Multimodal Transport Networks

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1 Introduction

The movement of goods takes place over multiple modes of transportation, including highways, railroads, oceans, and waterways. While trucks are mostly used to move US freight over shorter distances, railways account for almost two-thirds of freight moved over longer distances (1000 miles or more, Department of Transportation). As a result, intermodal terminals and their mode-switching costs play a major role in facilitating how goods are transported over this network. The economic and environmental returns from new technologies and infrastructure investments in transportation can depend importantly on the level of integration across modes as well as the presence of bottlenecks at intermodal terminals.

This project studies multimodal transport networks and their impact on the economic and environmental returns to new technology and infrastructure investments. In particular, we focus on how these outcomes will depend on the intermodal terminals and their costs, as well as diversion across transport modes. This project contributes to three goals in the "Economics of Transportation in the 21st Century" research initiative, namely (abridged): (1) the consequences of new technologies for managing multimodal freight transportation, (2) the returns to investments in transportation infrastructure, including roads, rail, ports, and intermodal transfer facilities, and (3) the effects of the transportation sector on greenhouse gas emissions and on the environment.

We first develop a quantitative spatial equilibrium model of multiple transport modes and routing choice. The model combines a standard workhorse economic geography model with a constant elasticity import demand system over origin-differentiated goods with a multimodal extension of the routing formulation of transport cost in Allen and Arkolakis (2019). By exploiting the properties of partitioned matrices and by using realistic assumptions on the number of switches between modes, we are able to preserve tractability despite the increased dimensionality of the underlying network and derive closed-form expressions for the modal transport shares between all origins and destinations within the US.

Next, we estimate the costs of intermodal switching. By combining our model with a detailed network of the US multimodal transportation system that incorporates data on road, rail and maritime linkages, as well as the location of intermodal switching facilities, we derive the modal transport shares between all origins and destinations within the US. We then recover these intermodal switching costs that best rationalize our model predictions and the observed transport modal shares in the data. In particular, our switching costs generate results that match the change in modal composition shares across different distance bands—the modal substitution that takes place between truck and rail as freight is moved over longer distances.

Third, we evaluate the general equilibrium welfare impacts of mode-specific infrastructure investments, technology improvements, and pollution reduction efforts. In order to evaluate these counterfactuals, we require estimates of within-mode and across-mode elasticities of substitution. We estimate these empirically by examining the introduction of new technology in transportation—the double-stacked railroad transport technology. By allowing for rail lines to double their capacity by stacking intermodal containers on top of each other, this technology potentially has both a direct within-mode impact of increasing rail usage on the intensive margin as well as a modal diversion impact of diverting the usage of other modes to rail. For this purpose we have been granted access to the Confidential Carload Waybill Sample by the Surface Transportation Board which provides detailed information on freight flows along US railroads since 1984.

The quantitative spatial economics literature has developed extremely useful tools that can answer a range of questions taking the underlying spatial distribution of economic activity into account (see Redding (2020) for a recent survey). Within that literature, there have been multiple efforts to merge the disaggregated network structure of transportation infrastructure with a general equilibrium economic geography model. In particular, Allen and Arkolakis (2019) proposed a tractable way of incorporating the optimal routing choice into an spatial equilibrium model, allowing the authors to examine the general equilibrium implications of transportation improvements. While much theoretical progress has been made, the literature has often focused on one mode of transportation, approximating transport costs with either maritime or road transportation costs. Our project

adds to this literature by incorporating multiple modes of transportation as well as intermodal switching terminals. Our project also contributes to this literature by estimating intermodal switching costs. To the best of our knowledge, this is the first paper to do so.

Additionally, the transportation literature has developed computationally complex models to evaluate the need for infrastructure investments in a multimodal setting such as the Freight Analysis Framework. While they provide useful insights for policy recommendation, their intractability and computational intensity make them less versatile for counterfactual policy evaluations. Quantitative spatial equilibrium models remain tractable and can be conveniently used to determine the economic and welfare properties of counterfactual interventions. However, so far that literature has abstracted from the details of the multimodal domestic transport system. Our project seeks to bridge this divide. Our model allows us to evaluate optimal infrastructure investment policies in the context of multimodal transportation and can be integrated tightly with a general equilibrium framework while preserving the flexibility that is the hallmark of the quantitative spatial economics literature.

The remainder of the project proposal is structured as follows. Section 2 gives a brief overview of the multimodal routing model. We describe how we estimate intermodal switching costs in Section 3 and give an overview of the data and empirical exercise in 4. Section 5 provides a description of the planned quantitative exercise on pollution reduction and 6 concludes with our financial disclosure statement.

2 A Tractable Model of Multimodal Routing with Switching Costs

In our setting, transportation requires a freight forwarder to make a sequential choice. First, a decision is being made which mode of transportation is being used (both uni- and multimodal transport combinations are considered: road, road and rail, road and sea, etc.). Next, conditional on the modal choice, the freight forwarder decides on the optimal route. If the modal choice implies the usage of multiple modes of transportation, then routes with switches across the mode specific transportation networks are being considered. We first introduce the modal choice of the freight forwarder given the expected transportation cost per mode, and then describe the routing choice that determines the expected transport cost given the modal choice. In a final step, we illustrate how the model - once combined a standard economic geography model - gives rise to a straightforward decomposition of the effects of mode specific infrastructure improvements.

2.1 Transport Mode Choice

First, a freight forwarder chooses the the transportation mode m that minimizes the transport cost between an origin o and destination d from all available combinations $\mathcal{M}_{od}$: $m \in \arg\min_{m \in \mathcal{M}_{od}} \{\tau_{odm} \times \epsilon_{odm}\}$, where τ_{odm} is the iceberg transport cost between origin-destination pair (o, d) using transport mode m and ϵ_{odm} is the mode-specific preference shock that is drawn from the Weibull distribution. Accordingly, the typical properties of the extreme value distribution give rise to closed-form expressions for the modal choice probabilities and the expected transport cost, i.e.

$$\omega_{odm} = \frac{[\tau_{odm}]^{-\theta}}{\sum_{m \in \mathcal{M}_{od}} [\tau_{odm}]^{-\theta}} \qquad \tau_{od} = \Gamma\left(\frac{\theta - 1}{\theta}\right) \left(\sum_{m \in \mathcal{M}_{od}} [\tau_{odm}]^{-\theta} \right)^{-\frac{1}{\theta}} \tag{1}$$

where ω_{odm} represents the mode specific choice probability and τ_{od} is the expected transport cost and is defined as the expected transport cost that arises from the modal choice problem.

2.2 Multimodal Routing

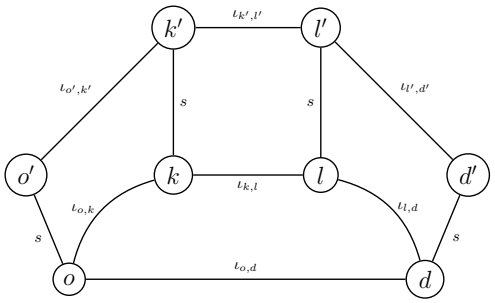
Next, we extend the routing-based formulation of transport cost in Allen and Arkolakis (2019) to allow for multi- and intermodal routing and to derive a closed-form expression for the mode-specific expected transport cost, τ_{odm}. For simplicity this section introduces a multimodal routing model with just two modes of transportation, road and rail. In the paper we extend this to allow for transport over water (oceans and inland waterways). Locations are organized along a weighted graph $G = (N, E)$ where N is the set whose elements are the nodes of the graph corresponding to cities or intersections of the transportation network, while E is the set whose elements are the linkss which connects them. We further define set N to be the union of all nodes that belong to the road network $(k, l, m \in \mathcal{N}_R)$ and the rail network $(k', l', m' \in \mathcal{N}_T)$. Reflecting freight logistics operations where the last mile takes place by road, we make the assumption that city nodes the form part of the road network $(\mathcal{N}_R)$. Since cities are the location of production and consumption, this implies that all traffic originates and terminates on the road network (we call this the "Last Mile by Road" Assumption). Each modal transport network has an

associated infrastructure matrix, i.e. $\tilde{\boldsymbol{T}}_R = [\iota_{ij} \geq 1]$ and $\tilde{\boldsymbol{T}}_T = [\iota_{i'j'} \geq 1]$, where ι_{ij} denote the iceberg travel cost along $i \to j$, which are symmetric and greater than 1.

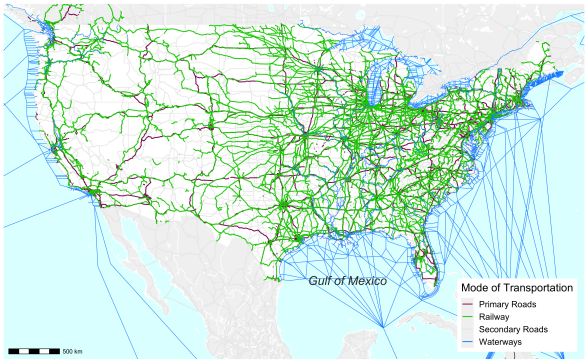
Transportation from i to j requires taking a path r, where a path is a set of connected links from origin to destination. The cost it takes to travel a path is the product of the costs of each link. Each node k on the road transport network has an associated node k' on the rail transport network and at some nodes a switch between road and rail network is possible, forming a link between k and k' with a fixed switching cost s. This introduces an additional intermodal infrastructure matrix $\boldsymbol{S} = [s_{kk'} \geq 1]$. Since switches are only possible between adjacent nodes, the off-diagonal elements in $\boldsymbol{S}$ are infinite and finite values on the diagonal indicate the existence of intermodal facilities. Panel (A) in Figure 1 depicts an example of a multimodal transportation network connecting origin o and destination d. The cost to provide transportation along the multimodal path $o \to o' \to k' \to k \to l \to d$ is the product of the costs associated with each link which includes both the mode-specific transport costs as well as the intermodal switching costs, that is $s_{oo'}\iota_{o'k'}s_{k'k}\iota_{kl}\iota_{ld}$ where $s_{oo'} = s_{k'k} = s$.

Figure 1: Multimodal Transportation Network

(A) Example of a Multimodal Network



(B) US Multimodal Network



Within this setting, we characterize the expected transport cost both for unimodal transportation using road only and multimodal transport using a combination of road and rail. A freight forwarder providing transportation from o to d chooses amongst the universe of feasible unimodal and intermodal paths. There are different types of routes defined by the number of switches between road and rail network, and together they form the set $\mathcal{R}_{od} = \{\mathcal{R}^0_{od}, \mathcal{R}^1_{od}, \ldots\}$, where $\mathcal{R}^i_{od}$ refers to the set of paths with i switches (back and forth) between the different modes of transportation. Freight forwarders derive idiosyncratic dis-utility $\nu(r)$ from each potential path, drawn from a Frechet distribution with dispersion parameters θ and location parameter zero. The expected transport cost can then be defined as the expected minimand of this problem and—using the properties of the Frechet distribution—can be written out explicitly in terms of all available routes. For the unimodal case we obtain,

$$\tau_{od,road} \equiv \mathbb{E}\left[\min_{r \in \mathcal{R}^0_{odm}} \iota_r \cdot v(r)\right] = \Gamma\left(\frac{\nu_{road}-1}{\nu_{road}}\right)\left(\sum_{r \in \mathcal{R}^0_{odm}} [\iota_r]^{-\nu_{road}}\right)^{-\frac{1}{\nu_{road}}} = \Gamma\left(\frac{\nu_{road}-1}{\nu_{road}}\right)\left((\mathbb{I} - \boldsymbol{T}_R)^{-1}_{(o,d)}\right)^{-\frac{1}{\nu_{road}}}$$

which mirrors the expression in Allen and Arkolakis (2019) and expresses the universe of routes in terms of the road infrastructure network only. For the multimodal case, we can apply the inverse of the partitioned matrix to obtain an closed-from expression,

$$\tau_{od,multi} \equiv \mathbb{E}\left[\min_{r \in \mathcal{R}_{odm} \setminus \mathcal{R}^0_{odm}} \iota_r \cdot v(r)\right] = \Gamma\left(\frac{\nu_{multi}-1}{\nu_{multi}}\right)\left(\sum_{i=1}^{\infty}\left(\sum_{r \in \mathcal{R}^i_{odm}} [\iota_r]^{-\nu_{multi}}\right)\right)^{-\frac{1}{\nu_{multi}}} = \Gamma\left(\frac{\nu_{multi}-1}{\nu_{multi}}\right)\left(\mathbf{M}_{(o,d)}\right)^{-\frac{1}{\nu_{multi}}}$$

where $\mathbf{M} \equiv (\mathbb{I} - \boldsymbol{T}_R)^{-1}\mathbf{S}\mathbf{D}^{-1}\mathbf{S}(\mathbb{I} - \boldsymbol{T}_R)^{-1}$ characterizes all routes with switches between rail and road, and where $\mathbf{D}$ is the Schur complement of the partitioned infrastructure matrix. This implies that the overall expected transport cost is given by,

$$\tau_{od} = \Gamma\left(\frac{\theta-1}{\theta}\right)\left(\tau^{-\theta}_{od,road} + \tau^{-\theta}_{od,multi}\right)^{-\frac{1}{\theta}}$$

We can further substitute this into equation (1) to obtain closed-form expressions of the modal shares as a function of the observed multimodal transport network.

2.3 Impact of Infrastructure Improvements

The freight forwarding choice model can be embedded into a quantitative spatial equilibrium framework (Redding and Rossi-Hansberg, 2016). In our project we combine an Armington type trade model with the multi-modal routing problem above. Doing so, we can derive the impact of mode-specific transport cost changes ($d\tau_{odm} \neq 0$) on observed trade flows by total differentiation, i.e.

$$\frac{dX_{odm}}{X_{odm}} = \underbrace{(1-\sigma)(1-\pi_{od})\,\omega_{odm}\frac{d\tau_{odm}}{\tau_{\text{odm}}}}_{\text{Direct Substitution}} - \nu_m \underbrace{(1-\omega_{\text{odm}})\frac{d\tau_{\text{odm}}}{\tau_{\text{odm}}}}_{\text{Modal Diversion}} - \underbrace{(1-\sigma)\sum_{o'\neq 0}\pi_{o'd}\omega_{o'dm}\frac{d\tau_{o'dm}}{\tau_{o'dm}}}_{\text{Change in Multilateral Resistance}}$$

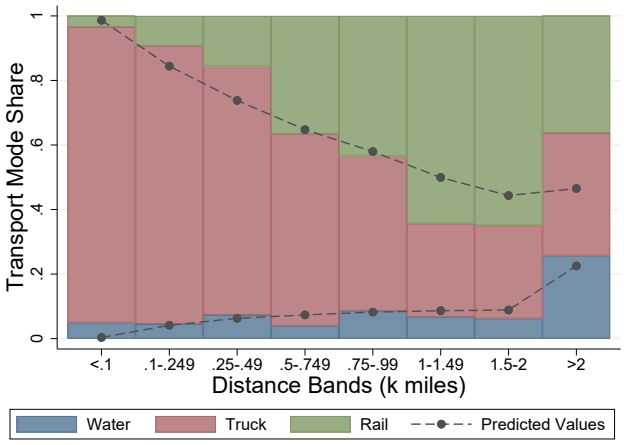
where X_{odm} are the mode-specific transport flows and π_{od} is the bilateral trade share. The impact of an infrastructure change can be decomposed into three distinct terms: First, direction substitution measures to what extent lower transport costs translate into additional demand from a specific destination location. Second, modal diversion measures to what extent improvements in the railroad infrastructure translate to more goods being shipped intermodally. The final term measures changes in the multilateral resistance due to transport cost changes that lower the prices of competing goods in the destination location. Crucially, while the direct substitution effect depends on the demand elasticity, the modal diversion effect depends on the elasticity of substitution between modes (ν_m) as well as the switching costs that determine that mode-specific transport shares (ω_{odm}).

3 Estimation of Switching Costs

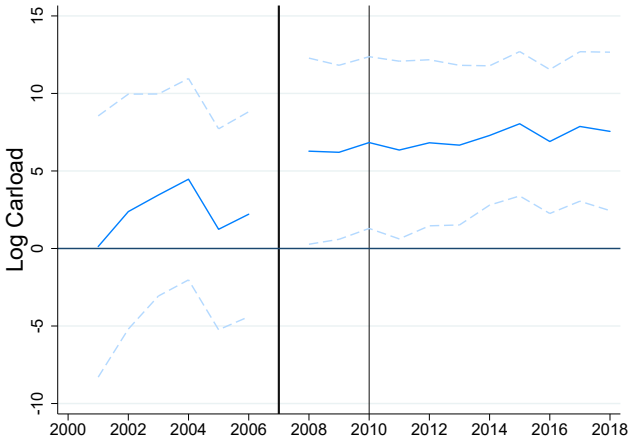
Using the geography of US multimodal transport network (rail, road, and waterways) in Panel (B) Figure 1 and the location of switching terminals, we estimate the switching costs between modes in two steps. In the first step, we calibrate the link-specific transport costs to cost-per-km estimates from a wide range of sources. Given this calibration and a guess for the switching cost between road and rail as well as road and sea, we can generate modal shares between CFS regions using equation (1). The structural estimation then chooses the optimal switching costs between modes to match the modal shares by distance band from the US Department of Transportation (Panel (A), Figure 2). We find that the (iceberg) switching cost between road and rail corresponds to 1.03 and 1.16 for road and sea. The stylized model does well in replicating the importance of different modes across different distance bands as seen in Panel (A) of Figure 2. This is a key feature of the domestic transportation that is difficult to replicate without switching costs and and a realistic multi-modal routing choice.

Figure 2: US Transport Mode Shares by Distance, Model Fit, and the Impact of Double-Stacking Technology

(A) US Transport Mode Shares by Distance and Model Fit



(B) Double-Stacking Impact on Freight Carloads



Notes: The model fit in Panel (A) is shown by plotting the predicted values line, as calculated by the authors, against the observed data on US transport mode shares by distance bands. Robust standard errors in Panel (B) are clustered by origin and destination. Panel (A) Source: Freight Analysis Framework, US Department of Transportation, and authors' calculations. Panel (B) Source: Authors' calculations using confidential rail data from the Surface Transportation Board.

4 Mode-Specific Infrastructure Investment: Double-Stacking

In order to estimate the direct impact of infrastructure improvements, we present preliminary empirical evidence on the impact of a large infrastructure improvement that is mode-specific on US regional rail traffic flows. The Heartland Corridor is a $150 million infrastructure plan to increase capacity of rail lines by increasing height clearance in tunnels/bridges to allow for double-stack intermodal trains. This new route saves double-stack trains 230 miles (up to 2 days) between Norfolk & Chicago.

The main dataset we are using to guide our analysis is a sample of US rail waybills submitted by railroad companies which reports the origin location, origin rail station, interchange stations, terminating station, and destination location of the commodities they transport. The rich geographical information in this confidential data set allows us to study the routing of these commodities through the railroad network over this time period. Additionally, this data set also contains commodity-specific information including number of car loads, weight, freight charges, whether it is a domestic or international shipment, and its inter-modality—if the movement of this commodity included other transport modes.

Using waybill rail data, we estimate the evolution of rail shipment flows as a result of Heartland Corridor:

$$Y_{odt} = \sum_{t'=2001\setminus 2007}^{2018} \beta_{t'} \Delta D_{od} \mathbb{1}_{t'} + \lambda_{ot} + \theta_{dt} + \varepsilon_{odt}$$

where Y_{odt} is the trade flows from origin o to destination d at year t, ΔD_{od} is change in log shortest rail distance between o and d before and after the Corridor, indicator $\mathbb{1}_{t'}$ equals one for year t', λ_{ot} is origin-year-level fixed effects, and θ_{dt} is destination-year fixed effects. The key parameter of interest, $\beta_{t'}$, is the cumulative Heartland Corridor impact on the trade flows outcome by each year. Corridor construction started in 2007 and is the base year for outcome changes. Preliminary results show that the Heartland Corridor has resulted in an increase of about 60 percent in US rail traffic immediately after its implementation, after which they accumulate more slowly but continue to rise (Panel (B), Figure 2). Work is currently in progress to merge this dataset with the Commodity Flow Survey in order to estimate the modal diversion effects of the Heartland Corridor.

5 Environmental Impact of Multimodal Transport Improvements

Freight transport accounted for a sizeable 24 percent of global CO2 emissions in 2016 (WRI 2019). With governments across the world focusing their efforts towards carbon neutrality, lowering the carbon intensity of domestic freight transportation systems has become a key focal point. One viable strategy is to promote modal substitution towards rail, with rail being up to 9 times less carbon intensive than road transportation (Dept of Transportation). The challenge is to develop and understand what type of investments across the complex interlocking multi-modal transport network has the largest potential for modal diversion and therefore the largest environmental impact.

In the context of our model we can characterize modal substitution from counterfactual infrastructure improvements. We can account for CO_2 emissions following Shapiro (2016) by calculating the mode-specific ton-miles for counterfactual scenarios and applying the estimates of mode-specific fuel efficiency to obtain aggregate GHG emissions for the freight transportation system.

6 Team and Financial Disclosure

The research team is composed of the principal investigator Woan Foong Wong (U of Oregon) and the co-investigator Simon Fuchs (FRB Atlanta). We plan to hire a part-time research assistant for data collection and computer simulations. We have no financial ties to the transportation industry or other conflict of interest.

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