Multimodal Transport Networks

Simon Fuchs
FRB of Atlanta

Woan Foong Wong
University of Oregon

Economics of Transportation in the 21st Century
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Preliminary

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    - In part fueled by containerization and the natural geography of origins and destinations

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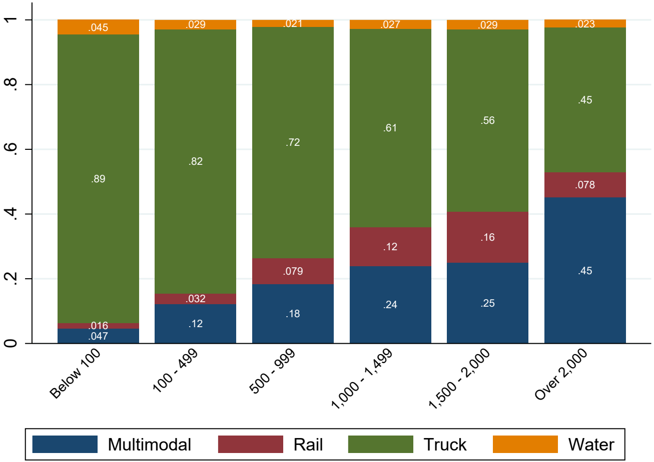
- This paper studies multimodal transport networks and their impact on infrastructure investments

US Modal Value Shares by Distance

- Trucks mostly transport shorter distances, while rail & multiple modes are used for longer



Modal Shares by Weight

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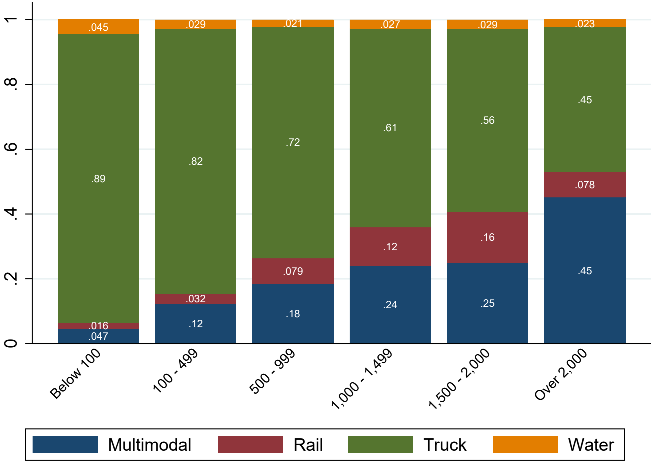
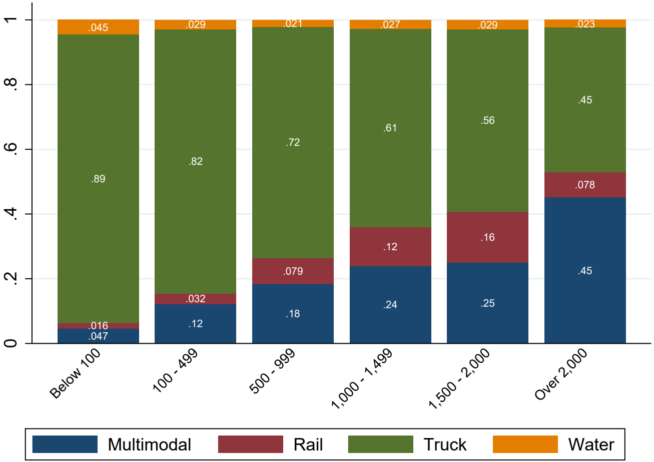
  - $\geq$ 1000 mi, more than 1/3 by value & half by weight



Modal Shares by Weight

US Modal Value Shares by Distance

- Trucks mostly transport shorter distances, while rail & multiple modes are used for longer
  - $\geq$ 1000 mi, more than 1/3 by value & half by weight; $\geq$ 2000 mi, $>$ half by value (ex.LA-Chi)



Modal Shares by Weight

This Paper

- Develop tractable spatial eqm model with multiple modes and mode switching
    - Introduce transport mode choice into optimal route choice model (Allen & Arkolakis,2022)
    - Derive derive closed-form expressions for modal transport shares despite increased dimensionality and complexity of multimodal transport networks

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  - Derive derive closed-form expressions for modal transport shares despite increased dimensionality and complexity of multimodal transport networks
- Theory to Data: Calibrate model to fit traffic and geography of US multimodal network
  - Estimate congestion at intermodal port terminals using AIS vessel data
  - Estimate multimodal impact of port congestion on nearby rail stations

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  - Estimate multimodal impact of port congestion on nearby rail stations
- Counterfactual: Evaluate welfare effects of investments at intermodal terminals across US
  - 1% costs reduction in top 10 most impactful terminals generate welfare gains $\approx$200-300 million USD of additional GDP

Related Literature

- **Transportation networks in spatial equilibrium**
  - Infrastructure investment with focus on road networks and congestion (Redding & Turner (2015), Fajgelbaum & Schaal (2017), Allen & Arkolakis (2022), Fan and Luo (2020), Fan, Lu, and Luo (2021))
  - Domestic transport cost and regional comparative advantage (Cosar & Demir (2016), Martincus et al. (2017), Cosar & Fajgelbaum (2016), Cosar, Demir, Ghose, & Young (2020), Fajgelbaum & Redding (2020), Jaworski, Kitchens, & Nigai (2021))
  - Maritime shipping networks (Ganapati, Wong, & Ziv (2022), Heiland, Moxnes, Ulltveit-Moe, & Zi (2022), Kalouptsidi, Brancaccio, & Papageorgiou (2020), Wong (2022))
  - Urban transportation (Allen & Arkolakis (2022), Severen (2022), Zarate (2021), Tsivanidis (2022), Almagro, Barbieri, Castillo, Hickock & Salz (2022), Kreindler & Miyauchi (2021), Miyauchi, Nakajima & Redding (2022))
- **Multimodal transport in transportation literature**
  - Estimation of freight transport price elasticities (Winston (1981), McFadden, Winston & Boersch-Supan (1986), Rich, Kveiborg & Hansen (2011), Beuthe, Jourquin & Urbain (2014))
  - Examining traffic assignment problems using stochastic user equilibrium (Bell (1995), Kitthamkesorn, Chen & Xu (2015), Boyles, Lownes & Unnikrishnan (2021), Li, Xie & Bao (2022))

Overview

Data: US Domestic Freight Transportation, Traffic, and Congestion

Theory: Spatial Eqm Model with Multiple Modes and Switching

Theory to Data: Multimodal Network and Congestion at Intermodal Terminals

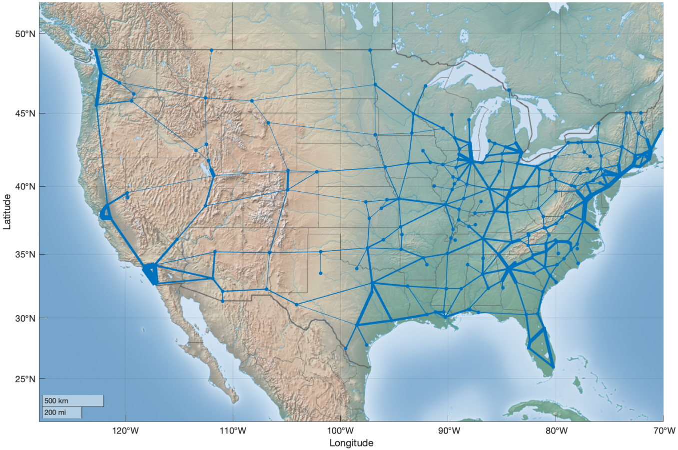
Counterfactual: Infrastructure Improvement at Intermodal Terminals

Conclusion

Data

1. US multimodal freight network
   - Truck and rail make up increasing majority of US freight transport (50% and 40% by ton-miles, 2017), ocean & waterway declining (10%), air 0.34% Mode shares 1980-2017
   - Intermodal rail cargo grew by 5 times (15 mil railcar loads) 1984-2019
2. Traffic data for road and rail transport modes
3. Measure of congestion at intermodal terminals (Ports and Rail Stations)
   - Ports: AIS vessel traffic data at 1 minute intervals, matched to port geographic areas
   - Rail Stations: dwell time reports from railroad carriers, matched to ports

US Road Traffic

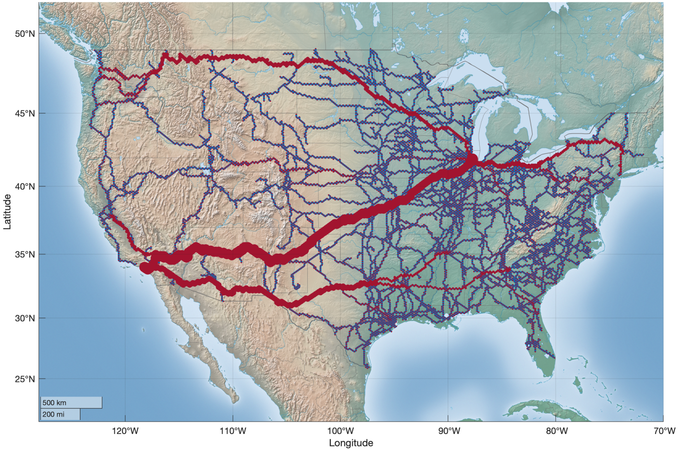


The traffic depicted is presents the traffic along the graph representation of the interstate highway system, depicting data from the 2012 Highway Performance Monitoring System (HPMS) dataset by the Federal Highway Administration.

US Rail Traffic

- Confidential waybill rail data, 1984-2019
  - Stratified sample of waybills representing 1-3% of all US rail traffic
  - Key Variables:
    - Route information: Origin-Interchanges-Destination at monthly level
    - Carloads, Tonnage, Weight, Freight Revenue
    - Product details: STCC (2 Digit) or HS
    - Car Type (intermodal vs not)

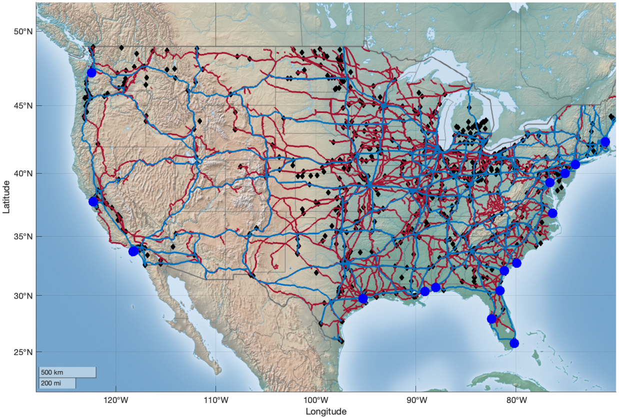
US Rail Traffic



Domestic rail traffic data for Class I carriers (largest in US) conditional on intermodal capability. Shortest routes are imputed between origin, interchange stations, and destination to assign total tonnage to individual rail segments along the multimodal network.

US Multimodal Freight Network

- Class I multimodal railroad (red lines), interstate highway (blue lines), intermodal terminals that allow road/rail switches (black diamonds), top ocean ports (blue circles)



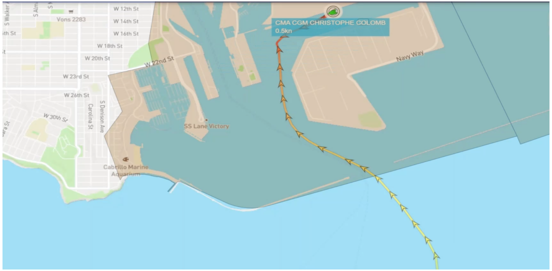
GIS information from Topologically Integrated Geographic Encoding and Referencing (TIGER) Database, Census Bureau.

Congestion at Intermodal Port Terminals

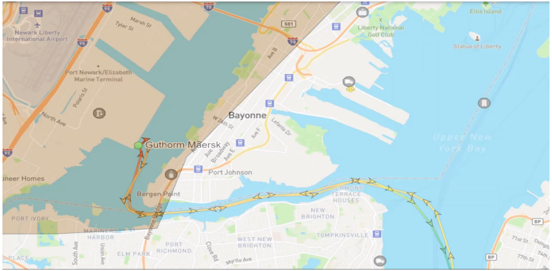
- AIS Vessel Traffic Data, June 2015 - December 2021 (Marine Cadastre)
  - Vessel location in US waters at 1-minute intervals (200 land-based receiving stations)
  - Vessel information (IMO & net tonnage capacity), lat/lon, speed, navigation status (moving, moored—held in position at pier, anchored)
  - **Ship dwell time** $\equiv$ time spent moored at zero speed
- Match ship location to geographic area of top 30 US ports (95% US container trade)
  - **Port Traffic** $\equiv$ daily sum of ship capacity moored $*$ % of day each ship spends at port
  - Calculate 28-day moving averages of daily port traffic (21-, 14-, 7-day av for robustness)

Ship Dwell Time Calculation

- Ship path indicated by line, redder color = slower speed. Darker regions are port areas



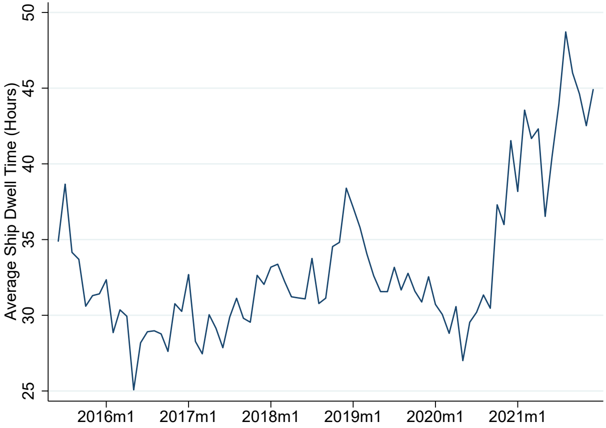
CMA CGM Christophe Colomb (13.8k TEUs) at Port of LA



Guthorm Maersk (11k TEUs) at Port of Newark

Containership Dwell Times at Port

- 1,444 containerships: Average 33.3 hours per ship (sd 5 hours). Post 2021 av 42.8 hours



Weighted by ship net tonnage

Containership Dwell Times at Port

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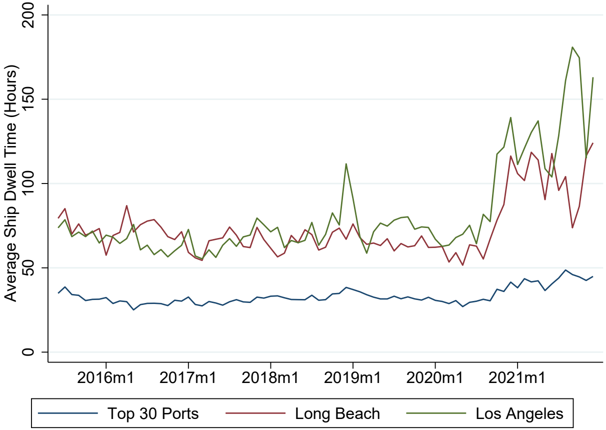
  - LB: 73.6 hours (post 2021, 104 hours); LA: 82.1 hours (post 2021, 136 hours)



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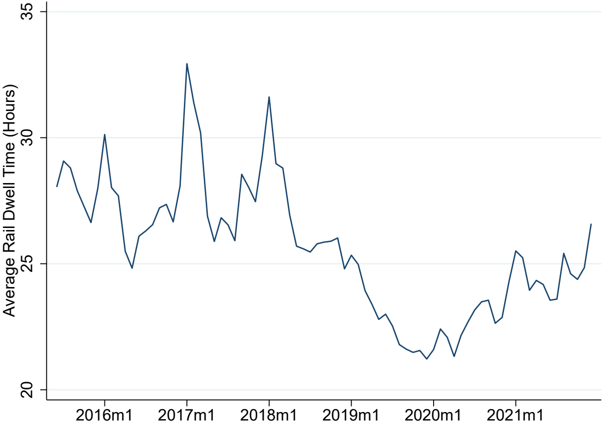
Congestion at Intermodal Rail Terminals

- Time a railcar spends at rail station (STB, 10 largest stations by Class I carriers)
  - Match stations to nearby ports using buffer area (150km buffer: 7 ports 12 rail stations)
  - Average of 25.8 hours per station (sd 2.7 hours)



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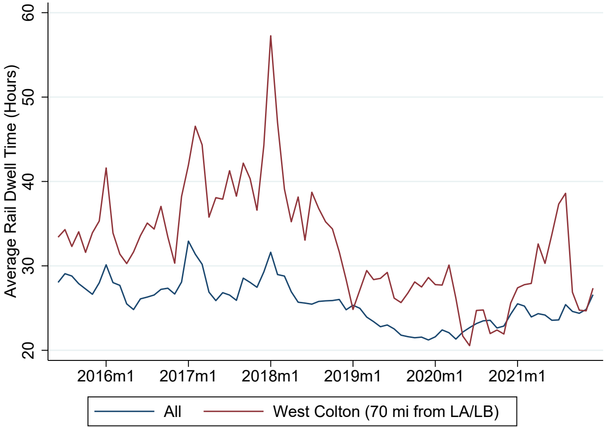
  - Average of 25.8 hours per station (sd 2.7 hours), 34.1 hours for stations close to LA/LB



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- Setup:
  - Consumption: CES preferences over goods $\nu \in [0,1]$ (elasticity of substitution σ) Details
  - CRS Production: Good ν transported to destination via primary & secondary transport networks (routes $r \in \mathcal{R}_{ij}^{1} \cup \mathcal{R}_{ij}^{1,2}$), subject to route-specific iceberg costs and iid Frechet shock

$$p_{ij,r}(\nu) = \frac{w_i}{A_i} \frac{\prod_{k=1}^{K} t_{r_{k-1},r_k}}{\varepsilon_{ij,r}(\nu)} \equiv \frac{w_i}{A_i} \tau_{ij,r}(\nu)$$

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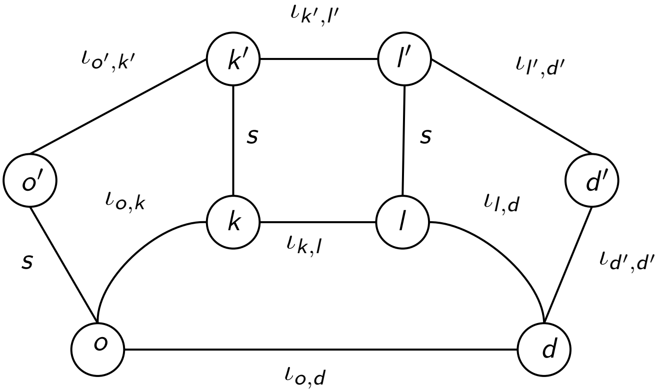
- Start with stylized illustration of multimodal transport network

Example of Multimodal Transport Network from o to d

- Transportation from city o to city d requires a set of connections (route r)



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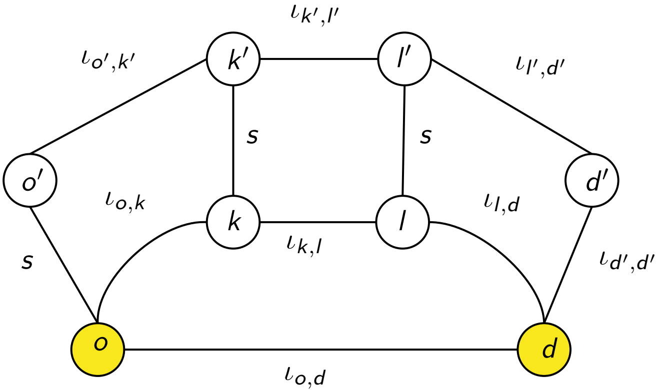
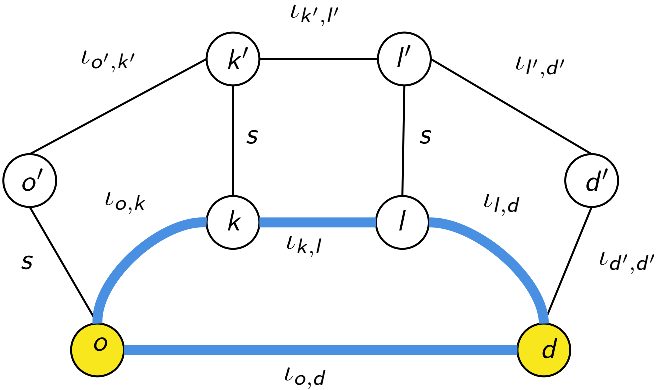


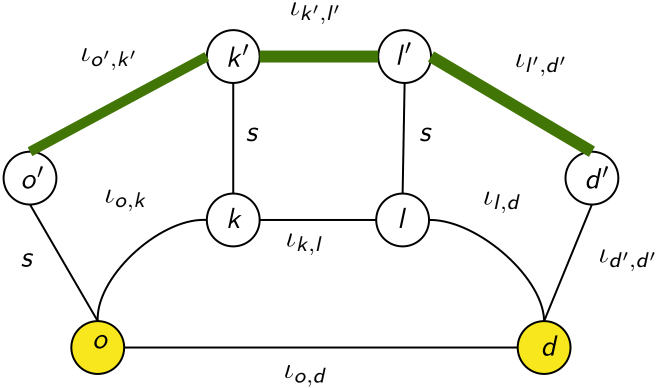
Example of Multimodal Transport Network from o to d

- Just utilizing the road network (blue), all possible routes are $r \in \mathcal{R}_{ij}^{1}$



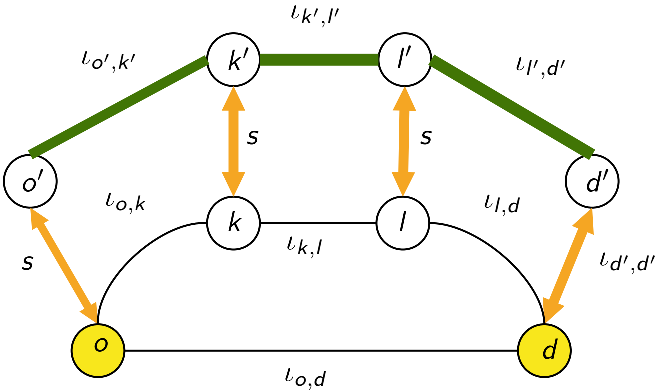
Example of Multimodal Transport Network from o to d

- Additionally, multimodal rail network can be utilized for transport (green)



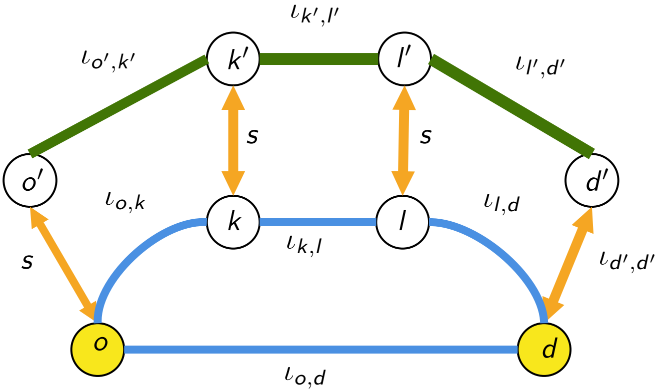
Example of Multimodal Transport Network from o to d

- Switch between modes is possible with intermodal terminals and switching cost s



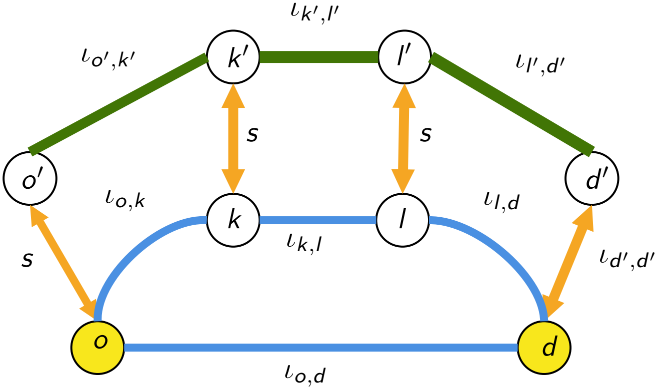
Example of Multimodal Transport Network from o to d

- On the multimodal network, all paths start & end on road network ("First & Last Mile")



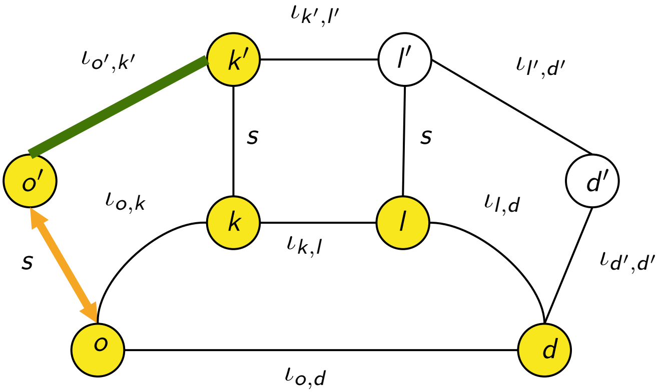
Example of Multimodal Transport Network from o to d

- Example of multimodal path $o \to o' \to k' \to k \to l \to d$



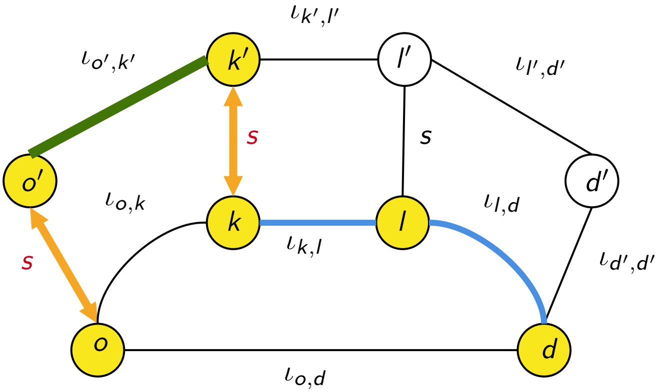
Example of Multimodal Transport Network from o to d

- First switch to rail from origin $o \to o'$, then along rail network $o' \to k'$



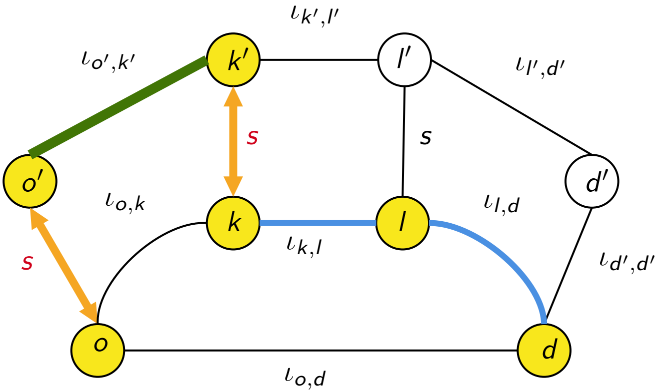
Example of Multimodal Transport Network from o to d

- Next switch back to road $k' \to k$, then along road network to destination $k \to l \to d$



Example of Multimodal Transport Network from o to d

- Cost along this multimodal path is $\tau_{od,r} = s_{oo'}\iota_{o'k'}s_{k'k}\iota_{kl}\iota_{ld}$, where $s_{oo'} = s_{k'k} = s$



Transport Cost over Multimodal Network

- Expected transport cost from i to j is sum of separable sets of routes on road and multimodal network

$$\tau_{ij} = \int_{\mathcal{R}_{ij}^{1} \cup \mathcal{R}_{ij}^{1,2}} \tau_{ij,r}(\nu) dr$$

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- Introduce matrix notation (geo sum of road network matrix **B**, intermodal linkages **S**) and apply formula for inverse of partitioned matrix Details

$$\tau_{ij}^{-\theta} = [\underbrace{\mathbf{B}}_{\substack{\text{Unimodal costs over} \\ \text{road network}}} + \underbrace{\mathbf{BS}\left(S(\Omega)^{-1}\right)\mathbf{S}'\mathbf{B}}_{\substack{\text{Multimodal costs over} \\ \text{road and secondary networks}}}]_{ij} = \left(\tau_{ij}^{1}\right)^{-\theta} + \left(\tau_{ij}^{1,2}\right)^{-\theta}$$

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Our contribution is $\mathbf{BS}\left(S(\Omega)^{-1}\right)\mathbf{S}'\mathbf{B} \Rightarrow$ characterization of the cost along multimodal routes *inclusive* of switching costs, despite increased dimensionality and complexity

Incorporate Congestion at Terminals

- Congestion at terminals: transiting cost through a terminal depends on overall traffic at the terminal ($\Xi^2_{kk'}$)

$$s_{kk'} = \bar{s}_{kk'} \left(\Xi^2_{kk'}\right)^{\lambda_2}$$

where λ_2 is strength of congestion at terminals, $\bar{s}_{kk'}$ is infrastructure of switching matrix connecting the two networks (exo)

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- Congestion at road network already included: direct transport cost of link kl depends on amount of traffic Ξ^1_{kl} that uses that link:

$$t_{kl} = \bar{t}_{kl} \left(\Xi^1_{kl}\right)^{\lambda_1}$$

  where λ_1 is strength of congestion on road network, $\bar{t}_{kl}$ is infrastructure network (exo)

EQM

- Solve for welfare equalization, income y_i, and labor densities l_i given
  - endogenous uni- and multimodal transport costs (τ_{ij})
  - geography of the local economy (productivity $\bar{A}_i$ and amenity $\bar{u}_i$ spillovers)
  - market clearing conditions
- $2N$ endo eqm values (income and labor densities) and $2N$ system of equations, where N is number of locations Details

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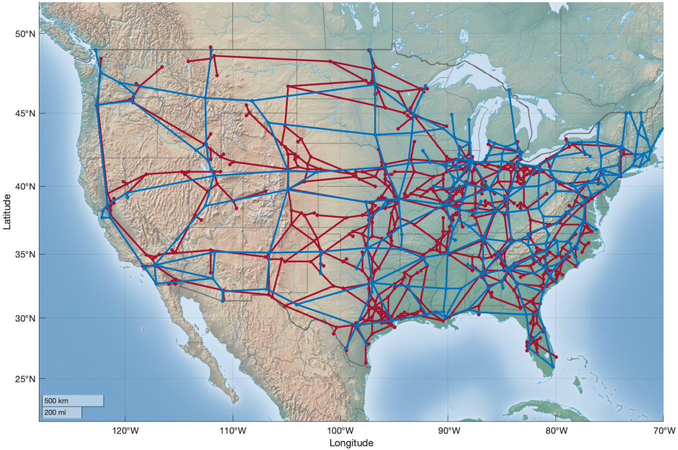
Theory to Data

1. Construct a multimodal transport network from detailed GIS data
2. Estimate congestion at intermodal terminals (λ_2)

Graph Representation of the US Freight Network

1. Income and road traffic data following Allen & Arkolakis (2022)
   - Preserve endpoints and intersections
   - Append income, population and traffic data (HPMS)
   - 228 nodes and and 704 edges
2. Rail network and rail traffic
   - Census' TIGER GIS information on Class 1 Multimodal Railroad network
   - Preserve intersections and endpoints
   - Use terminal locations connecting road and rail network (National Transportation Atlas)
   - Append rail traffic from STB's waybill sample
3. Append TEUs at Int'l Ports

Multimodal transport network



The figure shows the graph representation of the road (blue) and rail (red) network. Nodes are either population centers or intersections.

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Estimate intermodal congestion (λ_2)

$$\ln \text{ Ship Dwell Time }_{spdmy} = \beta_1 \ln \text{ Port Traffic }_{pdmy} + \delta_{dmy} + \alpha_{spm} + \epsilon_{spdmy}$$

where Ship Dwell Time$_{spdmy}$ is the hours ship s spent at port p on day d, month m, and year y, Port Traffic$_{pdmy}$ is 28-day moving average amount of port traffic at port p ending on that same day, δ_{dmy} is day-month-year fixed effects, and α_{spm} is ship-port-month fixed effects

- β_1 captures the elasticity of ship dwell times with respect to port traffic
- δ_{dmy} captures aggregate events that affect all ships, α_{spm} control for fixed ship-port characteristics (deep harbors, ship sizes), and time-varying port changes
- We find smaller magnitudes with shorter period of moving averages (21, 14, 7)—ship dwell times respond less to shorter period averages at port

Elasticity of Ship Dwell Times wrt Port Traffic

	(1)	(2)	(3)	(4)	(5)
Port Traffic	0.129	0.123	0.133		0.111
	(0.0404)	(0.0394)	(0.0401)		(0.0390)
Port Traffic × Before Mar 2020				0.131	
				(0.0421)	
Port Traffic × After Mar 2020				0.137	
				(0.0418)	
Day-Month-Year FE	✓	✓	✓	✓	✓
Ship-Port-Month FE			✓	✓	✓
Port-Month FE	✓	✓			
Ship-Port FE		✓			
Ship FE	✓				
Without West Coast Ports					✓
Observations	59551	59551	59551	59551	44920
R^2	0.65	0.73	0.81	0.81	0.72
F	10.23	9.76	10.94	5.70	8.17

Robust standard errors in parentheses are clustered by port. All variables are in logs. Port traffic is the 28-day moving average of total daily net tonnage at the port. Weighted by ship net tonnage.

Multimodal Impact of Port Congestion

- How much port traffic affect the amount of time a rail car spends at nearby rail stations

$$\ln \text{ Rail Dwell Time }_{rpwmy} = \beta_2 \ln \text{ Port Traffic }_{pwmy} + \gamma_{wmy} + \phi_{rpm} + \epsilon_{rpwmy}$$

where Rail Dwell Time_{rpwmy} is the average number of hours a rail car spends at a rail station r that is in the vicinity of port p for week w month m and year y, Port Traffic_{pwmy} is the total amount of port traffic at port p for week w month m and year y, γ_{wmy} is week-month-year fixed effects, and ϕ_{rpm} is rail station-port-month fixed effects.

  - β_2 captures the elasticity of rail dwell times with respect to port traffic
  - γ_{wmy} control for aggregate events. ϕ_{rpm} control for fixed (comparative adv/geography) and time-varying characteristics (technology changes) at the rail-port level

Elasticity of Rail Dwell Times with respect to Port Traffic

	(1)	(2)	(3)	(4)	(5)
Port Traffic	0.0267	0.0268	0.0273	0.0245	
	(0.00517)	(0.00518)	(0.00662)	(0.00641)	
Port Traffic × Before Mar 2020					0.0258
					(0.00886)
Port Traffic × After Mar 2020					0.0305
					(0.0134)
Port Buffer Area	150km	150km	150km	200km	150km
Week-Month-Year FE	✓	✓	✓	✓	✓
Rail Station-Port-Month FE		✓	✓	✓	✓
Port-Month FE	✓				
Rail Station FE	✓				
Without West Coast Ports			✓		
Observations	4087	4087	3361	4813	4087
R^2	0.81	0.81	0.81	0.81	0.81
F	26.79	26.87	17.01	14.65	23.10

Robust standard errors in parentheses are clustered by port. All variables are in logs.

Data: US Domestic Freight Transportation, Traffic, and Congestion

Theory: Spatial Eqm Model with Multiple Modes and Switching

Theory to Data: Multimodal Network and Congestion at Intermodal Terminals

Counterfactual: Infrastructure Improvement at Intermodal Terminals

Conclusion

Infrastructure Improvements at Intermodal Terminals

- While previous work focused on improving individual US highway segments, less is known about improving the level of integration within US multimodal transport networks

Infrastructure Improvements at Intermodal Terminals

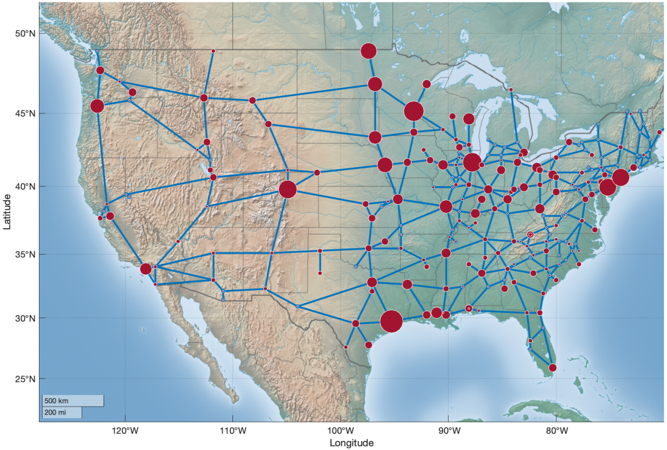
- While previous work focused on improving individual US highway segments, less is known about improving the level of integration within US multimodal transport networks
- Estimate the aggregate welfare impact of a 1% decrease in switching cost at each intermodal terminal within the US multimodal transport network
- Employ Hat Algebra and express CF equilibrium in terms of changes:
    - Given observed road and rail traffic flows $\left(\Xi^1_{ij}, \Xi^2_{i'j'}\right)$, economic activity at CBSAs (income and expenditure (Y_i, E_j)), and calibrated parameters $\{\alpha, \beta, \theta, \lambda_1, \lambda_2, \nu\}$, solve for the equilibrium change in economic outcomes $\left(\hat{y}_i, \hat{l}_i, \hat{\chi}\right)$ CF Eqm

Calibration of parameters

- Take key parameters from literature (Ahlfeldt et al., 2015):
  - Shape parameter $\theta = 6.83$
  - Local productivity spillovers $\alpha = 0.12$
  - Local amenity spillovers $\beta = -0.1$
- Road network congestion parameter is $\lambda_1 = 0.092$ (Allen & Arkolakis, 2022)
- Multimodal network congestion parameter $\lambda_2 = \beta_1 + \beta_2 = 0.1363$
  - Preliminary: time cost conversion, estimate using IV

Welfare Effects of Intermodal Terminal Investments

- Intermodal terminals that generate the largest gains are in the center of US, highlighting the role of multimodal network transporting goods from coastal regions to the interior



Larger dots indicate larger gains. Blue lines indicate graph representation of the primary road network.

Welfare Effects of Intermodal Terminal Investments: Top 10

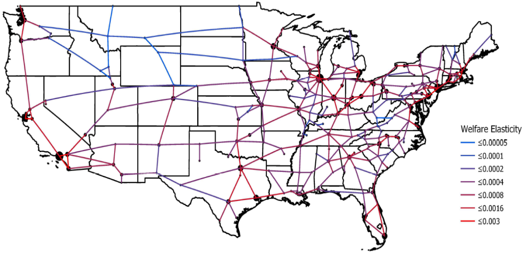
- These intermodal terminals are highly central to the multimodal transportation system and important bottlenecks: welfare gains ≈200-300 million USD of additional GDP

	CBSA Name	Welfare	Benefit	Population	Throughput
1	Houston-Sugar Land-Baytown, TX	0.0015	287.10	3133212	29047
2	Minneapolis-St. Paul-Bloomington, MN-WI	0.0013	241.95	2886766	16634
3	Chicago-Joliet-Naperville, IL-IN-WI	0.0011	205.63	9368268	203226
4	Denver-Aurora-Broomfield, CO	0.0010	191.97	2252276	78636
5	New York-Northern New Jersey-Long Island, NY-NJ-PA	0.0009	174.07	14745610	16899
6	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	0.0008	147.61	4532390	6114
7	Cavalier, ND	0.0007	137.90	5407	43352
8	Omaha-Council Bluffs, NE-IA	0.0007	125.16	646308	46166
9	Fargo, ND-MN	0.0006	112.79	232866	65755
10	Portland-Vancouver-Hillsboro, OR-WA	0.0006	110.13	1641801	6050

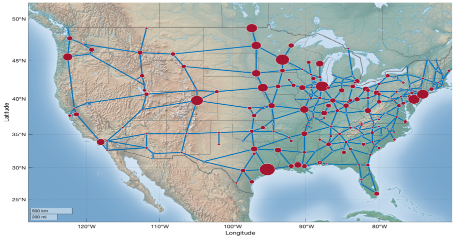
Top ten terminals where one percent reduction of transport cost generates the highest benefit. Column (3) shows the welfare change in percentage points, & Column (4) calculates how much 2012 US GDP would need to increase in order to match the overall welfare gains in Column (3). The terminal's population & rail throughput is in Columns (5) and (6).

Welfare Effects of Intermodal Terminal Investments: Comparison

- Rel to unimodal network: largest gains from (1) short coastal segments linking densely populated areas, like Boston-PHL & LA-San Diego, & (2) trade thoroughfares via Indiana

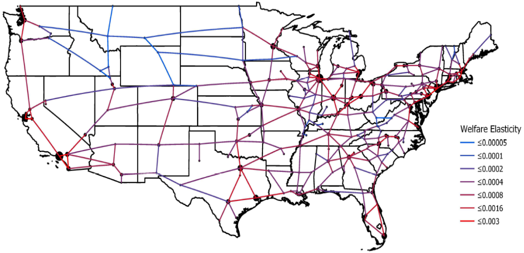


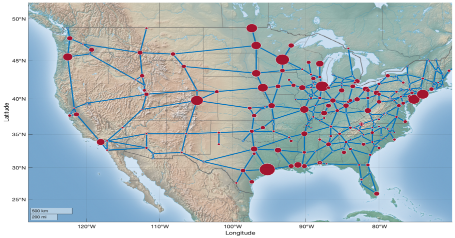
AA (2022) Fig 5(a): Highway links improvement



Welfare Effects of Intermodal Terminal Investments: Comparison

- Rel to unimodal network: largest gains from (1) short coastal segments linking densely populated areas, like Boston-PHL & LA-San Diego, & (2) trade thoroughfares via Indiana
- Our gains are mostly in the center of the US: indicative of multimodal transportation taking place over longer distances and linking coastal to interior regions

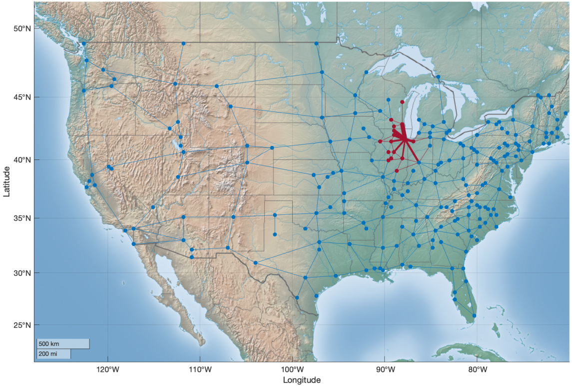




AA (2022) Fig 5(a): Highway links improvement

Implications from Infrastructure Investments

- One takeaway: Investment in one transport mode generates spillovers onto other modes
- Modal Substitution: Improving Chicago's terminals decreases road traffic locally

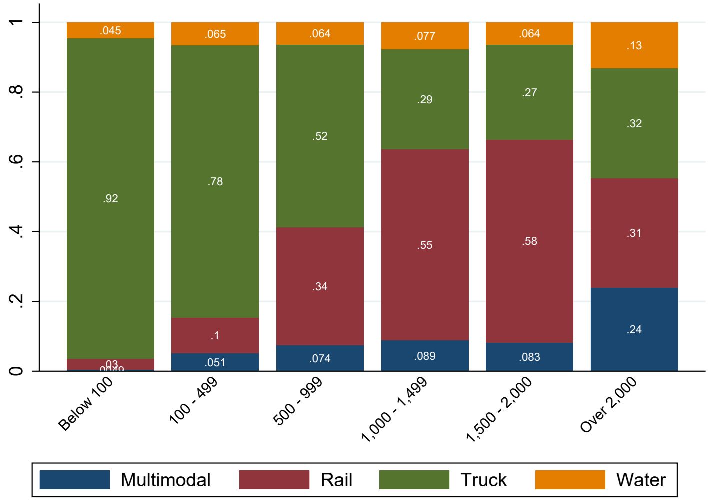


Changes in road traffic due to 1% reduction in transport costs at Chicago. Red indicates decreases in traffic while blue indicates increases. Thicker lines indicate larger changes.

Conclusion

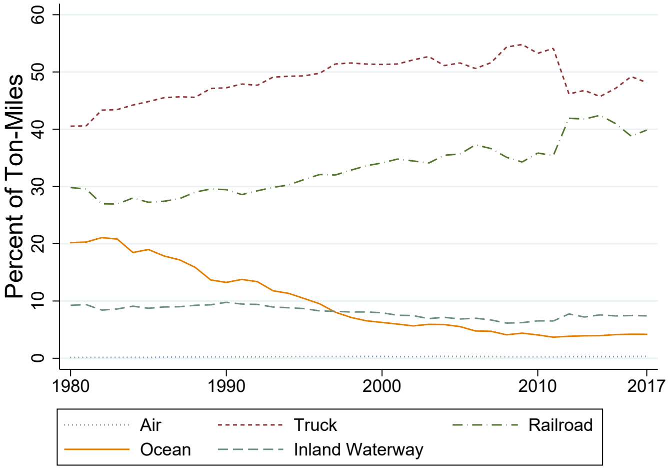
- We study multimodal transport networks and their impact on infrastructure investments
- Develop tractable spatial eqm model with multiple modes and mode switching
- Estimate congestion at intermodal port terminals and multimodal impact of this congestion on nearby rail stations
- Evaluate welfare from intermodal terminal investments: largest gains in center of US
- In progress: validation exercises, mode extensions, CF on benefits from rail network ...

Modal Weight Shares by Distance Band



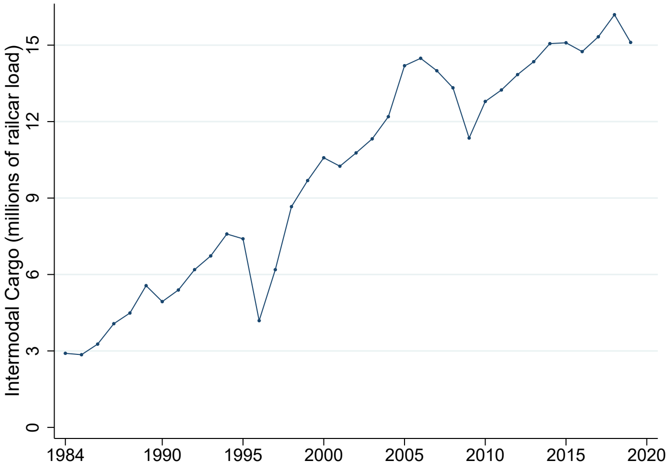
back

Freight Share 1980-2017



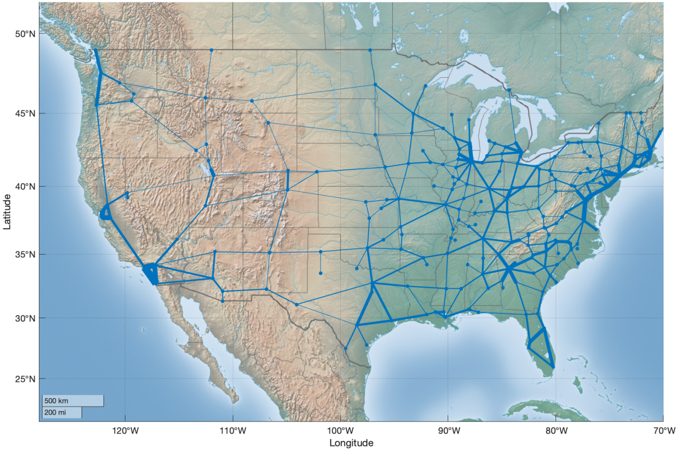
Data Multimodal Map

Intermodal Rail 1984-2019



Data Multimodal Map

US Road Traffic

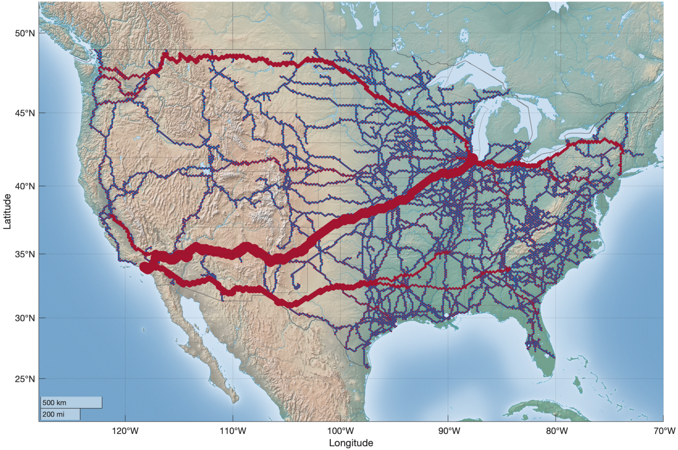


The traffic depicted is presents the traffic along the graph representation of the interstate highway system, depicting data from the 2012 Highway Performance Monitoring System (HPMS) dataset by the Federal Highway Administration.

US Rail Traffic

- Confidential waybill rail data, 1984-2019
  - Stratified sample of waybills representing 1-3% of all US rail traffic
  - Key Variables:
    - Origin-Interchanges-Destination at monthly level
    - Carloads, Tonnage, Weight, Freight Revenue
    - Product details: STCC (2 Digit) or HS
    - Car Type (intermodal vs not)

US Rail Traffic



Rail traffic data for Class I carriers (largest in US) conditional on intermodal capability. Shortest routes are imputed between origin, interchanges, and destination to assign total tonnage to individual rail segments along the multimodal network.

Data

Model Details

- CES preferences: rep agent in j supplies unit endowment of labor inelastically, earns wage w_j, and purchases continuum of goods, $\nu \in [0,1]$ with EoS $\sigma \geq 0$:

$$U_j = \left(\sum_{\nu} q_{ij}^{\frac{\sigma-1}{\sigma}}(\nu) \right)^{\frac{\sigma}{\sigma-1}}$$

- CRS Production: price of good ν in destination j from origin i along route $r \in \mathcal{R}_{ij}^1 \cup \mathcal{R}_{ij}^{1,2}$

$$p_{ij,r}(\nu) = \frac{w_i}{A_i} \tau_{ij,r}(\nu) = \frac{w_i}{A_i} \frac{\prod_{k=1}^{K} t_{r_{k-1},r_k}}{\varepsilon_{ij,r}(\nu)}$$

MC in i is $\frac{w_i}{A_i}$, local wages w_i, and each worker produces A_i units of goods. Assume $\epsilon_{ij,r}(\nu)$ is iid Fréchet distributed across routes and goods with scale parameter $1/A_i$ where A_i captures origin-specific efficiency and shape parameter θ regulates the inverse of shock dispersion Back

Transport Cost over Multimodal Network

- Enumerating in matrix notation, where $\mathbf{A_1} = [a_{ij}] = \left[t_{ij}^{-\theta}\right]$ is $N^1 \times N^1$ adjacency matrix for road network, $\mathbf{A_2} = [a_{i'j'}] = \left[t_{i'j'}^{-\theta}\right]$ is $N^2 \times N^2$ adjacency matrix for multimodal network, $\mathbf{S} = [s_{ii'}]$ is diagonal matrix representing linkages between the two:

$$\tau_{ij}^{-\theta} = \left(\sum_{K=0}^{\infty} \left(\left(\sum_{K=0}^{\infty} \mathbf{A}_1^K \right) \left(\mathbf{S} \left(\sum_{K=0}^{\infty} \mathbf{A}_2^K \right) \mathbf{S}' \right) \right)^K \left(\sum_{K=0}^{\infty} \mathbf{A}_1^K \right) \right)_{ij} \quad (1)$$

- If spectral radius of matrices < 1, define $\mathbf{B} \equiv (\mathbf{I} - \mathbf{A}_1)^{-1}$ as geo sum of matrix $\mathbf{A}_1$ and $\mathbf{D} \equiv \mathbf{S} \left(\sum_{K=0}^{\infty} \mathbf{A}_2^K\right) \mathbf{S}'$ as geo sum of $\mathbf{A}_2$ inclusive of switching linkages between network $\mathbf{S}$
- Define the inverse of the Schur complement of the Laplacian of the partitioned infrastructure matrix for the multimodal transport network as $\mathbf{E} \equiv \left(\mathbf{B}^{-1} - \mathbf{D}\right)^{-1} \equiv S(\Omega)^{-1}$
- Apply definitions to (1) and invoke the recursive formula for inverse of sum of matrices

Back

Spatial Equilibrium

Assuming localized amenity and productivity spillovers, i.e.

$$A_i = \bar{A}_i L_i^{\alpha}, \quad u_i = \bar{u}_i L_i^{\beta} \tag{2}$$

The equilibrium system solves for the endogenous variables, $\{y_j, l_j\}$, given the uni- and multimodal transport cost $\{\tau_{ij}^{1}, \tau_{ij}^{1,2}\}$ as well as the geography of the economy, $\{\bar{a}_j, \bar{u}_j\}$

$$\bar{A}_i^{-\theta} y_i^{1+\theta} l_i^{-\theta(1+\alpha)} = \chi \sum_{j=1}^{N} \left(\tau_{ij}^{1}\right)^{-\theta} \bar{u}_j^{\theta} y_j^{1+\theta} l_j^{\theta(\beta-1)} + \chi \sum_{j=1}^{N} \left(\tau_{ij}^{1,2}\right)^{-\theta} \bar{u}_j^{\theta} y_j^{1+\theta} l_j^{\theta(\beta-1)} \tag{3}$$

$$\bar{u}_i^{-\theta} y_i^{-\theta} l_i^{\theta(1-\beta)} = \chi \sum_{j=1}^{N} \left(\tau_{ij}^{1}\right)^{-\theta} \bar{A}_j^{\theta} y_j^{-\theta} l_j^{\theta(\alpha+1)} + \chi \sum_{j=1}^{N} \left(\tau_{ij}^{1,2}\right)^{-\theta} \bar{A}_j^{\theta} y_j^{-\theta} l_j^{\theta(\alpha+1)} \tag{4}$$

where $\chi \equiv \left(\frac{L(\alpha+\beta)}{\bar{W}}\right)^{\theta}$ is an endogenous scalar that is inversely related to welfare.

Spatial Equilibrium with Road and Rail Traffic

The equilibrium system solves for the endogenous variables, $\{y_j, l_j\}$, given the uni- and multimodal transport cost $\{\tau_{ij}^{1}, \tau_{ij}^{1,2}\}$ as well as the geography of the economy, $\{\bar{A}_i, \bar{u}_i\}$

$$\begin{aligned} y_i^{\frac{1+\theta\lambda+\theta}{1+\theta\lambda}} l_i^{\frac{-\theta(1+\alpha+\theta\lambda(\alpha+\beta))}{1+\theta\lambda}} &= \chi \bar{A}_i^{\theta} \bar{u}_i^{\theta} y_i^{\frac{1+\theta\lambda+\theta}{1+\theta\lambda}} l_i^{\frac{\theta(\beta-1)}{1+\theta\lambda}} \\ &+ \chi^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\bar{t}_{ij} \bar{L}^{\lambda}\right)^{-\frac{\theta}{1+\theta\lambda}} \bar{A}_i^{\theta} \bar{u}_i^{\theta \frac{\theta\lambda}{1+\theta\lambda}} \bar{A}_j^{-\frac{\theta}{1+\theta\lambda}} y_j^{\frac{1+\theta}{1+\theta\lambda}} l_j^{-\frac{\theta(1+\alpha)}{1+\theta\lambda}} \\ &+ \sum_j s_{ii'}^{-\theta} \tau_{i'j'}^{-\theta} s_{j'j}^{-\theta} \bar{A}_j^{-\theta} y_j^{1+\theta} l_j^{-\theta(1+\alpha)} \bar{A}_i^{\theta} l_i^{-\theta(\beta-1)\frac{\theta\lambda}{1+\theta\lambda}} y_i^{-\theta\frac{\theta\lambda}{1+\theta\lambda}} \end{aligned} \tag{5}$$

$$\begin{aligned} y_i^{-\frac{\theta(1-\lambda)}{1+\theta\lambda}} l_i^{\frac{\theta(1-\beta-\theta\lambda(\alpha+\beta))}{1+\theta\lambda}} &= \chi \bar{A}_i^{\theta} \bar{u}_i^{\theta} y_i^{-\frac{\theta(1-\lambda)}{1+\theta\lambda}} l_i^{\frac{\theta(\alpha+1)}{1+\theta\lambda}} \\ &+ \chi^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\bar{t}_{ji} \bar{L}^{\lambda}\right)^{-\frac{\theta}{1+\theta\lambda}} \bar{A}_i^{\theta \frac{\theta\lambda}{1+\theta\lambda}} \bar{u}_i^{\theta} \bar{u}_j^{-\frac{\theta}{1+\theta\lambda}} l_j^{\frac{\theta(1-\beta)}{1+\theta\lambda}} y_j^{-\frac{\theta}{1+\theta\lambda}} \\ &+ \sum_j s_{jj'}^{-\theta} \tau_{j'i'}^{-\theta} s_{i'i}^{-\theta} \bar{u}_j^{-\theta} y_j^{-\theta} l_j^{\theta(1-\beta)} \bar{u}_i^{\theta} l_i^{-\theta(1+\alpha)\frac{\theta\lambda}{1+\theta\lambda}} y_i^{\frac{\theta\lambda(1+\theta)}{1+\theta\lambda}} \end{aligned} \tag{6}$$

Back

Counterfactual Equilibrium

Given observed traffic flows $\left(\Xi^1_{ij}, \Xi^2_{i'j'}\right)$, economic activity in the geography (Y_i, E_j), and parameters $\{\alpha, \beta, \theta, \lambda_1, \lambda_2, \nu\}$, the equilibrium change in economic outcomes $\left(\hat{y}_i, \hat{l}_i, \hat{\chi}\right)$ is the solution of the following system of equations:

$$
\begin{aligned}
\hat{l}_i^{\frac{-\theta\left(1+\alpha+\theta\lambda_1(\alpha+\beta)\right)}{1+\theta\lambda_1}} \hat{y}_i^{\frac{-\theta(1-\lambda_1)}{1+\theta\lambda_1}} &= \hat{\chi}\left(\frac{Y_i}{Y_i+\sum_j \Xi^1_{ji}+\sum_j \Xi^2_{ji}}\right) \hat{y}_i^{\frac{-\theta(1-\lambda_1)}{1+\theta\lambda_1}} \hat{l}_i^{\frac{\theta(\alpha+1)}{1+\theta\lambda_1}} \\
&+ \hat{\chi}^{\frac{\theta\lambda_1}{1+\theta\lambda_1}} \sum_j \left(\frac{\Xi^1_{ij}}{Y_i+\sum_j \Xi^1_{ji}+\sum_j \Xi^2_{ji}}\right) \hat{\bar{t}}_{ji}^{-\frac{\theta}{1+\theta\lambda_1}} \hat{l}_j^{\frac{\theta(1-\beta)}{1+\theta\lambda_1}} \hat{y}_j^{-\frac{\theta}{1+\theta\lambda_1}} \\
&+ \hat{\chi}^{\frac{2\theta\lambda_2}{1+\theta\lambda_2}} \left(\hat{l}_i^{\alpha+1}\hat{y}_i^{-\frac{\theta+1}{\theta}}\right)^{\frac{\theta^2(\lambda_1-\lambda_2)}{(1+\theta\lambda_1)(1+\theta\lambda_2)}} \sum_j \left(\frac{\Xi^2_{ij}}{Y_i+\sum_j \Xi^1_{ji}+\sum_j \Xi^2_{ji}}\right) \hat{\bar{s}}_{jj'}^{-\frac{\theta}{1+\theta\lambda_2}} \hat{\tau}_{j'i'}^{-\theta} \hat{\bar{s}}_{i'i}^{-\frac{\theta}{1+\theta\lambda_2}} \hat{l}_j^{\frac{\theta(1-\beta)}{1+\theta\lambda_2}} \hat{y}_j^{-\frac{\theta}{1+\theta\lambda_2}} \\
&\times \left(\sum_l \frac{\Xi^2_{i'l'}}{\sum_{l'} \Xi^2_{i'l'}} \hat{\tau}_{i'l'}^{-\theta} \hat{s}_{l'l}^{-\theta} \left(\hat{y}_l \hat{l}_l^{\beta-1}\right)^{-\theta}\right)^{-\frac{\theta\lambda_2}{1+\theta\lambda_2}} \left(\sum_l \frac{\Xi^2_{j'l'}}{\sum_{l'} \Xi^2_{j'l'}} \hat{\tau}_{j'l'}^{-\theta} \hat{s}_{l'l}^{-\theta} \left(\hat{l}_l^{\alpha+1}\hat{y}_l^{-\frac{\theta+1}{\theta}}\right)^{-\theta}\right)^{-\frac{\theta\lambda_2}{1+\theta\lambda_2}}
\end{aligned}
$$

Back