mathcal{S}}$ as follows:

$$B_{\mathcal{S}}^{(I)} = \sum_{ij} \mathbb{1}_{\mathcal{S}\in \boldsymbol{R}_{ij}} \text{Population}_{ij} \text{ and } B_{\mathcal{S}}^{(II)} = \sum_{ij} \mathbb{1}_{\mathcal{S}\in \boldsymbol{R}_{ij}} \text{Area}_{ij}, \tag{30}$$

where Population_{ij} is the sum of populations in states i and j in 1900 and Area_{ij} is the sum of their geographic areas. We then use $B_{\mathcal{S}}^{(I)}$ and $B_{\mathcal{S}}^{(II)}$ in logs in the first stage. The results of the second stage together with the first stage F-statistics are reported in Table **2**.

The IV coefficients on $N_{\mathcal{S}}$ are precisely estimated and equal 0.083 and 0.076, respectively. For our calibration and counterfactual experiments, we rely on the more conservative value of 0.076. This allows us to construct the counterfactual level of service for each $\mathcal{S}$ as:

$$\text{LOS}'_{\mathcal{S}} = \text{LOS}_{\mathcal{S}} - 0.076(N_{\mathcal{S}} - N'_{\mathcal{S}}),$$

where $\text{LOS}_{\mathcal{S}}$ and $N_{\mathcal{S}}$ are benchmark values. Note that upon a shock to trade costs, the

Table 2: The Relationship Between Level of Service and Traffic

	OLS	IV	IV
	(1)	(2)	(3)
$N_{\mathcal{S}}$	0.018	0.083	0.076
	(0.001)	(0.002)	(0.003)
F-statistic		3,487	2,039
Observations	78,281	78,281	78,281

Notes: The table shows the results of estimating (29) on all highway segments with positive traffic. The dependent variable is the level of service (LOS) on segment $\mathcal{S}$ in state i. All specifications include a set of ij-symmetric dummy variables that equal one if $\mathcal{S}$ is used for transporting goods to or from state i to j and zero otherwise. The log of $N_{\mathcal{S}}$ reflects the amount of trade-generated traffic on $\mathcal{S}$ and the log of distance$_{\mathcal{S}}$ is the distance (in miles) of segment $\mathcal{S}$. The first-stage F-statistic is the Kleibergen-Paap statistic. Robust standard errors are reported in parentheses.

model generates the value of $N'_{\mathcal{S}}$, which we use to calculate counterfactual levels of $\text{LOS}'_{\mathcal{S}}$. The latter identifies the counterfactual congestion speed coefficient $\mathcal{A}'_{\mathcal{S}}$ following the step function in equation (1).

Calibrating State-Port Trade Shares

The remaining component required for the counterfactuals is the state-port-country share, $\lambda^r_{in}(s)$, 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 $r \in j$. This corresponds to the following equation in the context of our theoretical framework:

$$\Lambda^r_i(s) = \sum_{n \neq i} \pi^r_{in}(s) Y_n(s) = \sum_{n \neq i} T_i(s) \left(\kappa_{ir}(s) \overline{\tau}_{ir}(s) \varepsilon^{m(ir)r}_r(s) \xi^r_r(s) t^r_{rn}(s) \right)^{-\theta(s)} P_n(s)^{\theta(s)} Y_n(s).$$

We pre-multiply $\Lambda^r_i(s)$ by $(\kappa_{ir}(s)\overline{\tau}_{ir}(s)\varepsilon^{m(ir)r}_r(s))^{\theta(s)}$ 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:

$$\Lambda^r_i(\kappa_{ir}(s)\overline{\tau}_{ir}(s)\varepsilon^{m(ir)r}_r(s))^{\theta(s)} = \exp\left(\text{state}_i(s) + \text{iport}_r(s)\right) + \epsilon_{ir}(s), \tag{31}$$

where $\text{state}_i(s)$ and $\text{iport}_r(s)$ are sector-state-specific and sector-port-specific fixed effects.

Note that the variation in the left-hand side variable allows us to obtain an estimate of $\text{state}_i(s)$, which is structurally related to an unknown parameter $T_i(s)$ such that $T_i(s) = \exp(\text{state}_i(s))$.

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 $n \neq i$):

$$\mathrm{V}_n^r(s) = \sum_{i \neq n} \pi_{in}^r(s) Y_n(s) = \sum_{i \neq j} T_i(s) \left(\kappa_{ir}(s)\overline{\tau}_{ir}(s)\varepsilon_r^{m(ir)r}(s)\xi_r^r(s)t_{rn}^r(s)\right)^{-\theta(s)} P_n(s)^{\theta(s)} Y_n(s)$$

We then estimate the following equation using Poisson Pseudo Maximum Likelihood and data on trade flows between each US port r and each foreign trading partner j:

$$\mathrm{V}_n^r(s) = \exp\left(\text{xport}_r(s) + \sum_{q=1}^{5} \psi_q(s)\mathcal{Q}_q \ln(\text{distance}_{rn}) + \text{country}_n(s)\right) + \epsilon_{rj}(s) \tag{32}$$

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 Appendix Figure B4. We recover international trade costs as:

$$t_{rn}(s)^{-\theta(s)} = \exp\left(\sum_{q=1}^{5} \hat{\psi}_q(s)\mathcal{Q}_q \ln(distance_{rn})\right)$$

Next note that $\text{xport}_r(s)$ is structurally related to unobserved port productivity level $\xi_r^r(s)$:

$$\exp\left(\text{xport}_r(s)\right) = \xi_r^r(s)^{-\theta(s)} \sum_{i \neq j} T_i(s) \left(\kappa_{ir}(s)\overline{\tau}_{ir}(s)\varepsilon_r^{m(ir)r}(s)\right)^{-\theta(s)}$$

Using this identity and our estimates of $T_i(s)$ from the first regression, we can recover port-specific productivity parameters as follows:

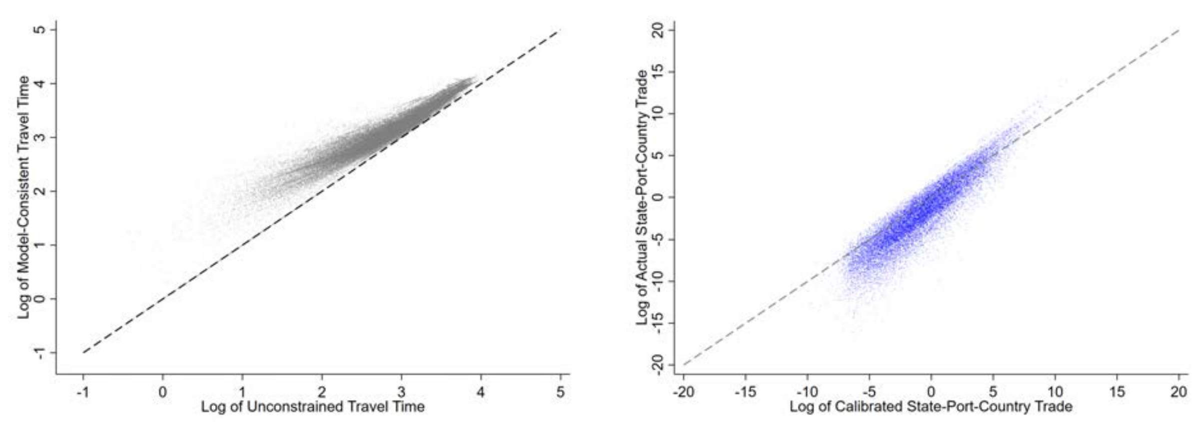
$$\xi_r^r(s)^{-\theta(s)} = \frac{\exp\left(\widehat{\text{xport}_r}(s)\right)}{\sum_{i \neq j} \exp\left(\widehat{\text{state}_i}(s)\right) \left(\kappa_{ir}(s)\overline{\tau}_{ir}(s)\varepsilon_r^{m(ir)r}(s)\right)^{-\theta(s)}}.$$

Once we have recovered $t_{rn}(s)^{-\theta(s)}$ and $\xi_r^r(s)$, we can calculate exporter-port-importer shares $\lambda_{in}^r(s)$ and $\lambda_{nj}^r(s)$.

4.2 Calibrated Model versus Data

In this section, we quantitatively evaluate two assumptions of the model against available data not targeted in the calibration. First, our procedure of aggregating counties into states as well as using state-level outcomes to inform county-level economic outcomes depends on the specification of trade costs in equation (9), where we assume that there is a common export county $c(ij)$ used by all counties in i to export to j. We compare how accurately this specification reflects travel time when no restrictions are imposed. In Panel A of Figure 4, we plot travel time between all $c \in i$ and $m^* \in j$ calculated as the lowest travel time not constrained by the assumptions of the model ("unconstrained") versus travel time that follows the routing assumptions of the model ("model-consistent"). Unconstrained travel times are lower than their model-consistent counterparts, which is not surprising as outcomes of any constrained optimization should deliver relatively longer travel times uniformly for all ij-pairs. However, for our purposes it is important to match the spatial variation in travel times across different origins and destinations. The figure suggests that our multiplicative specification of trade costs is able to do so; the spatial correlation between model-consistent ij-specific travel times and their unconstrained counterparts is 0.96.

Figure 4: Calibrated Model versus Data



A. Travel Time B. State-Port-Country Trade

Notes: Panel A shows the relationship between unconstrained average county-to-county trade costs and their model consistent counterparts. Panel B 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.

Second, we evaluate the accuracy of the calibrated exporter-port-importer shares. In particular, we compare the predictions of the model to additional 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 Panel B of Figure 4 suggest that our calibration of $\lambda_{in}^{r}(s)$ matches the data well; the correlation between predicted and actual aggregate state-port-country trade flows is 0.92.

5 Counterfactual Results

In this section, we use the calibrated model to carry out counterfactuals that quantify the value of the IHS and individual highways. First, we quantify the losses from removing the entire Interstate Highway System. We eliminate segments that belong to the IHS such that the counterfactual available road network is $\boldsymbol{S}' \subseteq \boldsymbol{S}$ and producers are forced to re-optimize by choosing different shipping routes and generally face higher trade costs relative to the benchmark equilibrium. Second, we evaluate the losses from removing individual segments of the IHS (I-5, I-10, etc). For these counterfactuals we focus on ten of the largest numbered interstates. Finally, we consider the added value of four proposed highways that have been identified for improvements. These highways are on the Federal Highway Administration's high priority corridor list and represent the most likely portions of the highway system to be improved in the future. For example, these upgrades are part of proposals contained in several pieces of legislation, including the Intermodal Surface Transportation Efficiency Act (1991), the Safe, Accountable, Flexible, Efficient Transportation Equity Act (2005), the Moving Ahead for Progress in the 21st Century Act (2012), and the Infrastructure Investment and Jobs Act (2021).

In addition, the model allows us to decompose the aggregate effect into the contribution of domestic versus international trade costs components. To isolate the domestic component of total welfare costs, we assume that producers use counterfactual road network $\boldsymbol{S}' \subseteq \boldsymbol{S}$ for interstate trade but not for international exports and imports. The value of the international component is then calculated as the difference between the total value and the value due to the domestic component. Hence, the interpretation of the international component is the marginal value due to better international market access conditional on using counterfactual highway network for domestic trade. By design we rule out a possibility that counterfactual domestic roads are used exclusively for international trade. Note that our counterfactuals quantify the value of the entire IHS and its individual segments through the lens of domestic and international trade. Hence, our results should be interpreted as the value the IHS provides due to the easier movement of goods across domestic and international locations while taking other potential benefits of the highway system, e.g. faster commuting, as given.

5.1 Result for Removing the Entire IHS

The baseline counterfactual results are shown in Table 3 and report counterfactual losses from removing the IHS including nearly 50,000 miles of limited-access roads graded for high travel speeds. The table is divided into two panels. In Panel A, we decompose the value of the IHS when we account for trade-related congestion effects, whereas the values presented in Panel B do not account for them.

Each panel has five rows that correspond to different cases for how technology and migration channels react to the counterfactual change in the highway network: **(1)** Assumes that there is no migration and that the intermediate production technology is close to the Leontief structure. For that, we set $\chi = 0.1$ from Atalay (2017) and turn off migration by setting $\varrho \to 0$. **(2)**Assumes $\chi = 0.1$ but allows for labor mobility by setting $\varrho \to \infty$. **(3)** Assumes that the intermediate production technology is Cobb-Douglas by setting $\chi \to 1$ as in Costinot and Rodriguez-Clare (2014) and Caliendo and Parro (2015) and labor is mobile. **(4)** Assumes that $\chi = 5$ as in Caliendo et al. (2022) such that the elasticity of substitution in the production of intermediates is higher than in the Cobb-Douglas case and labor is mobile. **(5)** Assumes that there are no input-output linkages as in Allen and Arkolakis (2014) and labor is mobile.

While there are no explicit dynamics in the model, the first four cases have intuitive interpretations in terms of the time horizons that govern adjustments in labor and technology. For example, the first case can be interpreted as the value of the IHS in the short term since workers cannot migrate and there is little substitution across intermediate inputs such that intermediate producers cannot adjust the production technology in response to the shock. The third case provides estimates for the value of the IHS in the medium term when workers can move but the substitution across intermediate inputs is limited due to the Cobb-Douglas technology. The fourth case reflects the long term when labor has time to adjust and intermediate producers have time to adjust technology and substitute relatively more easily across inputs.

Panel A gives the results for total value of the IHS in the presence of congestion effects. Depending on the underlying assumptions about labor mobility and production technology, real GDP losses from the removal of the IHS range between \$421 billion (or 2.6 percent) and

Table 3: Total Losses from Removing the IHS

	Panel A: Congestion			Panel B: No Congestion		
	Total (1)	Domestic (2)	International (3)	Total (4)	Domestic (5)	International (6)
(1) Nearly Leontief technology ($\chi = 0.1$), no labor mobility ($\varrho \to 0$)	577.5	408.1	169.4	489.0	382.9	106.1
(2) Nearly Leontief technology ($\chi = 0.1$), perfect labor mobility ($\varrho \to \infty$)	577.2	407.5	169.6	488.5	382.2	106.3
(3) Cobb-Douglas technology ($\chi \to 1$), perfect labor mobility ($\varrho \to \infty$)	536.6	383.5	153.1	460.7	362.7	98.0
(4) Flexible CES technology ($\chi = 5$), perfect labor mobility ($\varrho \to \infty$)	421.0	314.6	106.3	376.9	301.6	75.2
(5) No input-output linkages, perfect labor mobility ($\varrho \to \infty$)	224.5	153.8	70.8	188.7	143.3	45.3

Notes: The table shows results from counterfactual exercises removing the Interstate Highway System. Panels A and B, respectively, show results that allow or do not allow for endogenous congestion. In each panel, 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 and 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.

$577 billion (or 3.6 percent) in 2012 dollars.[24] The calculated value is the highest for row 1 and is equal to $577 billion when neither workers nor producers can adjust to the shock. It goes down to $421 billion in row 4 when labor is allowed to move and it is relatively easy for the intermediate producers to substitute across inputs. The remaining columns in Panel A 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, $314.6-$408.1 and $106.3-$169.4 billion. It is noteworthy that the international component of trade costs accounts for roughly one quarter to one third of the total losses from removing the IHS. The total and decomposed losses presented in Panel A indicate both that the value of the IHS is substantial and that the access it provides to international markets is quantitatively important.

An important feature of our model is the presence of many sectors and linkages across sectors and countries through input-output relationships. This may be particularly impor-

[24] 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). Given upfront construction costs of $560 billion in 2007 dollars and assuming a 5 percent annual cost of capital, annual upfront construction costs are $28 Billion (see Federal Highway Administration, 2012). Including annual maintenance costs and capital improvements of $3.5 billion and $20.4 billion respectively, the annual payback of the IHS dwarfs the annual costs. 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).

tant 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. Row 5 of Table 3 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. In this case, total losses form removing the IHS are significantly lower and are equal to \$224.5 billion of which \$70.8 billion are attributed to worse international market access due to removal of the IHS.

We contrast the results in Panel A with those in Panel B to understand the role of trade-related congestion effects. The estimates of the total value of the IHS are significantly lower in Panel B and vary between \$377 billion and \$489 billion. This suggests that trade-generated congestion accounts for 10-15 percent of the total value.[25] In addition, the results for row 5 in Panel B are closest to 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. Our results are close to this range when we eliminate intermediate inputs from the model and focus only on the effect of the domestic trade cost components.

In the baseline model we allow for six alternative routes that producers can use to transport goods between each ij pair. In Table 4, we consider how the value of the IHS varies with the number of alternative routes. For this exercise, we focus on the "long term" scenario captured by row 4 in Table 3 in which congestion effects are active, labor is mobile, and intermediate producers can more easily substitute across inputs. The value of \$421 billion in the first column is the same as the aggregate value reported for row 4 in Panel A of Table 3. We find that reducing the number of potential routes increases the estimated value of the IHS. In addition, it is noteworthy that the effect of additional routes gets smaller such that adding routes more than six routes would not significantly change the main results. This suggests that our benchmark approach of using six available routes is accurate, while preserving computational feasibility.

Panel A of Figure 5 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. At the county level, all counties experience at least

[25] This means that trade-generated congestion costs are between \$135 and \$265 per person. These costs are large, but smaller than those estimated from surveys (e.g., INRIX Research, 2019).

Table 4: Robustness to an Alternative Number of Routes

	Number of Routes (R):					
	Six	Five	Four	Three	Two	One
	(1)	(2)	(3)	(4)	(5)	(6)
Flexible CES technology ($\chi = 5$), perfect labor mobility ($\varrho \to \infty$)	421.0	423.5	427.7	435.6	443.9	455.5
Interstate Travel Time Summary Statistics						
Mean	21.3	21.1	20.8	20.5	20.1	19.7
Standard Deviation	11.5	11.5	11.4	11.2	11.1	10.9

Notes: The table shows results from counterfactual exercises removing the Interstate Highway System in the case where production technology exhibits more substitution ($\chi = 5$) and perfect labor mobility ($\varrho \to \infty$), while allowing for a different number of alternative routes. Column 1 shows the results in the benchmark case when there are six alternative routes. The remaining columns consider the cases where there are five-one alternative routes. The last two rows report the average and standard deviation of interstate travel time in hours across all available routes for each case.

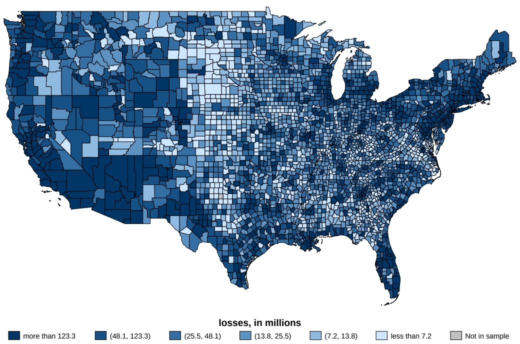
some loss, while the average loss is \$193.7 million. Panel B of Figure 5 shows the relationship between the log of average trade costs in 2010 and the losses (in percent) from removing the IHS, which indicates that losses are concentrated in counties that are more remote from domestic and international markets. Panels C and D of Figure 5 show 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 is 0.80. This suggests that the IHS plays different roles in facilitating trade across US counties and states. For example, total losses of \$65 billion for Texas are split more evenly between domestic and international trade costs (\$38 and \$26) than in smaller state economies, e.g., Alabama, where losses from the change in the domestic trade cost component are substantially more important.

Next, we calculate how the IHS shaped specialization patterns across locations in the United States. For that we use the concept of revealed comparative advantage as in Balassa (1965) for the twelve manufacturing sectors across US states. Let $E_i(s)$ denote total exports of state i of sector s goods, then the measure of comparative advantage is:

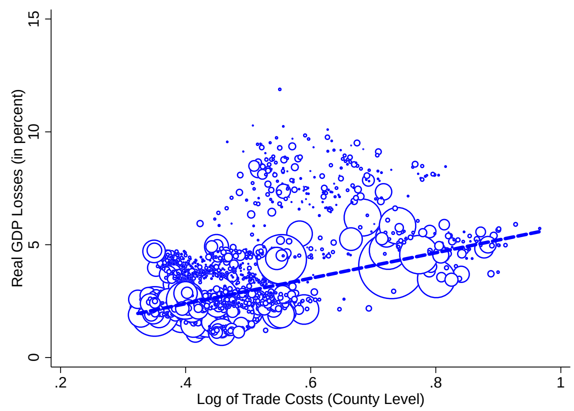
$$CA_i(s) = \frac{E_i(s)}{\sum_{s'} E_i(s')} / \frac{\sum_{i'} E_{i'}(s)}{\sum_{i',s'} E_{i'}(s')}$$

We calculate the change in $CA_i(s)$ under two scenarios. First, we calculate how the

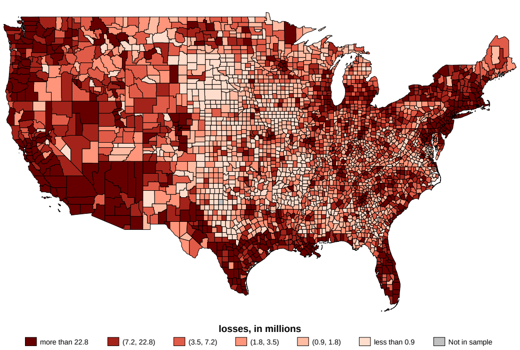
Figure 5: Spatial Distribution of Losses from Removing the IHS



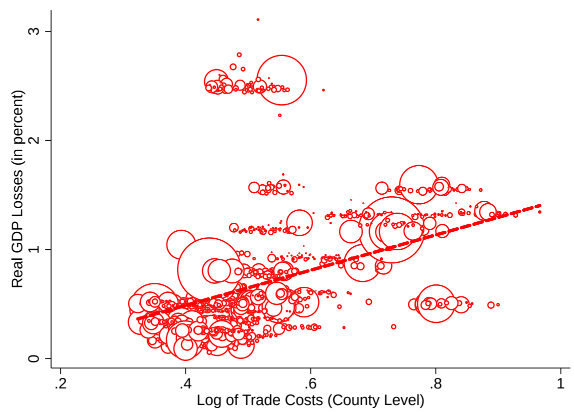
A. Contribution of Removing All Trade Costs



B. Reduction of Real GDP and All Trade Costs



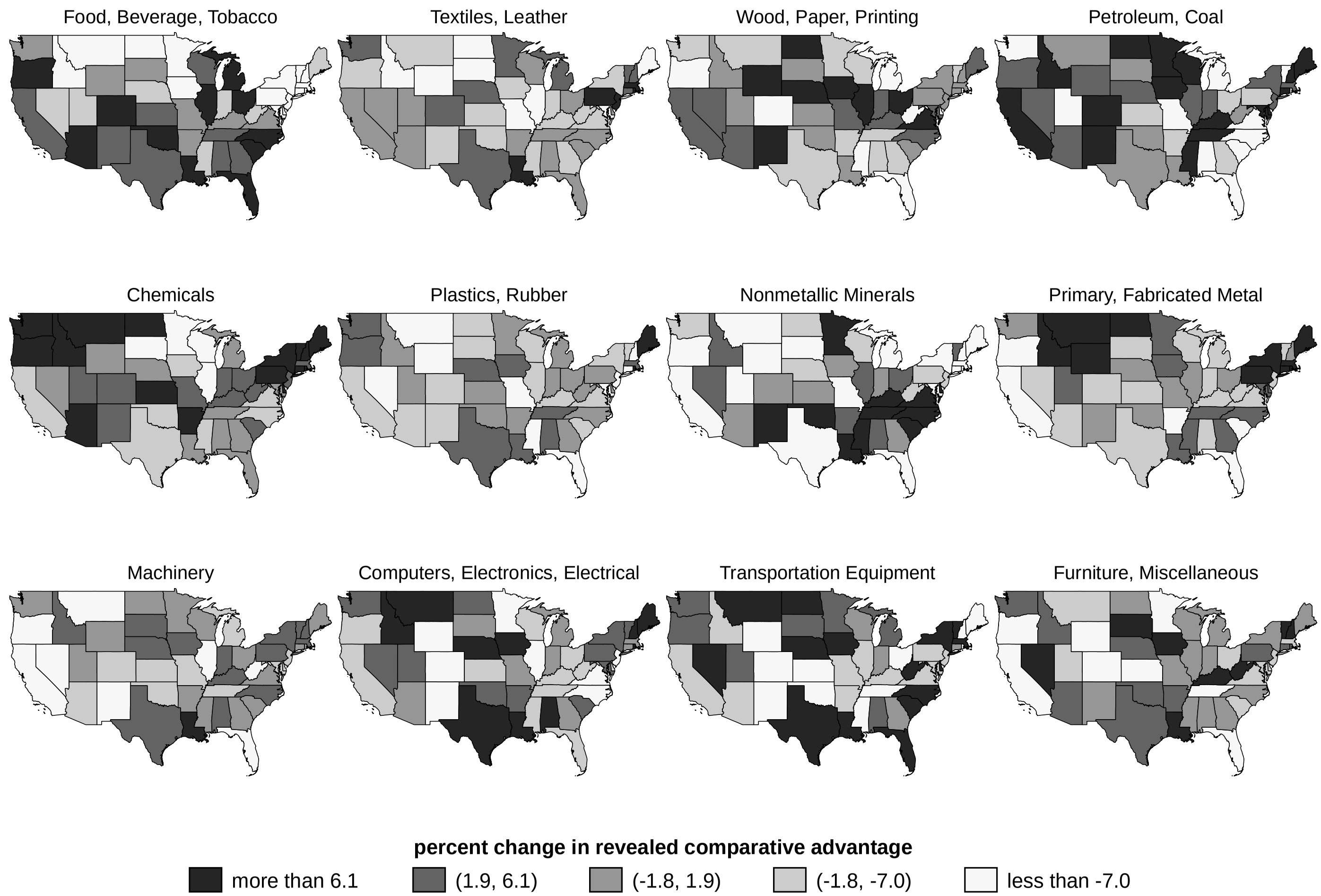
C. Contribution of Removing Foreign Trade Costs



D. Reduction of Real GDP and Foreign 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. Panel C shows the geographic distribution of the reduction in real GDP (in percent) from removing the IHS for the international components of trade costs. Panel D 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 6: 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): $(E_i(s)/\sum_{s'} E_i(s'))/(\sum_{i'} E_{i'}(s)/\sum_{i',s'} E_{i'}(s'))$.

measure of revealed comparative advantage changes in the absence of the IHS denoted by $\Delta CA_i(s)'$. However, these changes have two components. On the one hand, removal of the IHS changes market access for all states due to average reductions in trade costs. On the other hand, the IHS has a differential impact on specialization across locations. To isolate the latter, we also calculate changes in $CA_i(s)$ under uniform 34 percent increase in travel time (average change across all ij pairs) for all state pairs denoted by $\Delta CA_i(s)''$. We then plot the differences between these two changes, $\Delta CA_i(s)' - \Delta CA_i(s)''$ in Figure **6**. Hence, the results in Figure **6** reflect the role of the IHS in shaping regional specialization patterns net of average changes in trade costs. 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., *Food, Beverage, and Tobacco*), 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., *Machinery*), states on the coast export relatively less without access to the IHS. These findings complement work that shows how industrial composition and specialization change in response to trade costs (Michaels, 2008; Duranton, Morrow and Turner, 2014; Jaimovich, 2019) .

5.2 Results for Individual Highways

The results so far focus on removing the entire IHS. From the perspective of policymaking, it is also useful to consider smaller changes in the highway network that can serve as a guide for allocating funding for new construction, improvements, and maintenance. To do this, in this subsection, we consider counterfactuals that remove ten highways that form part of the the IHS. We provide further details on the location of these highways in Panel A of Appendix Figure B5 in Appendix B. These counterfactual experiments will shed light on the benefits associated with individual highways, the distribution of those gains across US states, and variation in the importance of the access provided to domestic versus international markets. For these counterfactuals, we remove all sections of the corresponding numbered interstate, including loops and spurs, 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. A few details are noteworthy. First, both I-10, I-40, I-70, and I-80 stand out with losses that are substantial relative to the other IHS segments. This reflects a combination of the lack of available alternate routes

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	(18.4, 27.4)	(13.3, 19.8)	(13.0, 21.0)	(5.5, 6.4)
I-10	2452	(32.0, 45.5)	(13.0, 18.6)	(25.1, 30.8)	(6.9, 14.7)
I-15	1438	(27.9, 40.0)	(19.4, 27.8)	(12.6, 17.9)	(15.3, 22.1)
I-35	1428	(13.9, 18.6)	(9.7, 13.1)	(10.1, 9.1)	(3.8, 9.5)
I-40	2528	(39.7, 50.1)	(15.7, 19.8)	(19.6, 20.2)	(20.1, 30.0)
I-70	2066	(25.7, 44.0)	(12.5, 21.3)	(18.6, 23.8)	(7.2, 20.2)
I-75	1752	(21.6, 32.0)	(12.3, 18.3)	(18.0, 22.2)	(3.6, 9.8)
I-80	2875	(68.7, 92.3)	(23.9, 32.1)	(43.3, 50.7)	(25.3, 41.6)
I-90	2797	(25.4, 38.1)	(9.1, 13.6)	(15.6, 19.5)	(9.9, 18.6)
I-95	1888	(19.4, 30.9)	(10.3, 16.4)	(8.3, 15.3)	(11.1, 15.6)

Notes: The table shows results from counterfactual exercises removing the ten 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.

along the West-East direction in the United States. Looking at the losses by numbered interstate on a per mile basis reveal that the primary east-west routes (I-10, I-70, and I-80) together with the coastal route (I-5) and north-south routes (I-15 and I-75) are the most valuable.[26] Coming back to the substantial losses associated with the removal of specific highways, it is clear from Columns 4 and 5 that these interstates generate a significant portion of their value by facilitating international trade. For example, the value generated by international trade from I-15 or I-40 is larger than the total value generated by I-35. This suggests that international market access provides a substantial portion of the value for individual highways.

In addition, it is useful to highlight variation in the losses across states. For example, removing I-5 generates up to $27.4 billion in total losses, but losses for California, Oregon, and Washington together are as high as $31.1 billion and gains accrue to some 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 removing a highway, there can be substantial differences in losses. For example, removing I-95 reduces real GDP in Maine by 1.5-1.9 percent and in Massachusetts by about 0.4-0.6 percent. These differences may highlight

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

Table 6: Results for Upgrading Portions of the IHS

Proposed Highway	Miles (1)	Total value, in millions (2)	Total value per mile, in thousands (3)
I-11	1498	(741.8, 896.2)	(495.2, 598.3)
I-14	1724	(712.9, 881.7)	(413.5, 511.4)
I-32	530	(170.3, 330.8)	(316.0, 613.7)
I-66	936	(507.1, 560.6)	(606.6, 670.6)

Notes: The table shows results from counterfactuals improving portions 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.

important regional implications of highway building and improvement.

Finally, we consider four extensions to the highway network that reflect planned additions currently under study for implementation. These include I-11 through Washington, Oregon, California, Nevada and Arizona, I-14 in between Texas and Georgia, I-32 in New Mexico and Texas, and I-66 between Kansas and West Virginia. A map depicting these highways is shown in Panel B of Appendix Figure B5. As with many planned improvements to the highway system, these improvements will come from upgrading existing highways for more capacity and grading for faster speeds. The results for the value of these improvements is presented in Table **6**. Column 1 shows the total number of miles for the improved portion of the IHS. In column 2 we report the range of values for each highway calculated across the different cases. All of the highways add value: the estimated total gains are \$741.8-\$896.2 million for I-11, \$712.9-\$881.7 million for I-14, \$170.3-\$330.8 million for I-32, and \$507.1-\$560.6 for I-66. These gains and the associated gains per mile are smaller than the values associated with the removal of individual highways reported in Table **5**. This reflects the fact these upgrades of the highway system improve existing portions of the highway rather than construct entirely new portions. They are also consistent with the intuition that adding more alternative routes to a network that already features a relatively large number of possible links can only marginally reduce trade costs. Overall, the results suggest that the benefits of these planned extensions are relatively limited.

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 incorporates the potential congestion of the US highway network that affects trade costs that 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 that the value ranges between \$421 and \$578 billion depending on the assumptions regarding labor mobility and flexibility of the production structure. In addition, we find that about one quarter of this effect is due to higher trade costs for accessing foreign markets, while up to 20 percent is due to congestion. We also show how to apply the model to estimate the value of current portions of the IHS as well as proposed upgrades.

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Appendix – For Online Publication

A 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 A1 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`. International trade flows are drawn from the World Input-Output Database for 2012 (see Timmer, Dietzenbacher, Los, Stehrer and De Vries, 2015).

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 (download here), 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 least cost route between CBSA's in each origin destination pair. When computing the cost minimizing intertate route, we identify the county where the route exits the origin state and the county where the route enters the destination state. We use the exit and entry counties as the aggregation points to construct the intrastate trade costs. Intrastate trade costs are then constructed by measuring the travel time and distance from an origin county to the exit county or, from the entry county to the final destination county. Because the entry/exit counties will differ for each interstate trading pair, the intrastate trade costs are specific to the origin and destination pair. 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 and all associated loops and spurs of 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.

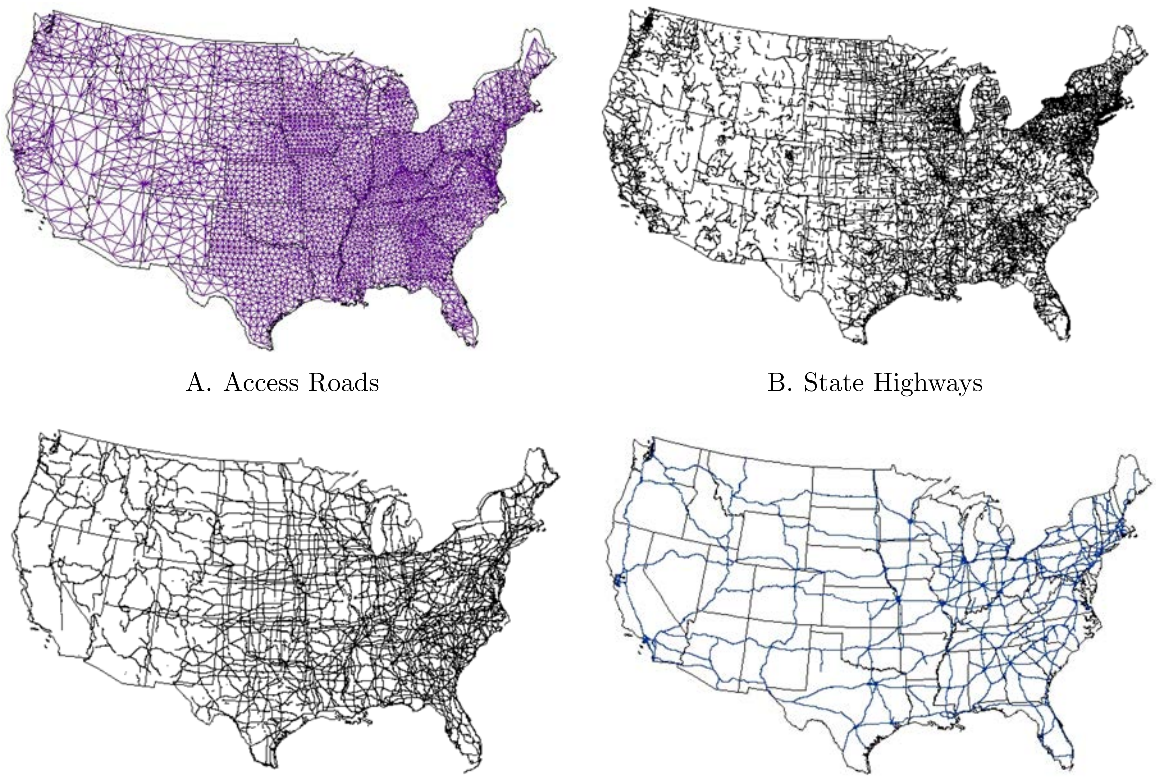
To account for congestion in the benchmark and all counterfactual scenarios we use ArcGIS to identify the which of the roughly 331,000 pieces of the US highway networkare used for particular interstate routes. Each piece of the highway network has a tabulated annual daily traffic entry based on data 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.

Table A1: 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 A1: Components of the US Highway Network



A. Access Roads B. State Highways

C. US Highways D. Interstate Highway System

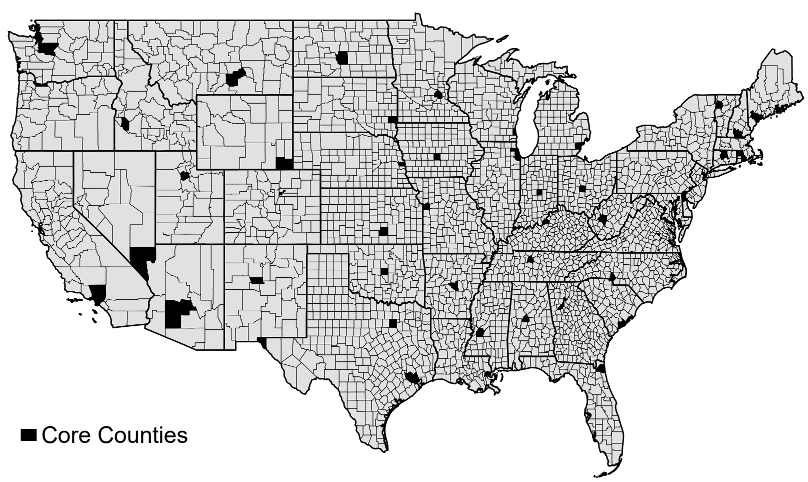
Notes: This figure shows the four components of the US highway network used to calculate travel time and trade costs. Panel A shows the access road network with assigned speed of 10 miles per hour, Panel B shows the state highway network with an assigned speed of 45 miles per hour, Panel C shows the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

B Additional Tables and Figures

Table B1: Summary of Model Parameters

Parameter	Interpretation	Source
$\alpha_i(s)$	Cobb-Douglas consumption share	Authors' calculations based on WIOD data
$\gamma_i(s)$	Sectoral value added share	Authors' calculations based on CBP and WIOD data
$\eta_i(\dot{s}s)$	Sectoral input-output shares	Authors' calculations based on WIOD data
χ	Input-output substitution parameter	Atalay (2017) and Caliendo et al. (2022)
$\theta(s)$	Sectoral trade elasticity	Estimated in Equation (26)
$\varphi(s)$	Sectoral time trade elasticity	Estimated in Equation (28)
σ	Transportation routes and mode substitution parameter	Allen and Arkolakis (2014)
ϱ	Migration elasticity	Values correspond to 'no migration' or 'free migration'
ζ	The effect of traffic on congestion	Estimated in Equation (29)

Figure B1: Core Counties

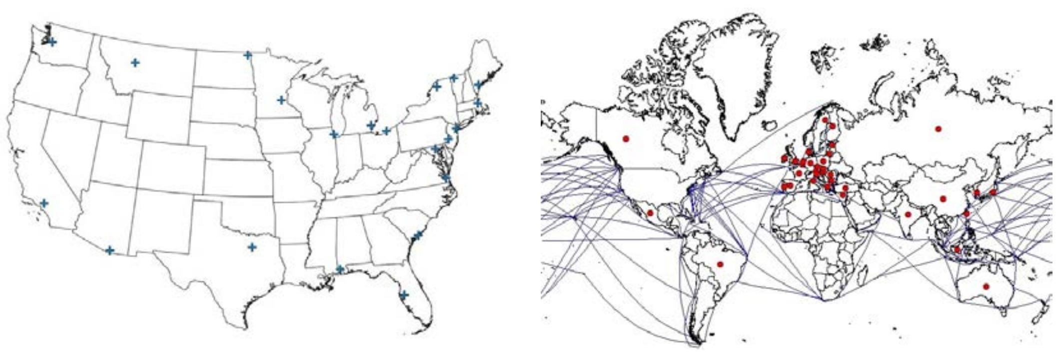


Notes: This figure shows the locations used as "core" counties in the quantitative analysis. Within California and Texas there are two and three locations, respectively. See text for more detail.

Figure B2: Alternative Interstate Routes for Colorado and Florida

Notes: This figures shows alternative interstate routes between Colorado and Florida. The first-best route is calculated as the fastest travel time route taking into account the actual traffic on each segment. The second- through fifth-best routes are calculated by decreasing the speed on segments of the fastest travel time route by 5, 10, 25, and 50 percent, respectively. Finally, we calculate the sixth-best and most expensive route by restricting the route to use no segments that belong to fastest route.

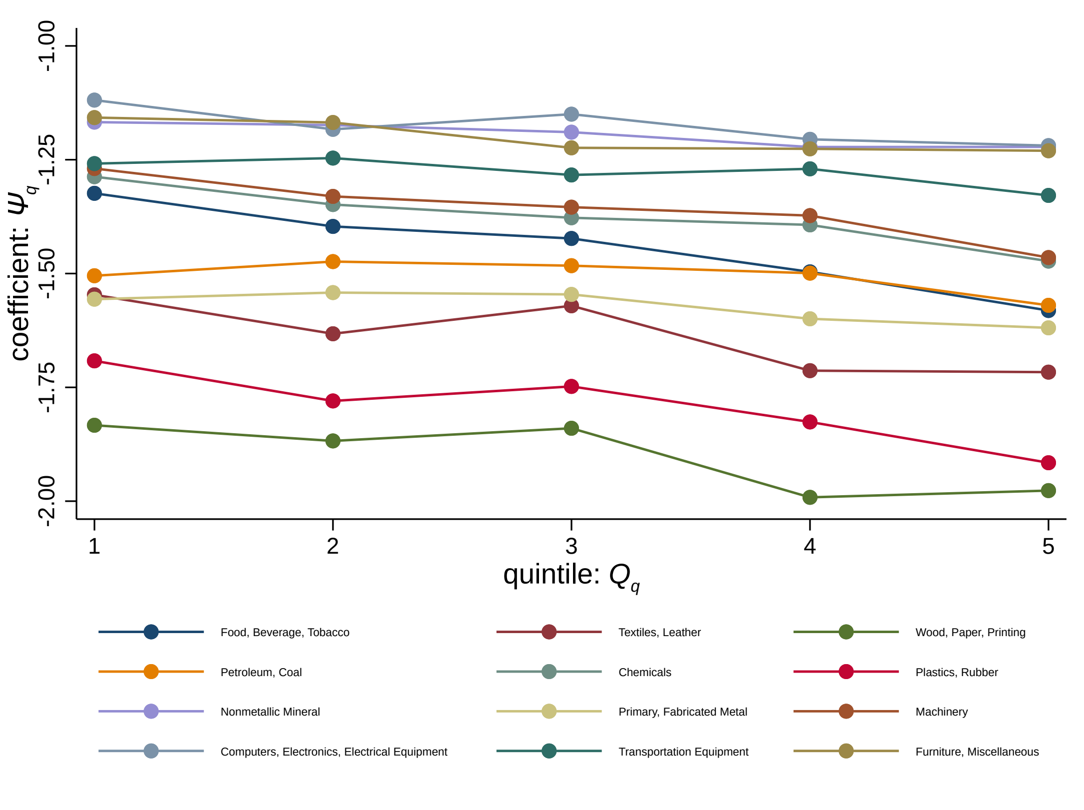
Figure B3: Ports and International Sea Shipping Routes



A. Ports B. Shipping Routes

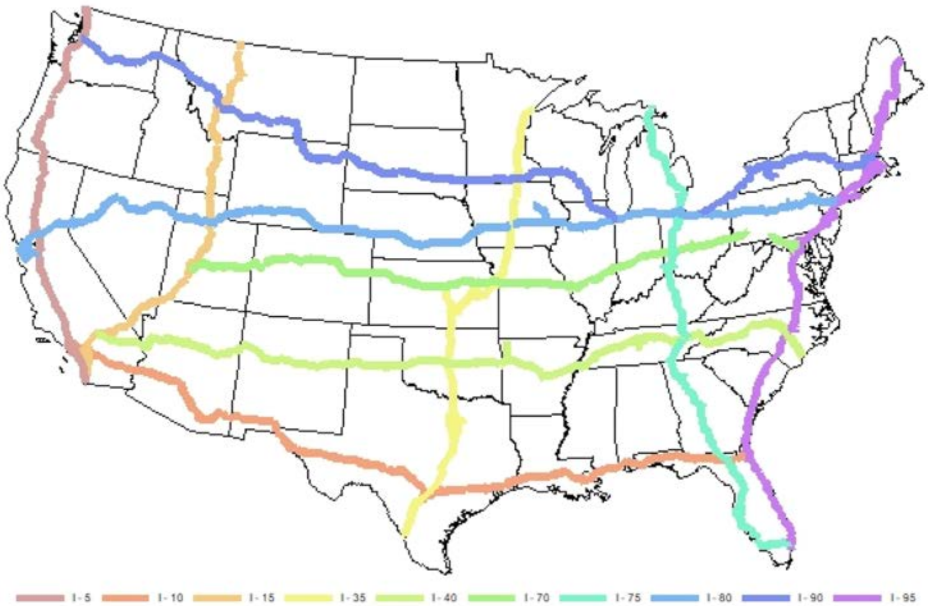
Notes: This figure shows the portions of the transportation network that contribute to international trade costs. Panel A shows the location of US ports. Panel B shows the international shipping lanes and country centroids.

Figure B4: Results for International Distance Coefficients

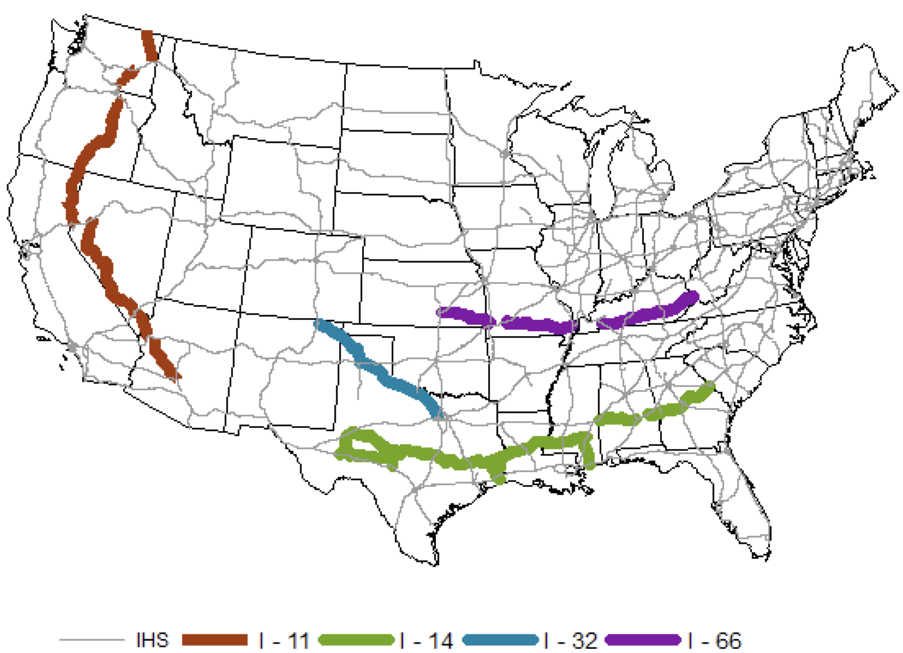


Notes: This figure shows the results of estimating equation (32) for each sector s. The dependent variable are the trade flows between each US port r and each foreign trading partner j. Each line plots the coefficients associated with the quintiles of distance (in miles) for a given sector. All specifications include port and country fixed effects.

Figure B5: Individual Highways Used in Counterfactuals



A. Existing Individual Interstates



B. Proposed Interstates

Notes: Panel A shows ten highways listed in Table 5. Panel B shows four highway listed in Table 6.