The Economics of Space 433: Lectures 13 and 14

Investment in Transportation Infrastructure

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Spatial Applications

- We have developed the theoretical apparatus to model the economics and geographic aspects of Space
- We will now proceed to a number of spatial applications
- Our first application is investment in infrastructure
  - This chapter is largely based on the ''Spatial Economics Primer'' written with Treb Allen and the 2014 joint article

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- What is the impact on the network?
  - Improvement in routing, subsequent effects on welfare

$$\frac{d \ln W}{d \ln \bar{t}_{ij}} = \sum_{k=1}^{N} \sum_{l=1}^{N} \frac{d \ln W}{d \ln \tau_{kl}} \times \frac{d \ln \tau_{kl}}{d \ln \bar{t}_{ij}}.$$

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  - Why the double summation?
    - Because all the routes are potentially improved from an investment in one link
- We also need to assess the cost of the investment, $c\left(\{\Delta \bar{t}_{ij}\}_{ij}\right)$, and compare

Roadmap

- **Routing Benefits of Investment in the Transportation Network**
- Welfare Benefits from Improvements in Routing Times
- The Cost of Investment in Transportation Infrastructure
- The Impact of Infrastructure Investment on the Level and the Allocation of Economic Activity

Investments in the Transportation Network

- Let us assess the different terms in sequence
  - How can we compute $\frac{d \ln \tau_{kl}}{d \ln \bar{t}_{ij}}$?
  - We need to implement variations of Dijkstra
- We have studied variations of the algorithm
  - And briefly looked at the actual routing benefits for the Interstate Highway System in the US
  - We will now come back study the US transportation network in detail

US Interstate Highways (Allen Arkolakis '14)

- Study the impact of the US Interstate Highway System (IHS) on the American economy
  - Can think of IHS as an improvement in multiple $\bar{t}_{ij}$ which we expect to improve all τ_{ij}

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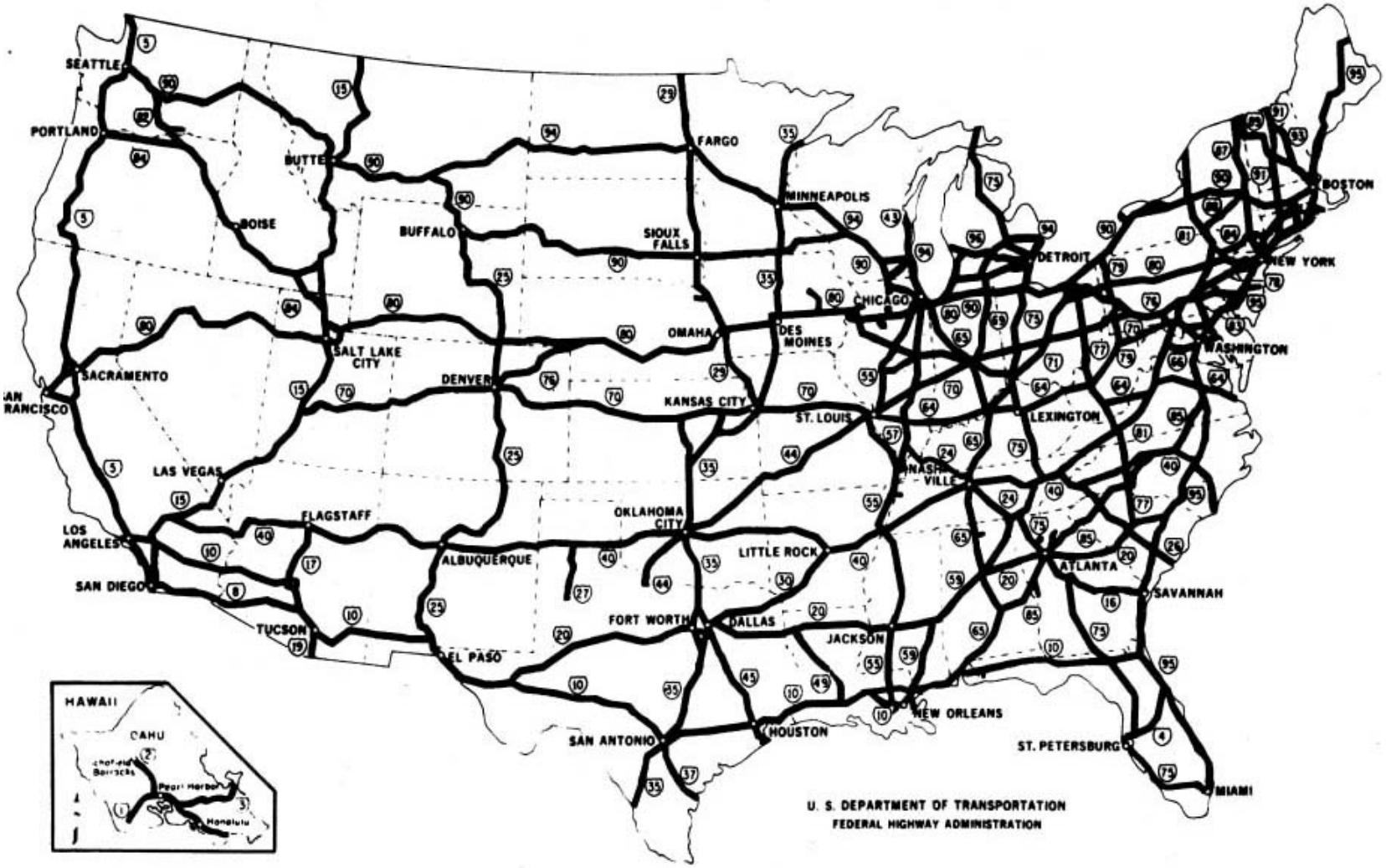
- Study the impact of the US Interstate Highway System (IHS) on the American economy
  - Can think of IHS as an improvement in multiple $\bar{t}_{ij}$ which we expect to improve all τ_{ij}
- Some facts about IHS:
  - Created by Eisenhower in 1956
  - Currently about 77,000 km
  - Speed 80-130 km/h
  - Main improvement of IHS (in our context) is allowing cars/trucks to maintain high speeds

US Interstate Highways: Original Planned Highways



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  - Define the max speed to be highest if there is an interstate highway at that point, slightly lower if a regular highway, and lowest if there is no highway at all

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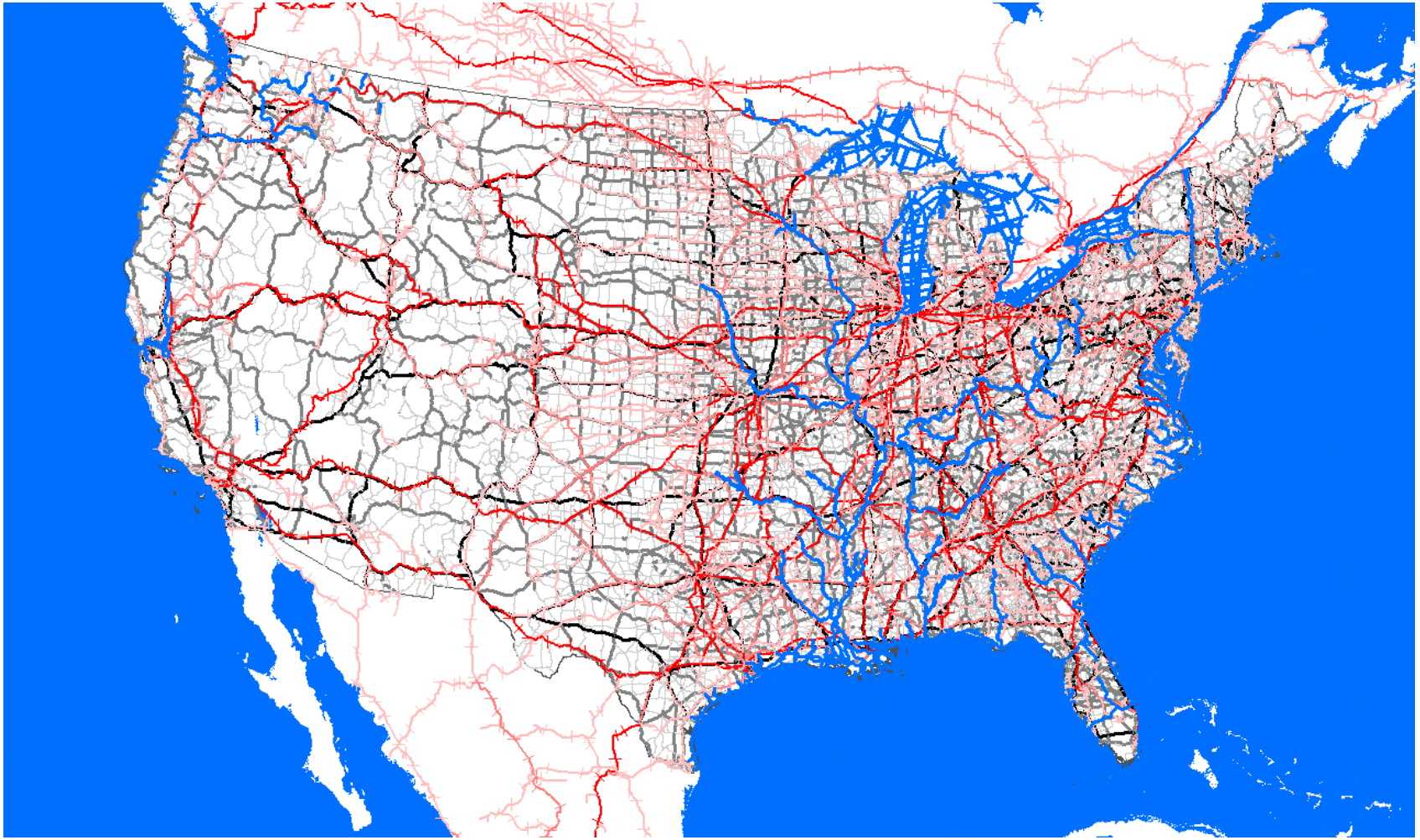
- Consider the routing problem, but this time we are looking for a path through continuous space
  - Fast Marching Method (generalization of Dijkstra to continuous space)
  - Given existing $\bar{t}_{ij}$ network, construct bilateral trade costs as minimum distance $\tau_{ij}(\bar{t}_{11}, \bar{t}_{12}, ..., \bar{t}_{NN})$

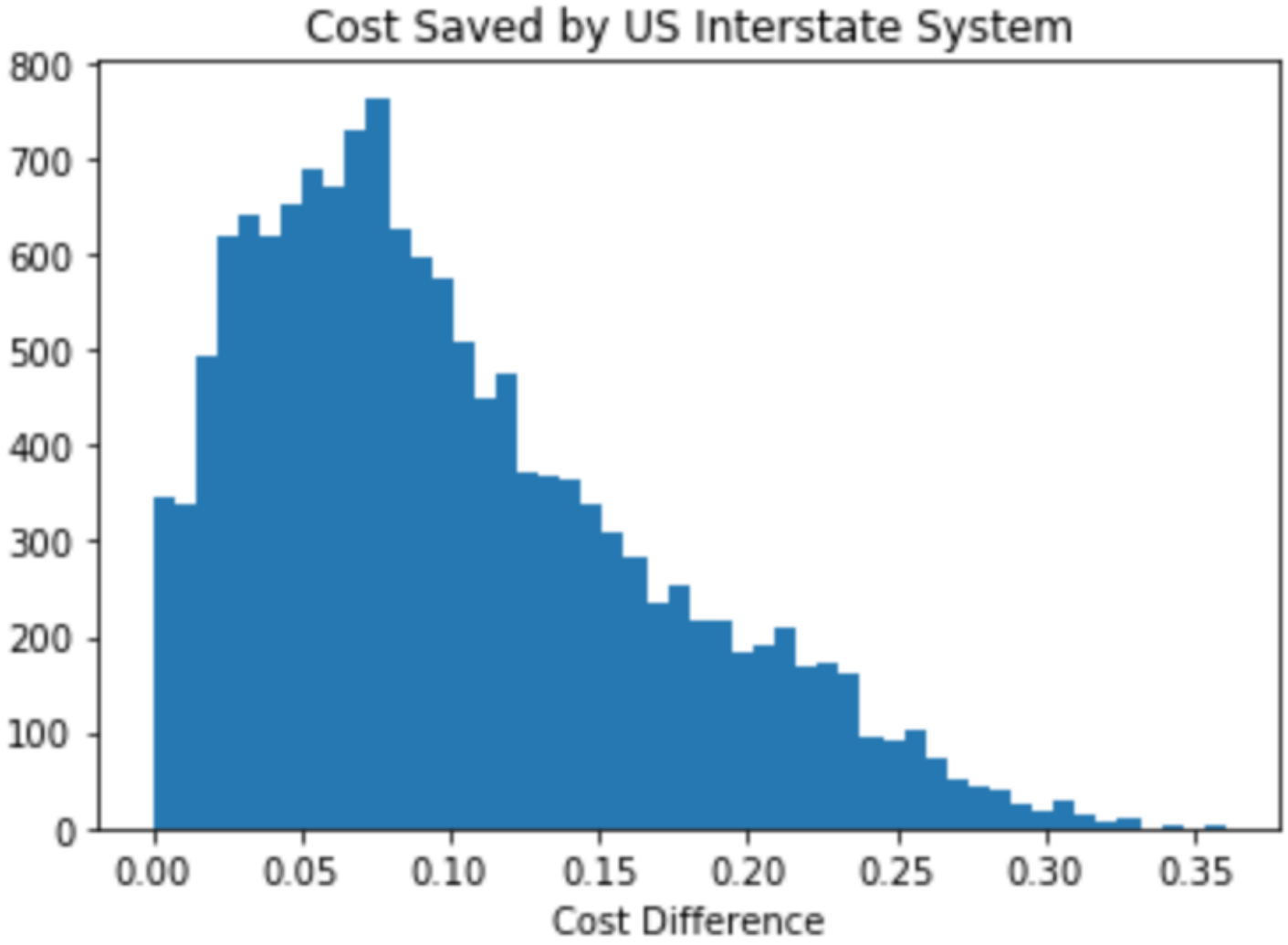
US Interstate Highways (Allen Arkolakis '14)

- Some technical details:
  - Units of space are the 151 Metropolitan Statistical Areas (roughly, areas around large cities)
  - Normalize the cost of driving at interstate highway speed in a straight line across the US to be 1
  - Define interstate highway speed to be 70mph, (non-interstate) highway speeds to be 55, arterial road speed to be 35, and all other space to be 20

The US Transportation Network



US Interstate Highways: Time Difference



US Interstate Highways (Allen Arkolakis '14)

Origin	Destination	With IHS	No IHS	Time Saved	Dist (km)
NY	LA	0.803	1.108	0.305	3936
NY	Jacksonville	0.347	0.450	0.103	1343
NY	Chicago	0.224	0.305	0.081	1153
NY	Seattle	0.837	1.083	0.246	3874
Kansas City	LA	0.460	0.653	0.192	2182
Kansas City	Jacksonville	0.385	0.458	0.073	1520
Kansas City	Chicago	0.154	0.191	0.038	670
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- Remember one unit of time is the time it takes to drive in a straight line across the country at IHS speeds

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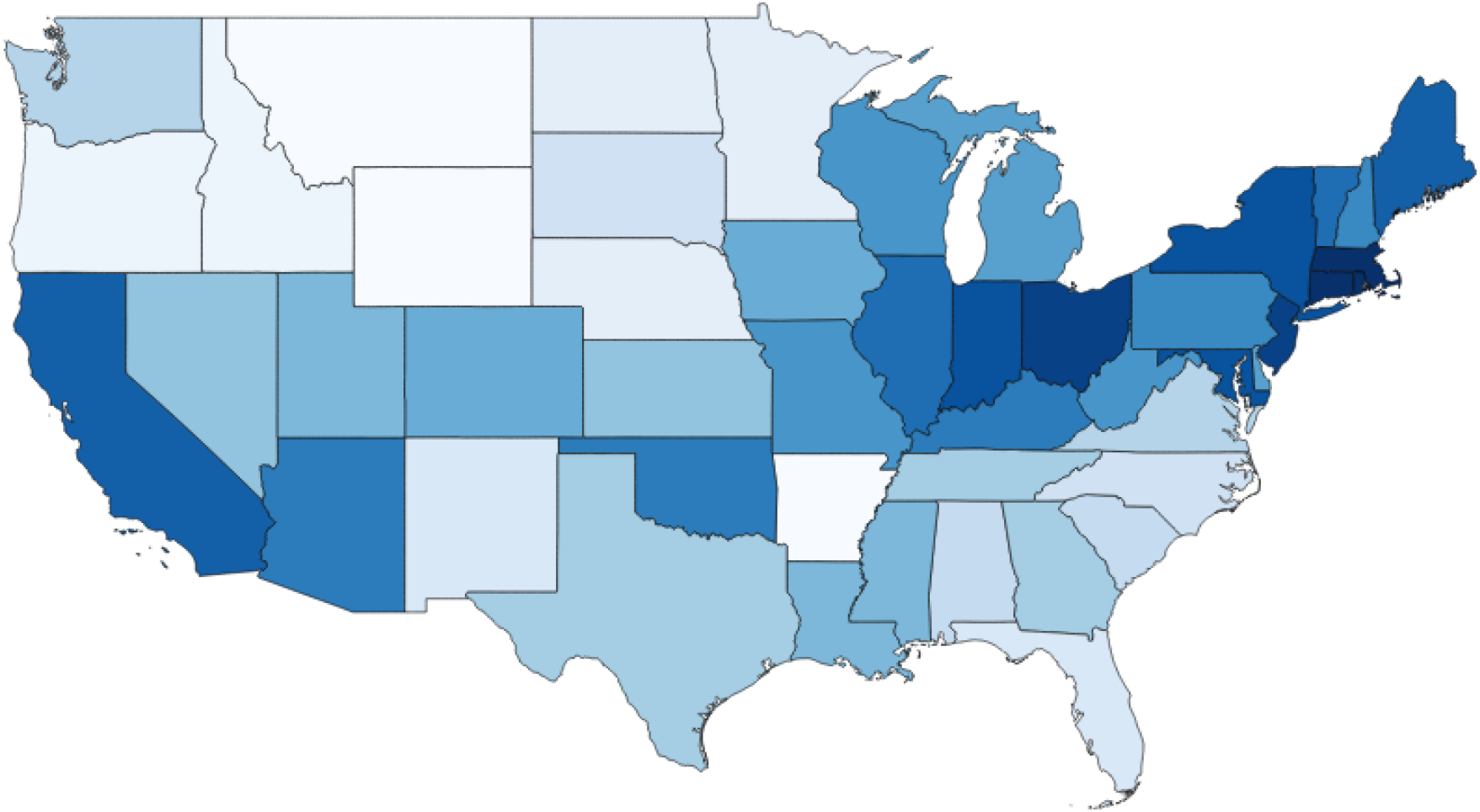
- Remember one unit of time is the time it takes to drive in a straight line across the country at IHS speeds
- Cost saved is highly correlated (unsurprisingly) with straight line distance in km

US Interstate Highways: Time Saved by State (pct)



Roadmap

- Routing Benefits of Investment in the Transportation Network
- **Welfare Benefits from Improvements in Routing Times**
- The Cost of Investment in Transportation Infrastructure
- The Impact of Infrastructure Investment on the Level and the Allocation of Economic Activity

Welfare Effects of Infrastructure and the Social Savings Formula

- Consider a change in price due to infrastructure benefit $\frac{\Delta \tau_{ij}}{\tau_{ij}}$
- What is the benefit?
  - Based on an argument of revealed preference, Fogel '64 postulated a *social savings* formula

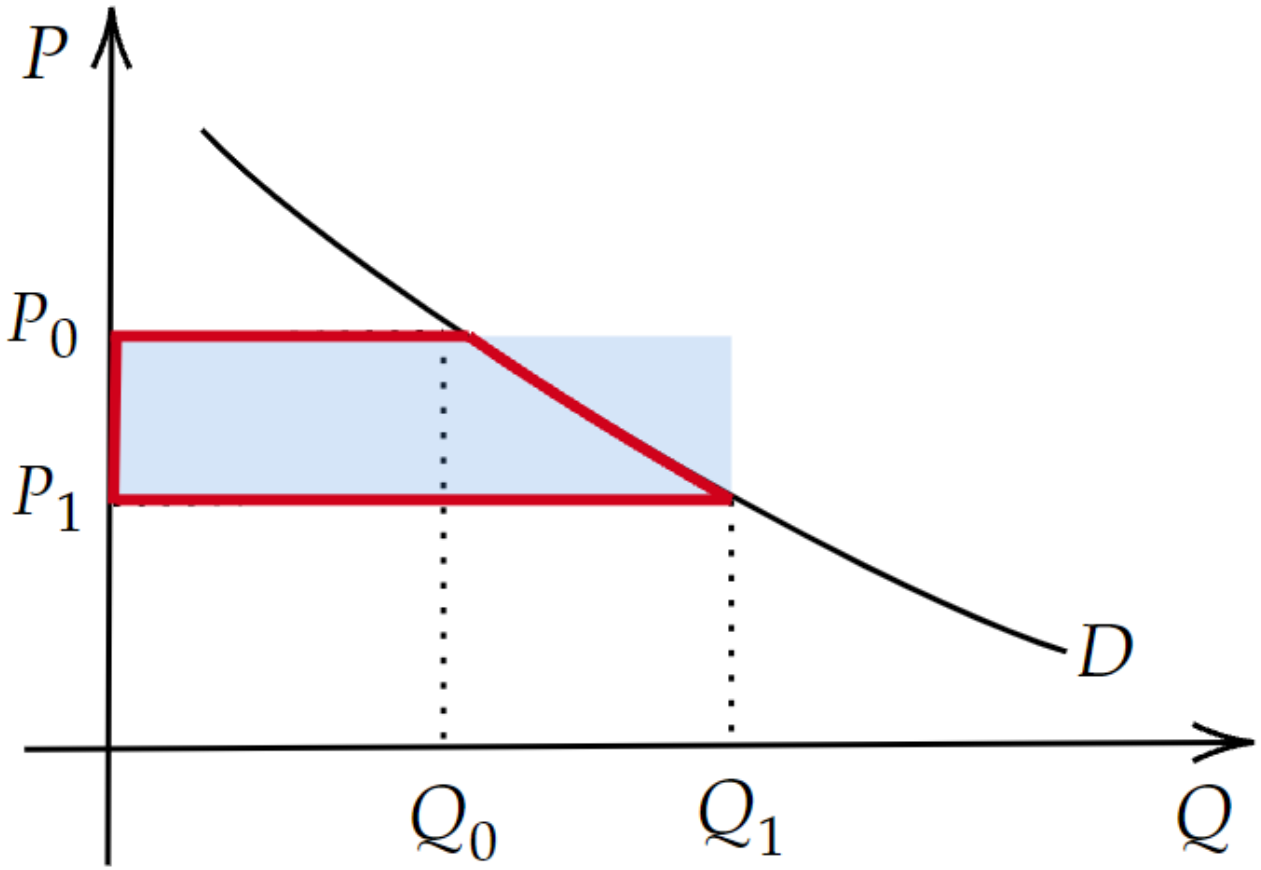
$$\underbrace{\frac{\Delta W}{W}}_{\text{social savings}} = \underbrace{p_{ij}\frac{\Delta \tau_{ij}}{\tau_{ij}}}_{\text{change in price}} \times \underbrace{q_{ij}}_{\text{final quantity}}$$

- Using quantitative methods, he calculated the effect of the absence of railroads
  - He estimated a 2.7% of GDP. Negligible by historian's standards
  - The formula also neglects General Equilibrium Effects, as well as the presence of Externalities

Intuition for the Social Savings Formula

- Consider the demand curve
  - We want to evaluate the welfare losses from the old technology $p_1 < p_0$
- To measure the benefit, we need to measure consumer surplus
  - That is, $\Delta CS = -\int_{p_0}^{p_1} q_i dp_i$. We may not know q_i other than q_1
- However, we know $q_1 > q_i$ for all i such that $p_i > p_1$.
  - We can derive an upper bound computing the envelope of the polygon $(p_1 - p_0)\, q_1$
  - Note: calculation is not as trivial, but can be formally derived using the Envelope Theorem

Intuition for the Social Savings Formula



Red polygon represents the benefit. Blue colored box represents an upper bound.

Welfare Effect

- Next, let us consider the welfare benefits in general equilibrium $\frac{d \ln W}{d \ln \tau_{kl}}$
  - See Atkeson Burstein '10, and Allen Arkolakis '21 for our labor mobility benchmark

- As you will show in the HW, when there are no spillover effects ($\alpha - \beta = 0$):

$$\frac{d \ln W}{d \ln \tau_{ij}} = -\frac{X_{ij}}{Y^W}$$

  - X_{ij} is the flow of trade from i to j, $Y^W$is world GDP

- This formula is equivalent to the heuristic Fogel '64 formula. To see that notice

$$p_{ij} \frac{\Delta \tau_{ij}}{\tau_{ij}} q_{ij} = \frac{\Delta \tau_{ij}}{\tau_{ij}} X_{ij} = X_{ij} \Delta \ln \tau_{ij}$$

  - Notable result. Indicates 'general equilibrium' effects do not affect social savings arithmetic
    - However, the formula is different if $\alpha - \beta \neq 0$

Measurement of Welfare Effects

- In practice, it is difficult to measure X_{ij} and its changes in the data
  - There are substantial externalities,i.e. $\alpha - \beta \neq 0$, and traffic congestion
- One methodology to measure impact of infrastructure suggested by Donaldson, Hornbeck '16
- The premise of their analysis is in equation from lecture 11-12

$$L_i^{1+\beta\sigma} = A_i^{\sigma-1} \bar{u}_i^{\sigma} \left(\bar{W}\right)^{-\sigma} P_i^{-\sigma} \Pi_i$$

  and

$$w_j = L_j^{\beta} \frac{\bar{W}}{\bar{u}_j} P_j$$

  under symmetric trade costs $\Pi_i \propto P_i^{1-\sigma}$. This relationship is derived in Appendix in the end of the slides
- Measure variation in Π_i because of transportation to evaluate impact on population/wages

The Approach of Measuring "Market Access"

- Recall

$$\Pi_i \equiv \sum_j \tau_{ij}^{1-\sigma} \frac{w_j L_j}{P_j^{1-\sigma}}$$

Donaldson Hornbeck '16 approximate $\Pi_i \approx \sum_j \tau_{ij}^{1-\sigma} L_j$. Measure τ_{ij} with historical US railroads

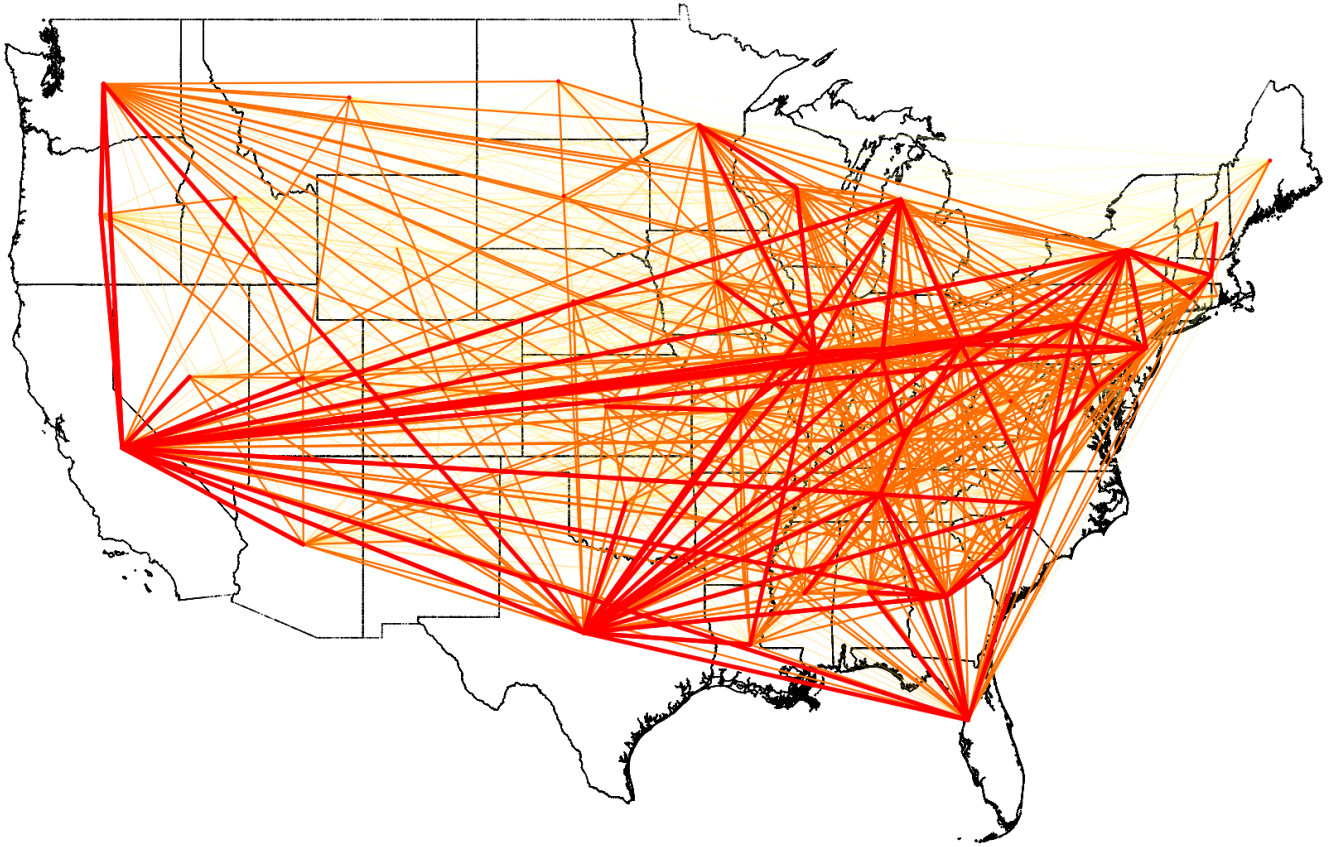
- Measure how variation in market access affects outcomes

TABLE I

ESTIMATED IMPACT OF MARKET ACCESS ON AGRICULTURAL LAND VALUE

	Log Value of Agricultural Land				
	(1) Baseline Specification	(2) Model-Derived Market Access	(3) Fixed 1870 Population	(4) 100-Mile Buffer Market Access	(5) Unweighted
Log market access	0.511	0.587	0.510	0.487	0.506
	(0.065)	(0.073)	(0.065)	(0.064)	(0.124)
Number of counties	2,327	2,327	2,327	2,327	2,327
R-squared	0.625	0.627	0.625	0.621	0.606

‘‘Market Access’’ Links in the US



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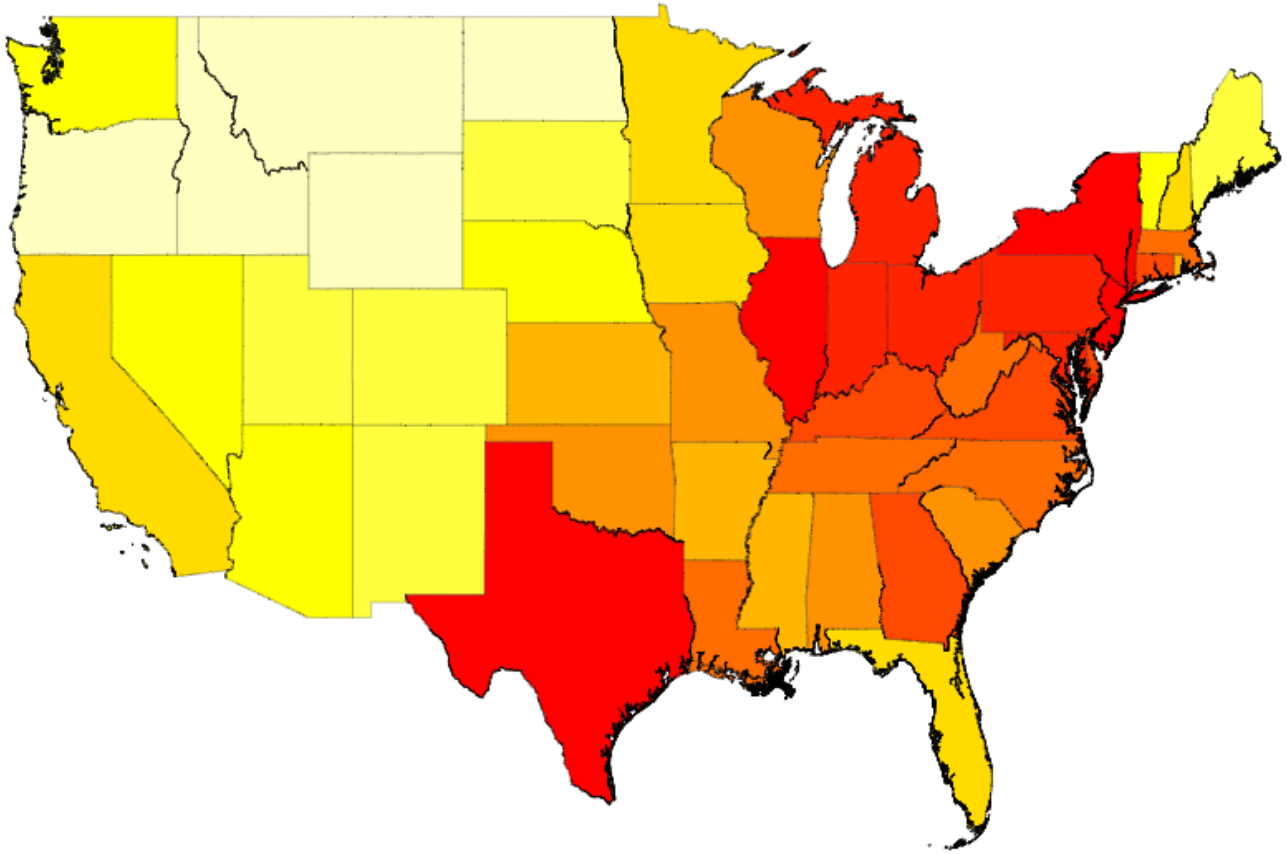

Limits of the Approach

- There are two limitations of that approach
  - We need to assume that market access is uncorrelated to $\bar{A}_i$
  - The shifter $\bar{W}$ is a summation of market access and other terms (i.e. endogenous and changes as market access changes)
- An alternative is to solve the entire model (clearly harder)

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Infrastructure Investment as a Fraction of GDP

- Using data from OECD, we can compare the infrastructure investment for a number of major countries
  - Includes road, rail, waterways, ports, and airports

Country\Year	1995	2000	2005	2010	2015
Canada	0.83	0.54	0.65	1.32	0.47
China	1.36	1.98	3.65	4.93	5.27
France	1.12	0.94	0.91	0.87	0.78
Germany	0.87	0.86	0.62	0.63	0.58
Greece	.	1.41	0.76	0.71	1.27*
S. Korea	.	1.72*	1.36	1.94	1.75
Russia	1.32	1.86	1.28	1.33	0.90
USA	0.59	0.65	0.55	0.62	0.62

- Note: No total EU reliable data are available

Road Expenditure and Usage

- What is the user cost (fees and subsidy) on roads by Federal/State/Locas?
  - It is substantial:

	User Fees	Other Taxes	Total
Total	$94 B	$99 B	$193 B
Per vehicle-kilometer travelled (4,786 Bill.)	$0.020/kilometer	$0.021/kilometer	$0.041/kilometer

- Source: Victoria Transport Policy Institute, Transportation Cost and Benefit Analysis II
  - https://www.vtpi.org/tca/tca0506.pdf

- Note: typical car moving costs $6.2 cents a kilometer (about 10.6 - 12.8 km per liter, with $0.79 a liter).
  - Enormous subsidy by the federal/state/local government

Rail Lines (Thousand km)

Country\Year	1990	2000	2010
EU	217	221	233
China	53	58	66
Russia	85	86	85
USA	193	159	228

- Source: World Bank

Goods Transported by Rails (Millions ton-km)

Country\Year	1990	2000	2010
UK	15	18	19
China	1,060	1,333	2,451
Russia	2,523	1,373	2,011
USA	1,530	2,142	2,468

- Source: World Bank
- Note: No total EU reliable data available

Road Investment Costs

- Estimates of the road investment costs

Cost (USD/lane $\times$ km)	Type of terrain/area	Type of Expansion
3,478,000	Urban	Add a lane
4,033,000	Rural Mountainous	Add a lane
1,630,000	Rural Rolling	Add a lane

Source: Federal Highway Administration '17 (Exhibit A-1)

- Expansion on major urban arteries can cost up to 30 million per lane/km
- Bridges are even more expensive and could cost dozens of million dollars
- Tunnels are incredibly expensive depending on traffic disruption, depth etc.
  - E.g., Big Dig underneath Boston cost 117 million USD/lane $\times$ km

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- In the spatial model, we have welfare equalization $W_j = \bar{W}$ because people can move freely
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- This is maybe not the best formulation: moving locations is costly!
  - Add labor migration frictions in the form of migration costs: $\kappa_{ij} \geq 1$
- Can think of κ_{ij} similar to τ_{ij}, except (the inverse of) κ_{ij} scales an *individual's* welfare, rather than price
  - Similar to τ_{ii}, write $\kappa_{ii} = 1$ for every i (no cost to staying in your location)

Extending the Model with Labor Migration Frictions

- To account for migration possibilities, we need an initial allocation of labor
  - Individuals are ''born'' in a region and all simultaneously face a decision problem of where to move (if they move at all)
  - Write this initial allocation in location i as L_i^0

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- Welfare is not equalized across locations
  - Two individuals who end in location j may have had to pay different migration costs and may have different utilities
  - E.g., individual ι_1 started in location 1 and ended in location 1, utility can be higher than individual ι_2 who started in location 2 and migrated to location 1 if $\kappa_{21} > 1$

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- Rather, welfare across individuals from the same starting location is equalized
  - Individuals born in the same location must be indifferent to moving to different locations (or staying)

Extending the Model: Welfare

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Extending the Model: Welfare

- Welfare across individuals from the same starting location is equalized
- This is different from the previous model. Fix a location i. Welfare of individuals who started in i is

$$W_i = \frac{w_j}{P_j} \frac{\bar{u}_j}{\kappa_{ij}} \left(\frac{L_{ij}}{L_i^0} \right)^{-\beta}$$

  for any region j (including i)
  - L_{ij} is the number of people who move from i to j

Extending the Model: Gravity for Labor Flows

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- Solve for how many workers from i move to j (or stay in i):

$$L_{ij} = L_i^0 W_i^{-1/\beta} \left(\frac{w_j \bar{u}_j}{P_j \kappa_{ij}} \right)^{1/\beta}$$

  - By summing up this expression obtain a nice expression for welfare (for each i):

$$L_i^0 = \sum_j L_{ij} = L_i^0 W_i^{-1/\beta} \sum_j \left(\frac{w_j \bar{u}_j}{P_j \kappa_{ij}} \right)^{1/\beta} \implies W_i = \left[\sum_j \left(\frac{w_j \bar{u}_j}{P_j \kappa_{ij}} \right)^{1/\beta} \right]^{\beta}$$

Gravity for Migration: Intuition

- Labor mobility:

$$L_{ij} = L_i^0 W_i^{-1/\beta} \left(\frac{w_j \bar{u}_j}{P_j \kappa_{ij}} \right)^{1/\beta} \tag{1}$$

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- More workers move from i to j if:
  - There are a lot of workers starting in i (L_i^0 high)
  - Wages in j are high (w_j high)
  - Prices in j are low (P_j low)
  - Amenities in j are high ($\bar{u}_j$ high)
  - Migration costs from i to j are low (κ_{ij} low)

Solution of the Simple Model

- Recall from the simple model that we need some equations to close the model
  - Welfare Equalization:
$$\bar{W} = W_j$$
  - Total labor:
$$\sum_i L_i = \bar{L}$$
  - Feasibility:
$$w_i L_i = \sum_j \frac{(w_i \tau_{ij}/A_i)^{1-\sigma}}{P_j^{1-\sigma}} w_j L_j$$
  - Definition of the price index:
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- Equations: $N + 1 + N + N = 3N + 1$ & Unknowns: $\{w_i, L_i, P_i\}_i, \bar{W}$
  - Note, by Walras Law, we can normalize one wage (or price)

Solution of New Model with Migration Frictions

- Now we consider our updated equations
  - Welfare Equalization across individuals from i:

$$W_i = \left[\sum_j \left(\frac{w_j \bar{u}_j}{P_j \kappa_{ij}} \right)^{1/\beta} \right]^{\beta}$$

  - Total labor from location i, given (1):

$$\sum_j L_{ij} = L_i^0$$

  - Feasibility:

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  - Definition of the price index:

$$P_j^{1-\sigma} = \sum_i \left(\frac{w_i \tau_{ij}}{A_i} \right)^{1-\sigma}$$

- More equations: $N + N + N + N = 4N$ & unknowns: $\{w_i, L_i, P_i, W_i\}_i$

Estimation

- We can observe many of these quantities in the data:
  - labor L_i and migrations L_{ij}
  - Wages w_i
  - Prices P_i
  - Trade flows (or shares) X_{ij} (or λ_{ij})

Estimation

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  - labor L_i and migrations L_{ij}
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- Using these observed quantities, want to estimate parameters of our model
  - Productivities $\bar{A}_i$
  - Amenities $\bar{u}_i$
  - Trade costs τ_{ij}
  - Migration costs κ_{ij}

Gravity Relationships: Trade and Migration Costs

- We exploit that both goods and worker flows follow a 'gravity' form. Recall

$$X_{ij} = \lambda_{ij} X_j = (\tau_{ij})^{1-\sigma} \left(\frac{w_i}{A_i}\right)^{1-\sigma} P_j^{\sigma-1} w_j L_j$$

$$L_{ij} = L_i^0 W_i^{-1/\beta} \left(\frac{w_j \bar{u}_j}{P_j \kappa_{ij}}\right)^{1/\beta}$$

- We take logs:

$$\ln X_{ij} = (1-\sigma) \ln \tau_{ij} + (1-\sigma) \ln \left(\frac{w_i}{A_i}\right) - (1-\sigma) \ln P_j + \ln w_j L_j$$

$$\ln L_{ij} = -(1/\beta) \ln \kappa_{ij} + \ln L_i^0 - (1/\beta) \ln W_i + (1/\beta) \ln \left(\frac{w_j \bar{u}_j}{P_j}\right)$$

Gravity Estimation: Trade and Migration Costs

- Previous equations:

$$\ln X_{ij} = (1-\sigma)\ln \tau_{ij} + (1-\sigma)\ln\left(\frac{w_i}{A_i}\right) - (1-\sigma)\ln P_j + \ln w_j L_j$$

$$\ln L_{ij} = -(1/\beta)\ln \kappa_{ij} + \ln L_i^0 - (1/\beta)\ln W_i + (1/\beta)\ln\left(\frac{w_j \bar{u}_j}{P_j}\right)$$

Gravity Estimation: Trade and Migration Costs

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$$\ln L_{ij} = -(1/\beta)\ln \kappa_{ij} + \ln L_i^0 - (1/\beta)\ln W_i + (1/\beta)\ln\left(\frac{w_j \bar{u}_j}{P_j}\right)$$

- Group the "i specific terms" and the "j specific terms":

$$\ln X_{ij} = (1-\sigma)\ln \tau_{ij} + \gamma_i^X + \delta_j^X + \epsilon_{ij}^X$$

$$\ln L_{ij} = -(1/\beta)\ln \kappa_{ij} + \gamma_i^L + \delta_j^L + \epsilon_{ij}^L$$

where ϵ_{ij}^T and ϵ_{ij}^L can be thought of as measurement errors, γ_i origin specific terms, and δ_j destination specific terms

Estimation: Trade and Migration Costs

- Reduced form equations:

$$\ln X_{ij} = (1-\sigma)\ln \tau_{ij} + \gamma_i^X + \delta_j^X + \epsilon_{ij}^X$$

$$\ln L_{ij} = -(1/\beta)\ln \kappa_{ij} + \gamma_i^L + \delta_j^L + \epsilon_{ij}^L$$

Estimation: Trade and Migration Costs

- Reduced form equations:

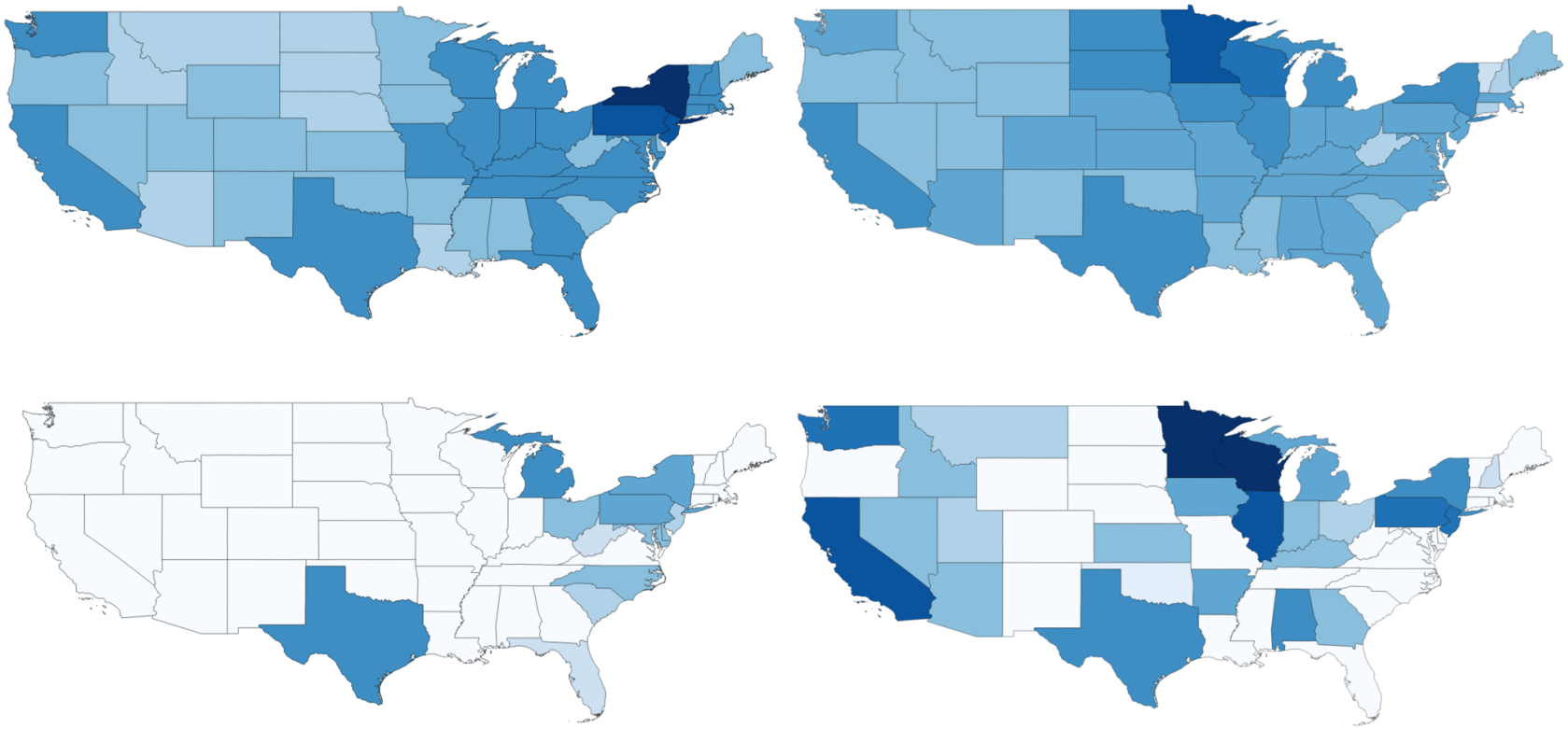
$$\ln X_{ij} = (1-\sigma)\ln \tau_{ij} + \gamma_i^X + \delta_j^X + \epsilon_{ij}^X$$

$$\ln L_{ij} = -(1/\beta)\ln \kappa_{ij} + \gamma_i^L + \delta_j^L + \epsilon_{ij}^L$$

- Assume some form of τ_{ij} and κ_{ij}, e.g., $\tau_{ij} = (\text{dist}_{ij})^{\varepsilon_\tau}$ and $\kappa_{ij} = (\text{dist}_{ij})^{\varepsilon_\kappa}$

- Run fixed effect regression to estimate $\tau_{ij}^{1-\sigma}$ and $\kappa_{ij}^{-1/\beta}$
  - With estimates of elasticities, we can recover $\varepsilon_\tau, \varepsilon_\kappa$ and thus τ_{ij}, κ_{ij}
    - We assume we know σ, β. These elasticities can be taken off-the-shelf or estimated in a different way with this model

Commodity Flow Survey: Exports by Road, Rail for NY, MN



Exports by road (top) and by rail (bottom)

Counterfactual Experiment: Removing the IHS

- We want to evaluate what is the welfare impact of the IHS
  - The answer requires a proper choice of τ_{ij} before the removal of the IHS and after
  - Construct $\tau_{ij}\left(\bar{t}_{11}, \bar{t}_{12}, ..., \bar{t}_{NN}\right)$ and $\tau_{ij}\left(\bar{t}'_{11}, \bar{t}'_{12}, ..., \bar{t}'_{NN}\right)$ where with prime we denote the times after the IHS removal
  - Now compute the model equilibrium with the two different trade costs and compare variables

Performing Counterfactuals

- Take known information on wages, labor, migration, trade from the data
  - Use this data to estimate the geography: back out productivities, amenities, elasticities

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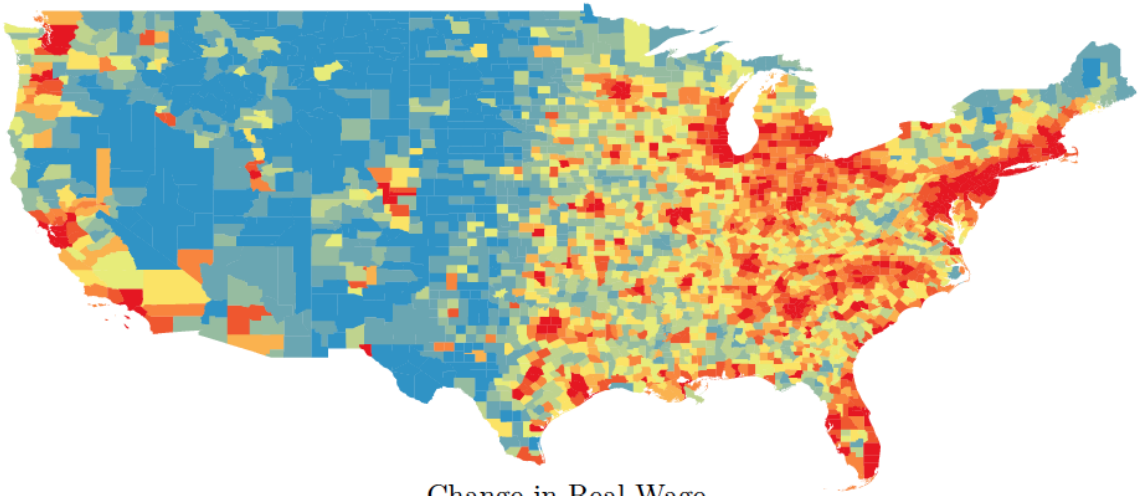
Performing Counterfactuals

- Take known information on wages, labor, migration, trade from the data
  - Use this data to estimate the geography: back out productivities, amenities, elasticities
  - With this fixed geography, change some element of the economy (e.g., remove the IHS so that τ_{ij} increases for most i, j pairs)
  - Solve the economy and observe the changes in parameters of interest (welfare, wages, etc.)

Performing Counterfactuals: Removing the IHS

Figure 18: Effect of removing the Interstate Highway System: No migration, costly trade

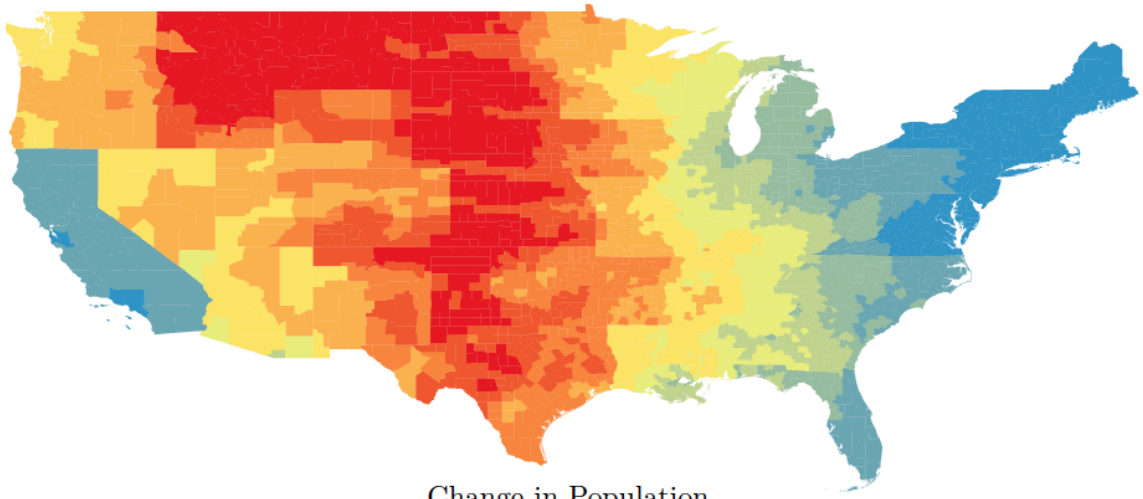
Change in Population



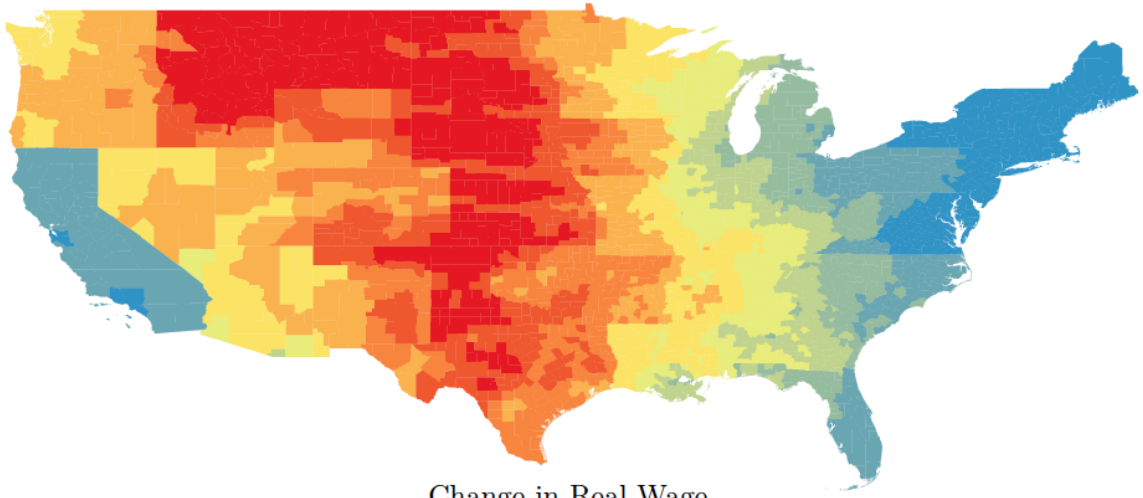
Change in Real Wage

Performing Counterfactuals: Removing the IHS

Figure 19: Effect of removing the Interstate Highway System: No trade, costly migration



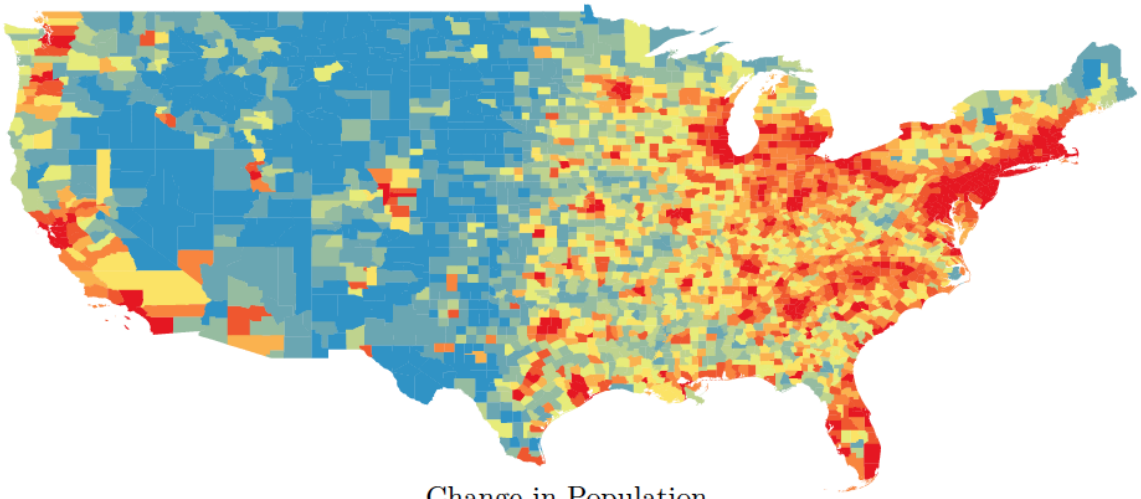
Change in Population



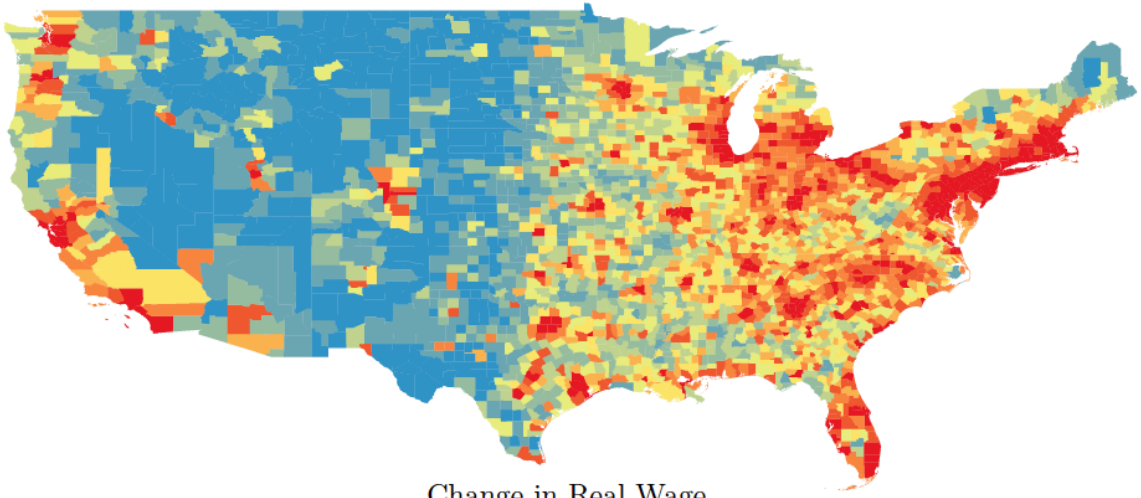
Change in Real Wage

Performing Counterfactuals: Removing the IHS

Figure 20: Effect of removing the Interstate Highway System: Costly trade, free migration



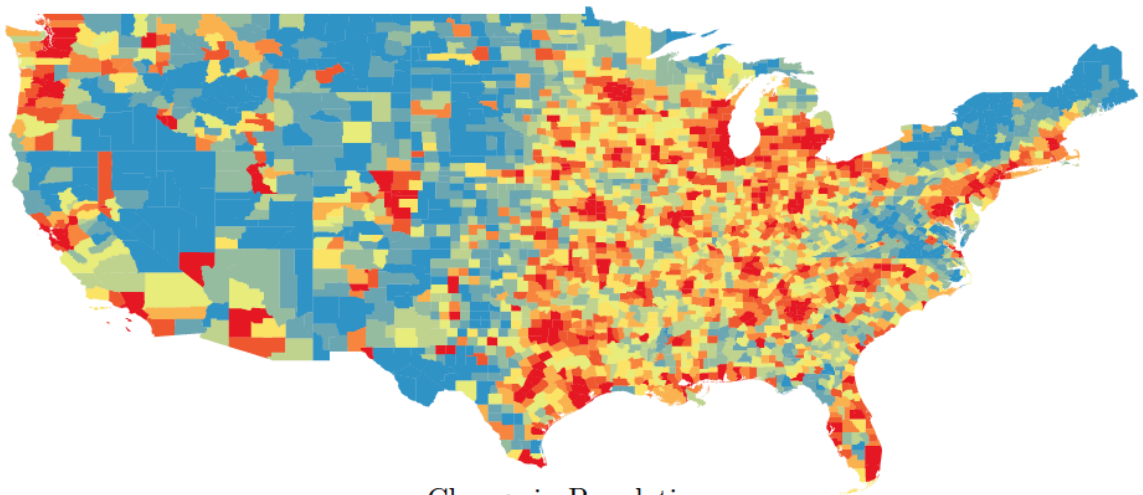
Change in Population



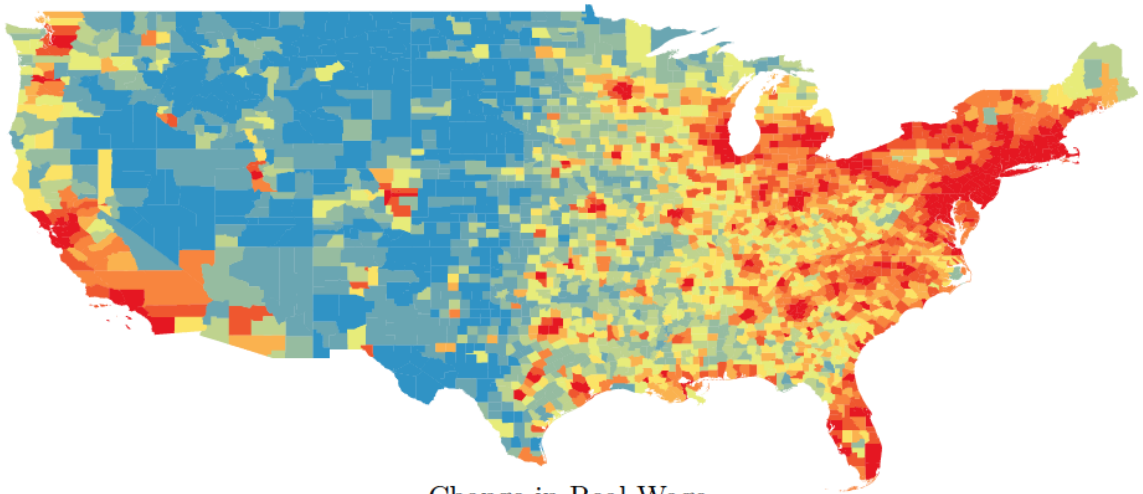
Change in Real Wage

Performing Counterfactuals: Removing the IHS

Figure 21: Effect of removing the Interstate Highway System: Free trade, costly migration



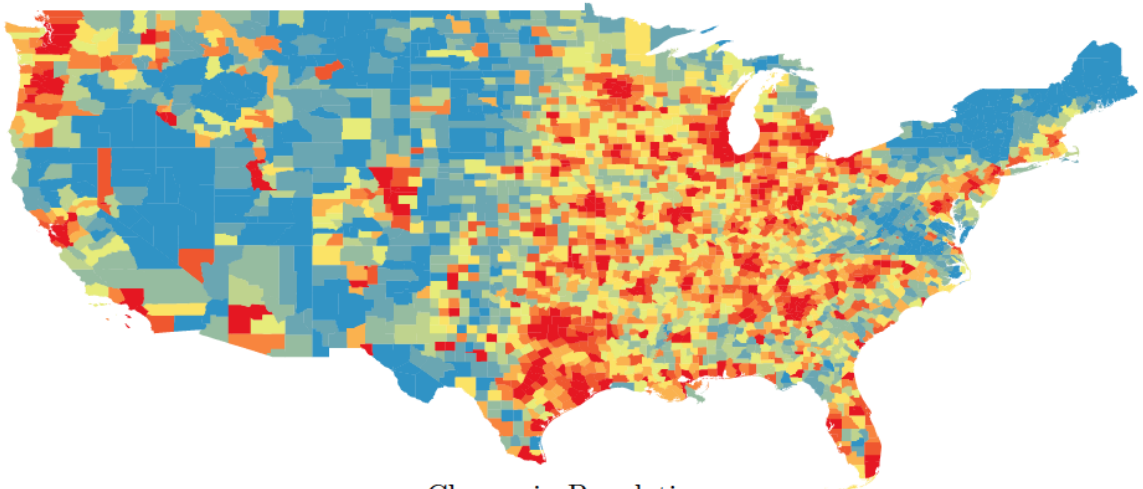
Change in Population



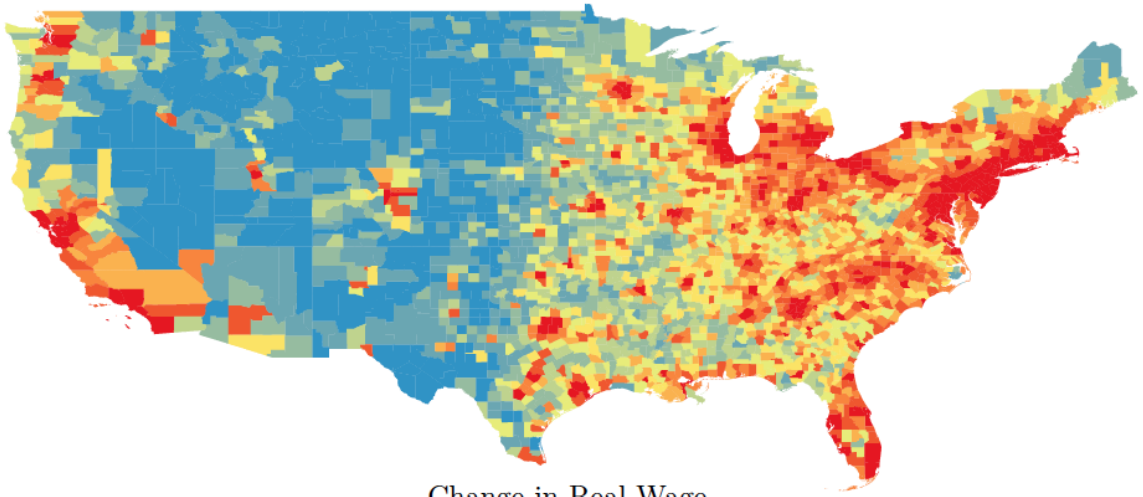
Change in Real Wage

Performing Counterfactuals: Removing the IHS

Figure 22: Effect of removing the Interstate Highway System: Costly trade, costly migration



Change in Population



Change in Real Wage

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Appendix: Market Access

- We derived the following two equilibrium conditions in Lecture 7-8

$$w_i L_i = \sum_j \frac{\left(w_i \tau_{ij} / A_i\right)^{1-\sigma}}{P_j^{1-\sigma}} w_j L_j \tag{2}$$

$$P_i^{1-\sigma} = \sum_k \left(\frac{w_k \tau_{ki}}{A_k}\right)^{1-\sigma} \tag{3}$$

Allen and Arkolakis '14 show that if bilateral trade costs are symmetric ($\forall i, j\ \tau_{ij} = \tau_{ji}$), $L_i P_i^{\sigma-1} w_i = \lambda A_i^{\sigma-1} w_i^{1-\sigma}$ is a solution to the system and the above two equations are equivalent. Substituting (2) into this guess yields

$$P_i^{1-\sigma} = \frac{1}{\lambda} \sum_j \frac{\left(\tau_{ij}\right)^{1-\sigma}}{P_j^{1-\sigma}} w_j L_j$$

- Since $\Pi_i = \sum_j \tau_{ij}^{1-\sigma} \frac{w_j L_j}{P_j^{1-\sigma}}$,

$$P_i^{1-\sigma} = \frac{\Pi_i}{\lambda}$$

- As Donaldson and Horenbeck '16 define consumer market access (CMA),

$$CMA_i = P_i^{1-\sigma}$$

- Hence,

$$\lambda CMA_i = \Pi_i$$

$$\Pi_i \propto CMA_i = P_i^{1-\sigma}$$