Traffic in the City

The Impact of Infrastructure Improvements in the Presence of Endogenous Traffic Congestion[1]

Treb Allen[1] Costas Arkolakis[2]

[1]Dartmouth and NBER [2]Yale and NBER

October 2020

[1]An excerpt from "The Welfare Effects of Transportation Infrastructure Improvements"

Motivation

- Recent “quantitative” revolution in urban economics
  - Spearheaded by flexible theory (Ahlfeldt Redding Sturm Wolf ’15)
  - Fueled with swaths of spatial data

Motivation

- Recent "quantitative" revolution in urban economics
  - Spearheaded by flexible theory (Ahlfeldt Redding Sturm Wolf '15)
  - Fueled with swaths of spatial data

- Key benefit: evaluation of major transportation infrastructure
  - Trains (Heblich Redding Sturm '20), subways (Severen '19), dedicated bus lanes (Tsivanidis '19)

Motivation

- Recent "quantitative" revolution in urban economics
  - Spearheaded by flexible theory (Ahlfeldt Redding Sturm Wolf '15)
  - Fueled with swaths of spatial data
- Key benefit: evaluation of major transportation infrastructure
  - Trains (Heblich Redding Sturm '20), subways (Severen '19), dedicated bus lanes (Tsivanidis '19)
- The "elephant in the room": Roads

Motivation

A New Quantitative Urban Framework with Traffic

- Quantitative urban framework:
  - Agents choose where to live, where to work, & commuting route.
  - Commute/route choice → traffic → congestion → commuting costs

A New Quantitative Urban Framework with Traffic

- Quantitative urban framework:
  - Agents choose where to live, where to work, & commuting route.
  - Commute/route choice → traffic → congestion → commuting costs

- Retains the old benefits...
  - Analytically tractable
  - "Exact hat" link to data to perform counterfactuals

A New Quantitative Urban Framework with Traffic

- Quantitative urban framework:
  - Agents choose where to live, where to work, & commuting route.
  - Commute/route choice → traffic → congestion → commuting costs

- Retains the old benefits...
  - Analytically tractable
  - "Exact hat" link to data to perform counterfactuals

- ...But with new benefits too:
  - A gravity equation for traffic.
  - Counterfactuals use (easily observed) traffic data.
  - Scale matters.

A New Quantitative Urban Framework with Traffic

- Quantitative urban framework:
  - Agents choose where to live, where to work, & commuting route.
  - Commute/route choice $\rightarrow$ traffic $\rightarrow$ congestion $\rightarrow$ commuting costs

- Retains the old benefits...
  - Analytically tractable
  - "Exact hat" link to data to perform counterfactuals

- ...But with new benefits too:
  - A gravity equation for traffic.
  - Counterfactuals use (easily observed) traffic data.
  - Scale matters.

- Illustration: Estimate ROI of adding lane-miles to every link in Seattle road network.

Related literature

- Quantitative evaluations of transportation infrastructure
  - Donaldson '12, Allen and Arkolakis '14, Ahlfeldt et. al. '15, Donaldson and Hornbeck '16, Alder '16, Severen '19, Tsivanidis '19, Heblich Redding Sturm '20
- Empirical evidence on importance of congestion
  - Duranton and Turner '11, Anderson '14
- Optimal transportation policy computationally
  - Alder '16, Fajgelbaum and Schaal '20

Outline of Talk

Standard components

- City comprises $i \in \{1, ..., N\} \equiv \mathcal{N}$ locations, $\bar{L}$ agents.

Standard components

- City comprises $i \in \{1, ..., N\} \equiv \mathcal{N}$ locations, $\bar{L}$ agents.
- Agents choose where to live & work, yielding *commuting gravity*:

$$L_{ij} = \left(\frac{\overbrace{u_i}^{\text{amenity at home}} \times \overbrace{A_j}^{\text{productivity at work}}}{\underbrace{\tau_{ij}}_{\text{commuting cost}}} \right)^{\theta} \times \left(\frac{\overbrace{\bar{L}}^{\text{aggregate population}}}{\underbrace{W^{\theta}}_{\text{expected welfare}}} \right)$$

Standard components

- City comprises $i \in \{1, ..., N\} \equiv \mathcal{N}$ locations, $\bar{L}$ agents.
- Agents choose where to live & work, yielding *commuting gravity*:

$$L_{ij} = \left(\frac{\overbrace{u_i}^{\text{amenity at home}} \times \overbrace{A_j}^{\text{productivity at work}}}{\underbrace{\tau_{ij}}_{\text{commuting cost}}} \right)^{\theta} \times \left(\frac{\overbrace{\bar{L}}^{\text{aggregate population}}}{\underbrace{W^{\theta}}_{\text{expected welfare}}} \right)$$

- Productivities and amenities in each location can be written as:

$$A_i = \underbrace{\bar{A}_i}_{\text{first nature}} \times \underbrace{\left(L_i^F\right)^{\alpha}}_{\text{second nature}}$$

$$u_i = \underbrace{\bar{u}_i}_{\text{first nature}} \times \underbrace{\left(L_i^R\right)^{\beta}}_{\text{second nature}}$$

Standard components

- City comprises $i \in \{1, ..., N\} \equiv \mathcal{N}$ locations, $\bar{L}$ agents.
- Agents choose where to live & work, yielding *commuting gravity*:

$$L_{ij} = \left(\frac{\overbrace{u_i}^{\text{amenity at home}} \times \overbrace{A_j}^{\text{productivity at work}}}{\underbrace{\tau_{ij}}_{\text{commuting cost}}} \right)^{\theta} \times \left(\frac{\overbrace{\bar{L}}^{\text{aggregate population}}}{\underbrace{W^{\theta}}_{\text{expected welfare}}} \right)$$

- Productivities and amenities in each location can be written as:

$$A_i = \underbrace{\bar{A}_i}_{\text{first nature}} \times \underbrace{\left(L_i^F\right)^{\alpha}}_{\text{second nature}}$$

$$u_i = \underbrace{\bar{u}_i}_{\text{first nature}} \times \underbrace{\left(L_i^R\right)^{\beta}}_{\text{second nature}}$$

- Given elasticities $\{\alpha, \beta, \theta\}$, geography $\left\{\bar{A}_i, \bar{u}_i\right\}$, and costs τ_{ij}, equilibrium is $\left\{L_i^F, L_i^R\right\}$ such that:

$$L_i^R = \sum_{j \in \mathcal{N}} L_{ij}, \; L_j^F = \sum_{i \in \mathcal{N}} L_{ij}$$

New component: Endogenous commuting costs

- Commuting costs τ_{ij} are *endogenous*, depend on:
  - Agents' routing problem: What is the optimal path through the infrastructure network (taking traffic as given)?
  - Traffic congestion: How do agents' route choice, choice of where to live and work affect use of each link in the infrastructure network?

New component: Endogenous commuting costs

- Commuting costs τ_{ij} are *endogenous*, depend on:
  - Agents' routing problem: What is the optimal path through the infrastructure network (taking traffic as given)?
  - Traffic congestion: How do agents' route choice, choice of where to live and work affect use of each link in the infrastructure network?
- Feedback loop: traffic congestion affects route choice & choice of where to live and work.

Infrastructure network

- N locations arrayed on a weighted network.

Infrastructure network

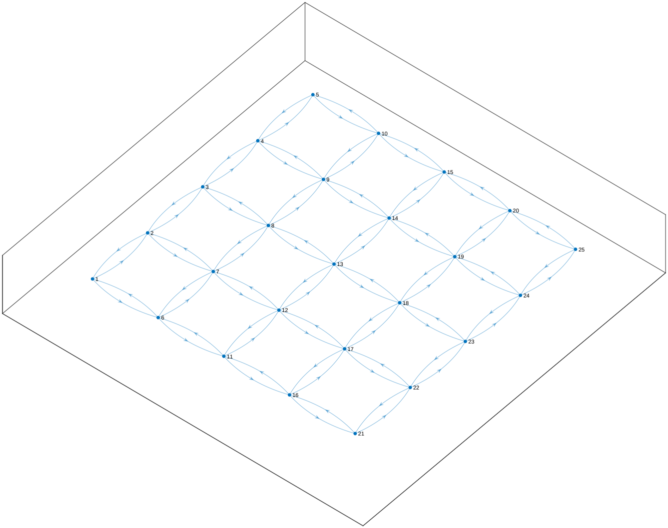
- N locations arrayed on a weighted network.

- Let $t_{kl} \geq 1$ be the iceberg commuting cost incurred by traveling from k to l on the infrastructure network, where:

$$t_{kl} = \bar{t}_{kl} \times (\Xi_{kl})^{\lambda} \tag{1}$$

  where:
  - $\bar{t}_{kl} \geq 1$ is the (first nature) quality of the infrastructure connection.
  - If $\bar{t}_{kl} < \infty$, we say that k and l are a *link*.
  - Ξ_{kl} is the traffic on link k to l.
  - λ is strength of traffic congestion ($\lambda = 0$ in a standard model).

Example of infrastructure network



Outline of Talk

The routing choice problem

- A *route* from i to j of length K is a sequence of locations beginning with i and ending with j:

$$r = \{i, r_1, r_2, ...r_{K-1}, j\}$$

The routing choice problem

- A *route* from i to j of length K is a sequence of locations beginning with i and ending with j:

$$r = \{i, r_1, r_2, ...r_{K-1}, j\}$$

- Let $\Re_{ij}$ be the set of all possible routes from i to j. Then a route $r \in \Re_{ij}$ incurs an iceberg cost of:

$$\tau_{ij,r} = \prod_{l=1}^{K} t_{r_{l-1},r_l}$$

The routing choice problem

- A *route* from i to j of length K is a sequence of locations beginning with i and ending with j:

$$r = \{i, r_1, r_2, \ldots . r_{K-1}, j\}$$

- Let $\Re_{ij}$ be the set of all possible routes from i to j. Then a route $r \in \Re_{ij}$ incurs an iceberg cost of:

$$\tau_{ij,r} = \prod_{l=1}^{K} t_{r_{l-1}, r_l}$$

- Assume agents choose where to live, where to work, & route to maximize:

$$V_{ij,r}(\nu) = \left(A_j u_i / \prod_{l=1}^{K} t_{r_{l-1}, r_l} \right) \times \varepsilon_{ij,r}(\nu).$$

with Frechet distributed idiosyncratic shock $\varepsilon_{ij,r}(\nu)$.

Endogenous commuting costs

- Solving the maximization problem and summing across all possible routes from i to j yields commuting gravity equation from above:

$$L_{ij} = \left(\frac{u_i \times A_j}{\tau_{ij}} \right)^{\theta} \times \left(\frac{\bar{L}}{W^{\theta}} \right)$$

where:

$$\tau_{ij} \equiv \left(\sum_{r \in \Re_{ij}} \left(\prod_{l=1}^{K} t_{r_{l-1}, r_l} \right)^{-\theta} \right)^{-\frac{1}{\theta}}$$

is the *endogenous* commuting cost.

An analytical solution

- Define the *weighted adjacency matrix* $\mathbf{A} \equiv \left[a_{ij} \equiv t_{ij}^{-\theta}\right]$.
  - Define $\mathbf{B} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ and $b_{ij} \equiv [\mathbf{B}]_{ij}$.

An analytical solution

- Define the *weighted adjacency matrix* $\mathbf{A} \equiv \left[a_{ij} \equiv t_{ij}^{-\theta}\right]$.
    - Define $\mathbf{B} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ and $b_{ij} \equiv [\mathbf{B}]_{ij}$.

- If $\rho(\mathbf{A}) < 1$ then:

$$\tau_{ij} = c b_{ij}^{-\frac{1}{\theta}} \tag{2}$$

    - Mapping from infrastructure network to commuting costs (!)

An analytical solution

- Define the *weighted adjacency matrix* $\mathbf{A} \equiv \left[a_{ij} \equiv t_{ij}^{-\theta}\right]$.
  - Define $\mathbf{B} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ and $b_{ij} \equiv [\mathbf{B}]_{ij}$.
- If $\rho(\mathbf{A}) < 1$ then:

$$\tau_{ij} = c b_{ij}^{-\frac{1}{\theta}} \tag{2}$$

  - Mapping from infrastructure network to commuting costs (!)
- Notes:
  - As $\theta \to \infty$, τ_{ij} converge to commuting cost for least cost route (generalization of Dijkstra algorithm).

An analytical solution

- Define the *weighted adjacency matrix* $\mathbf{A} \equiv \left[a_{ij} \equiv t_{ij}^{-\theta}\right]$.
  - Define $\mathbf{B} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ and $b_{ij} \equiv [\mathbf{B}]_{ij}$.
- If $\rho(\mathbf{A}) < 1$ then:

$$\tau_{ij} = c b_{ij}^{-\frac{1}{\theta}} \tag{2}$$

  - Mapping from infrastructure network to commuting costs (!)
- Notes:
  - As $\theta \to \infty$, τ_{ij} converge to commuting cost for least cost route (generalization of Dijkstra algorithm).
  - Analogy to path integral formulation of quantum mechanics: "space of all possible paths of the system in between the initial and final states, including those that are absurd by classical standards"

Outline of Talk

From routing to traffic

- Equation (2) yields the commuting cost taking traffic congestion as given. But what is the equilibrium traffic?

From routing to traffic

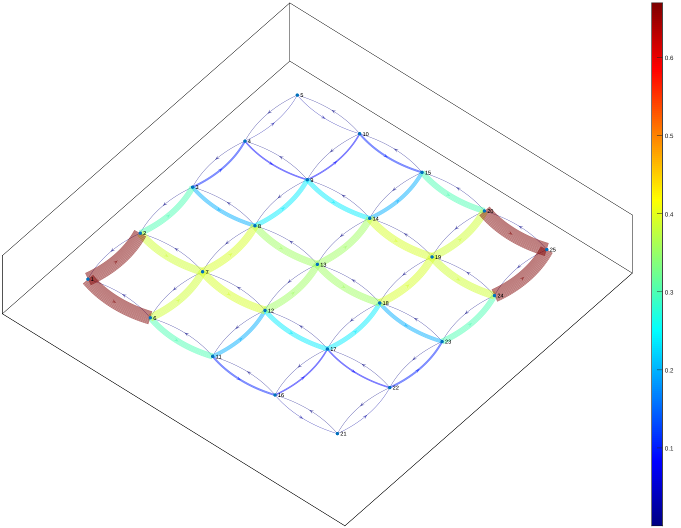
- Equation (2) yields the commuting cost taking traffic congestion as given. But what is the equilibrium traffic?

- First step: calculate the intensity with which a particular link is used on the way from i to j:

$$\pi_{ij}^{kl} = \left(\frac{\tau_{ij}}{\tau_{ik} \times t_{kl} \times \tau_{lj}} \right)^{\theta}$$

  - Intuition: More out of the way links are used less.

Link intensity: traveling from $i = 1$ to $j = 25$



From routing to traffic

- Equation (2) yields the commuting cost taking traffic congestion as given. But what is the equilibrium traffic?

- First step: calculate the intensity with which a particular link is used on the way from i to j:

$$\pi_{ij}^{kl} = \left(\frac{\tau_{ij}}{\tau_{ik} \times t_{kl} \times \tau_{lj}} \right)^{\theta}$$

  - Intuition: More out of the way links are used less.

- Second step: Sum over all origins and destinations to get traffic:

$$\Xi_{kl} = \sum_{i,j \in \mathcal{N}} L_{ij} \pi_{ij}^{kl}$$

A gravity equation for traffic

- Standard *commuting gravity equation*:

$$L_{ij} = \tau_{ij}^{-\theta} \times \frac{L_i^R}{RMA_i} \times \frac{L_j^F}{FMA_j} \times \frac{\bar{L}}{W^\theta},$$

where

- Residential market access: $RMA_i = \sum_j \tau_{ij}^{-\theta} \times \frac{L_j^F}{FMA_j}$
- Firm market access: $FMA_j = \sum_i \tau_{ij}^{-\theta} \times \frac{L_i^R}{RMA_i}$.

A gravity equation for traffic

- Standard *commuting gravity equation*:

$$L_{ij} = \tau_{ij}^{-\theta} \times \frac{L_i^R}{RMA_i} \times \frac{L_j^F}{FMA_j} \times \frac{\bar{L}}{W^\theta},$$

  where

  - Residential market access: $RMA_i = \sum_j \tau_{ij}^{-\theta} \times \frac{L_j^F}{FMA_j}$
  - Firm market access: $FMA_j = \sum_i \tau_{ij}^{-\theta} \times \frac{L_i^R}{RMA_i}$.

- New *traffic gravity equation:*

$$\Xi_{kl} = t_{kl}^{-\theta} \times FMA_k \times RMA_l \times \frac{\bar{L}}{W^\theta} \tag{3}$$

  - *Intuition*: Greater FMA_k, more traffic flowing in. Greater RMA_l, more traffic flowing out.

Outline of Talk

The effect of traffic congestion

- To summarize:

The effect of traffic congestion

- To summarize:
  - Traffic gravity equation (3) shows how market access affects equilibrium traffic flows...

The effect of traffic congestion

- To summarize:
  - Traffic gravity equation (3) shows how market access affects equilibrium traffic flows...
  - ... Through congestion (equation 1), traffic flows affects travel costs, which through routing choice (equation 2) affects commuting costs...

The effect of traffic congestion

- To summarize:
  - Traffic gravity equation (3) shows how market access affects equilibrium traffic flows...
  - ... Through congestion (equation 1), traffic flows affects travel costs, which through routing choice (equation 2) affects commuting costs...
  - ... And commuting costs affect market access through (standard) equilibrium channels.

The effect of traffic congestion

- To summarize:
  - Traffic gravity equation (3) shows how market access affects equilibrium traffic flows...
  - ... Through congestion (equation 1), traffic flows affects travel costs, which through routing choice (equation 2) affects commuting costs...
  - ... And commuting costs affect market access through (standard) equilibrium channels.
- A massive fixed point problem!

The effect of traffic congestion

- To summarize:
  - Traffic gravity equation (3) shows how market access affects equilibrium traffic flows...
  - ... Through congestion (equation 1), traffic flows affects travel costs, which through routing choice (equation 2) affects commuting costs...
  - ... And commuting costs affect market access through (standard) equilibrium channels.
- A massive fixed point problem!
  - ...but it turns out to not be too bad at all.

Equilibrium

- Eqm. conditions $L_i^R = \sum_j L_{ij}$, $L_i^F = \sum_j L_{ji}$ in a standard model are:

$$\left(l_i^R\right)^{1-\theta\beta} = \chi \sum_j \tau_{ij}^{-\theta} \bar{u}_i^{\theta} \bar{A}_j^{\theta} \left(l_j^F\right)^{\theta\alpha}$$

$$\left(l_i^F\right)^{1-\theta\alpha} = \chi \sum_j \tau_{ji}^{-\theta} \bar{u}_j^{\theta} \bar{A}_i^{\theta} \left(l_j^R\right)^{\theta\beta}$$

Equilibrium

- Eqm. conditions $L_i^R = \sum_j L_{ij}$, $L_i^F = \sum_j L_{ji}$ in a standard model are:

$$\left(l_i^R\right)^{1-\theta\beta} = \chi \sum_j \tau_{ij}^{-\theta} \bar{u}_i^{\theta} \bar{A}_j^{\theta} \left(l_j^F\right)^{\theta\alpha}$$

$$\left(l_i^F\right)^{1-\theta\alpha} = \chi \sum_j \tau_{ji}^{-\theta} \bar{u}_j^{\theta} \bar{A}_i^{\theta} \left(l_j^R\right)^{\theta\beta}$$

- With traffic congestion, they become:

$$\left(l_i^R\right)^{1-\theta\beta} \left(l_i^F\right)^{\frac{\theta\lambda(1-\alpha\theta)}{1+\theta\lambda}} = \chi \bar{A}_i^{\theta} \bar{u}_i^{\theta} \left(l_i^F\right)^{\frac{\theta(\alpha+\lambda)}{1+\theta\lambda}} + \chi^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\bar{t}_{ij} \bar{L}^{\lambda}\right)^{-\frac{\theta}{1+\theta\lambda}} \bar{A}_i^{\theta\frac{\theta\lambda}{1+\theta\lambda}} \bar{u}_i^{\theta} \bar{u}_j^{-\frac{\theta}{1+\theta\lambda}} \left(l_j^R\right)^{\frac{1-\beta\theta}{1+\theta\lambda}}$$

$$\left(l_i^R\right)^{\frac{\theta\lambda(1-\beta\theta)}{1+\theta\lambda}} \left(l_i^F\right)^{1-\theta\alpha} = \chi \bar{A}_i^{\theta} \bar{u}_i^{\theta} \left(l_i^R\right)^{\frac{\theta(\beta+\lambda)}{1+\theta\lambda}} + \chi^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\bar{t}_{ji} \bar{L}^{\lambda}\right)^{-\frac{\theta}{1+\theta\lambda}} \bar{A}_i^{\theta} u_i^{\theta\frac{\theta\lambda}{1+\theta\lambda}} \bar{A}_j^{-\frac{\theta}{1+\theta\lambda}} \left(l_j^F\right)^{\frac{1-\alpha\theta}{1+\theta\lambda}}$$

where $\chi \equiv \frac{\bar{L}^{\alpha+\beta}}{W}$, $l_i^R \equiv L_i^R/\bar{L}$ and $l_i^F \equiv L_i^F/\bar{L}$ are labor shares.

Equilibrium

- Eqm. conditions $L_i^R = \sum_j L_{ij}$, $L_i^F = \sum_j L_{ji}$ in a standard model are:

$$\left(l_i^R\right)^{1-\theta\beta} = \chi \sum_j \tau_{ij}^{-\theta} \bar{u}_i^\theta \bar{A}_j^\theta \left(l_j^F\right)^{\theta\alpha}$$

$$\left(l_i^F\right)^{1-\theta\alpha} = \chi \sum_j \tau_{ji}^{-\theta} \bar{u}_j^\theta \bar{A}_i^\theta \left(l_j^R\right)^{\theta\beta}$$

- With traffic congestion, they become:

$$\left(l_i^R\right)^{1-\theta\beta} \left(l_i^F\right)^{\frac{\theta\lambda(1-\alpha\theta)}{1+\theta\lambda}} = \chi \bar{A}_i^\theta \bar{u}_i^\theta \left(l_i^F\right)^{\frac{\theta(\alpha+\lambda)}{1+\theta\lambda}} + \chi^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\bar{t}_{ij} \bar{L}^\lambda\right)^{-\frac{\theta}{1+\theta\lambda}} \bar{A}_i^{\theta\frac{\theta\lambda}{1+\theta\lambda}} \bar{u}_i^\theta \bar{u}_j^{-\frac{\theta}{1+\theta\lambda}} \left(l_j^R\right)^{\frac{1-\beta\theta}{1+\theta\lambda}}$$

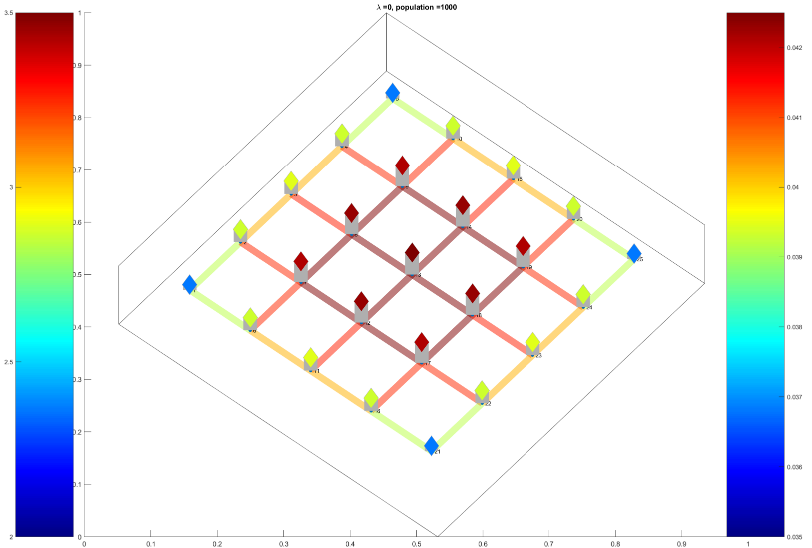
$$\left(l_i^R\right)^{\frac{\theta\lambda(1-\beta\theta)}{1+\theta\lambda}} \left(l_i^F\right)^{1-\theta\alpha} = \chi \bar{A}_i^\theta \bar{u}_i^\theta \left(l_i^R\right)^{\frac{\theta(\beta+\lambda)}{1+\theta\lambda}} + \chi^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\bar{t}_{ji} \bar{L}^\lambda\right)^{-\frac{\theta}{1+\theta\lambda}} \bar{A}_i^\theta u_i^{\theta\frac{\theta\lambda}{1+\theta\lambda}} \bar{A}_j^{-\frac{\theta}{1+\theta\lambda}} \left(l_j^F\right)^{\frac{1-\alpha\theta}{1+\theta\lambda}}$$

where $\chi \equiv \frac{\bar{L}^{\alpha+\beta}}{W}$, $l_i^R \equiv L_i^R / \bar{L}$ and $l_i^F \equiv L_i^F / \bar{L}$ are labor shares.

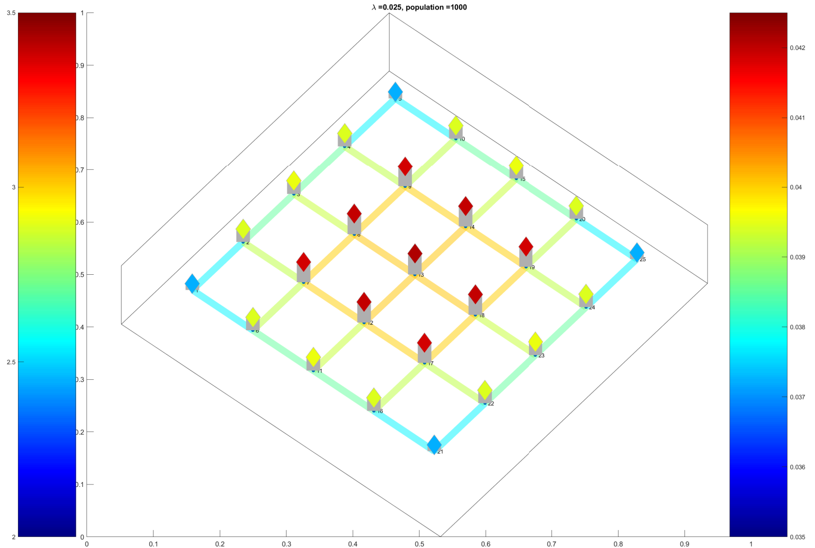
- Same number of equations & unknowns, new structure!

Outline of Talk

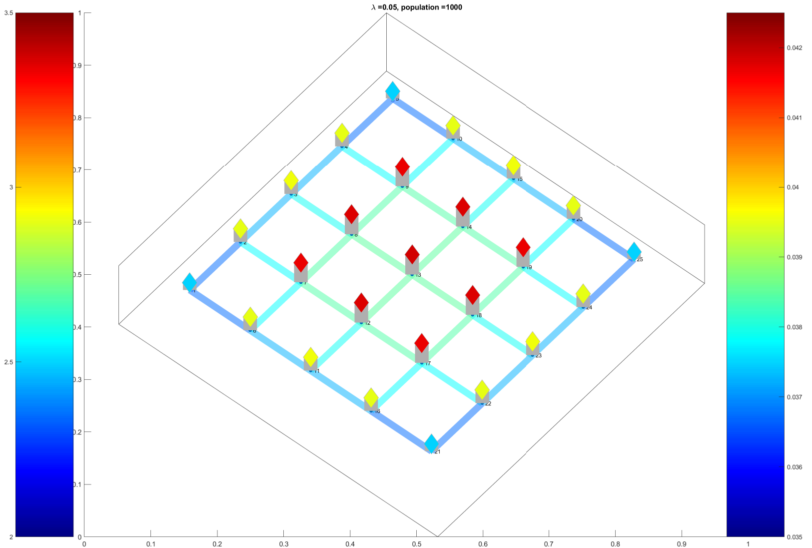
Traffic congestion acts like a standard dispersion force...



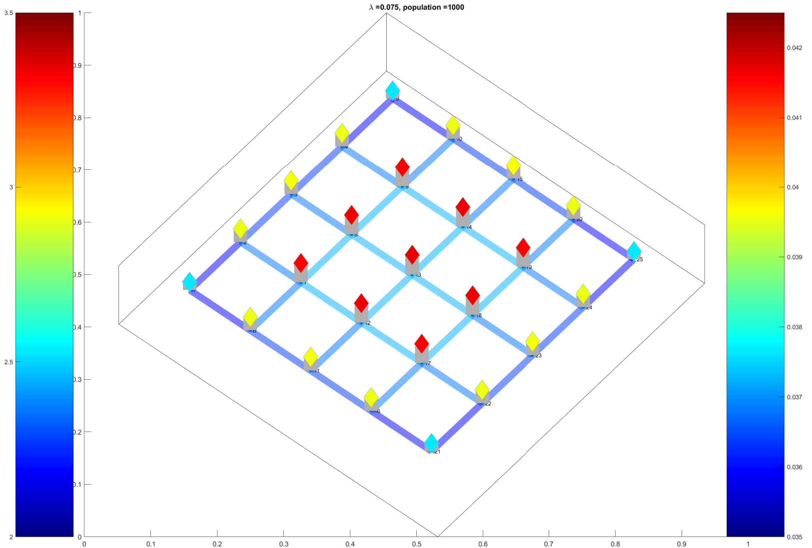
Traffic congestion acts like a standard dispersion force...



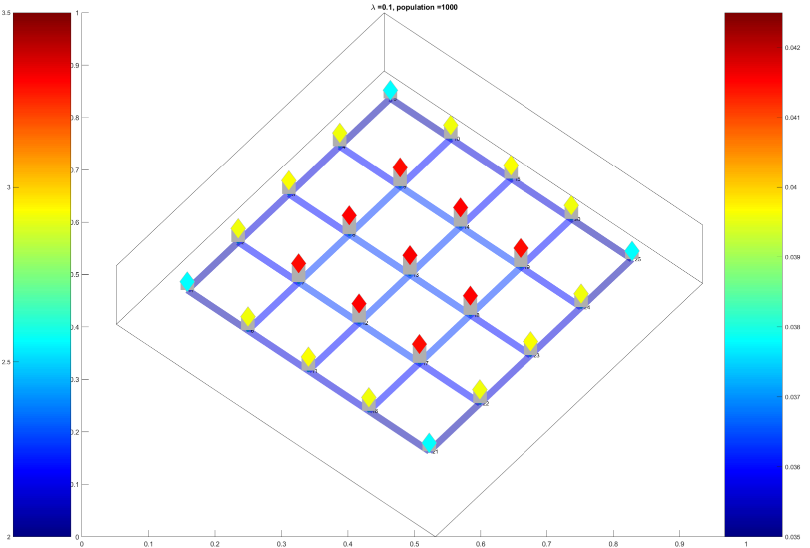
Traffic congestion acts like a standard dispersion force...



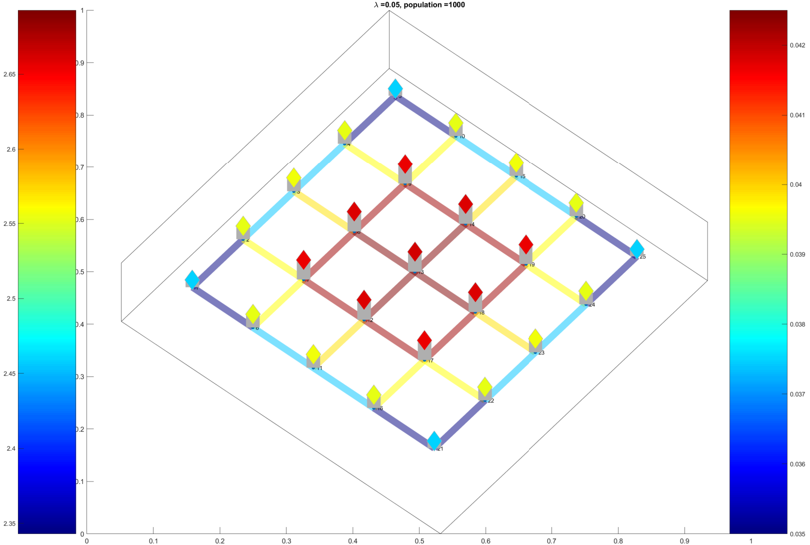
Traffic congestion acts like a standard dispersion force...



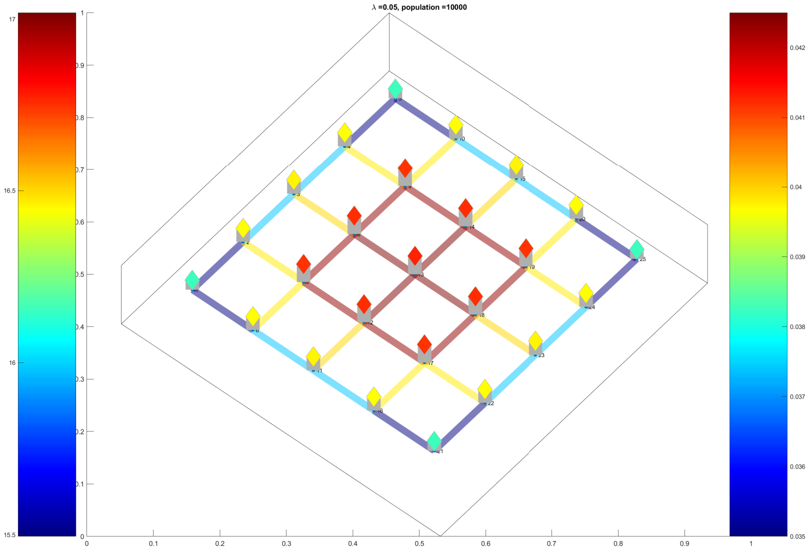
Traffic congestion acts like a standard dispersion force...



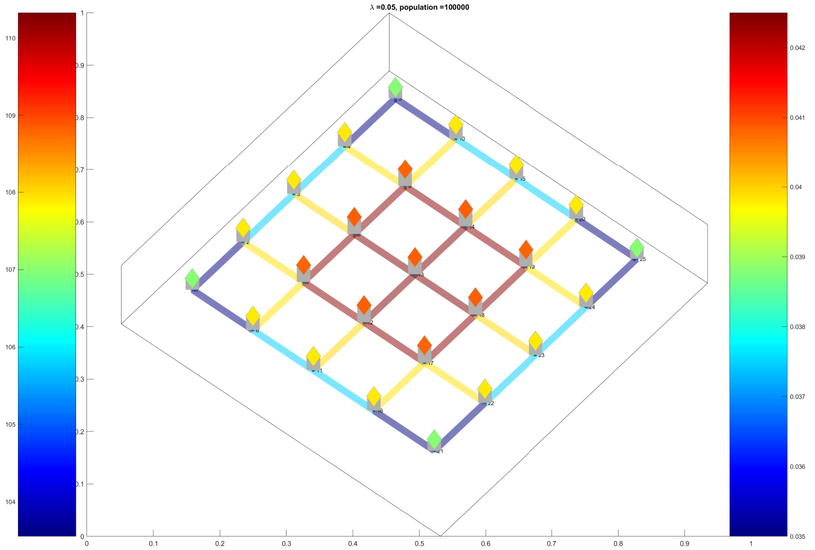
… but unlike a standard dispersion force, scale matters



... but unlike a standard dispersion force, scale matters



… but unlike a standard dispersion force, scale matters



Outline of Talk

Counterfactuals

- Standard model: write system in changes using observed data:

$$\left(\hat{I}_i^R\right)^{1-\theta\beta} = \hat{\chi}\sum_j \left(\frac{L_{ij}}{L_i^R}\right)\hat{\tau}_{ij}^{-\theta}\left(\hat{I}_j^F\right)^{\theta\alpha}$$

$$\left(\hat{I}_i^F\right)^{1-\theta\alpha} = \hat{\chi}\sum_j \left(\frac{L_{ji}}{L_i^F}\right)\hat{\tau}_{ji}^{-\theta}\left(\hat{I}_j^R\right)^{\theta\beta}$$

Counterfactuals

- Standard model: write system in changes using observed data:

$$\left(\hat{I}_i^R\right)^{1-\theta\beta} = \hat{\chi}\sum_j \left(\frac{L_{ij}}{L_i^R}\right)\hat{\tau}_{ij}^{-\theta}\left(\hat{I}_j^F\right)^{\theta\alpha}$$

$$\left(\hat{I}_i^F\right)^{1-\theta\alpha} = \hat{\chi}\sum_j \left(\frac{L_{ji}}{L_i^F}\right)\hat{\tau}_{ji}^{-\theta}\left(\hat{I}_j^R\right)^{\theta\beta}$$

- With traffic congestion:

$$\left(\widehat{I_i^R}\right)^{-\theta\beta+1}\left(\widehat{I_i^F}\right)^{\frac{\theta\lambda(1-\alpha\theta)}{1+\theta\lambda}} = \widehat{\chi}\left(\frac{L_i^F}{L_i^F+\sum_j \Xi_{ij}}\right)\left(\widehat{I_i^F}\right)^{\frac{\theta(\alpha+\lambda)}{1+\theta\lambda}} + \widehat{\chi}^{\frac{\theta\lambda}{1+\theta\lambda}}\sum_j\left(\frac{\Xi_{ij}}{L_i^F+\sum_j \Xi_{ij}}\right)\widehat{\bar{t}}_{ij}^{-\frac{\theta}{1+\theta\lambda}}\left(\widehat{I_j^R}\right)^{\frac{1-\beta\theta}{1+\theta\lambda}}$$

$$\left(\widehat{I_i^R}\right)^{\frac{\theta\lambda(1-\beta\theta)}{1+\theta\lambda}}\left(\widehat{I_i^F}\right)^{-\theta\alpha+1} = \widehat{\chi}\left(\frac{L_i^R}{L_i^R+\sum_j \Xi_{ji}}\right)\left(\widehat{I_i^R}\right)^{\frac{\theta(\beta+\lambda)}{1+\theta\lambda}} + \widehat{\chi}^{\frac{\theta\lambda}{1+\theta\lambda}}\sum_j\left(\frac{\Xi_{ji}}{L_i^R+\sum_j \Xi_{ji}}\right)\widehat{\bar{t}}_{ji}^{-\frac{\theta}{1+\theta\lambda}}\left(\widehat{I_j^F}\right)^{\frac{1-\alpha\theta}{1+\theta\lambda}}$$

Counterfactuals

- Standard model: write system in changes using observed data:

$$\left(\hat{l}_i^R\right)^{1-\theta\beta} = \hat{\chi} \sum_j \left(\frac{L_{ij}}{L_i^R}\right) \hat{\tau}_{ij}^{-\theta} \left(\hat{l}_j^F\right)^{\theta\alpha}$$

$$\left(\hat{l}_i^F\right)^{1-\theta\alpha} = \hat{\chi} \sum_j \left(\frac{L_{ji}}{L_i^F}\right) \hat{\tau}_{ji}^{-\theta} \left(\hat{l}_j^R\right)^{\theta\beta}$$

- With traffic congestion:

$$\left(\widehat{l_i^R}\right)^{-\theta\beta+1} \left(\widehat{l_i^F}\right)^{\frac{\theta\lambda(1-\alpha\theta)}{1+\theta\lambda}} = \widehat{\chi} \left(\frac{L_i^F}{L_i^F + \sum_j \Xi_{ij}}\right) \left(\widehat{l_i^F}\right)^{\frac{\theta(\alpha+\lambda)}{1+\theta\lambda}} + \widehat{\chi}^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\frac{\Xi_{ij}}{L_i^F + \sum_j \Xi_{ij}}\right) \widehat{\bar{t}}_{ij}^{-\frac{\theta}{1+\theta\lambda}} \left(\widehat{l_j^R}\right)^{\frac{1-\beta\theta}{1+\theta\lambda}}$$

$$\left(\widehat{l_i^R}\right)^{\frac{\theta\lambda(1-\beta\theta)}{1+\theta\lambda}} \left(\widehat{l_i^F}\right)^{-\theta\alpha+1} = \widehat{\chi} \left(\frac{L_i^R}{L_i^R + \sum_j \Xi_{ji}}\right) \left(\widehat{l_i^R}\right)^{\frac{\theta(\beta+\lambda)}{1+\theta\lambda}} + \widehat{\chi}^{\frac{\theta\lambda}{1+\theta\lambda}} \sum_j \left(\frac{\Xi_{ji}}{L_i^R + \sum_j \Xi_{ji}}\right) \widehat{\bar{t}}_{ji}^{-\frac{\theta}{1+\theta\lambda}} \left(\widehat{l_j^F}\right)^{\frac{1-\alpha\theta}{1+\theta\lambda}}$$

- Same close marriage between theory and data, but now using traffic data!

Outline of Talk

Why Seattle?

- The traffic in Seattle is bad.
  - Second highest commute times in the U.S.
  - No major public transportation system.

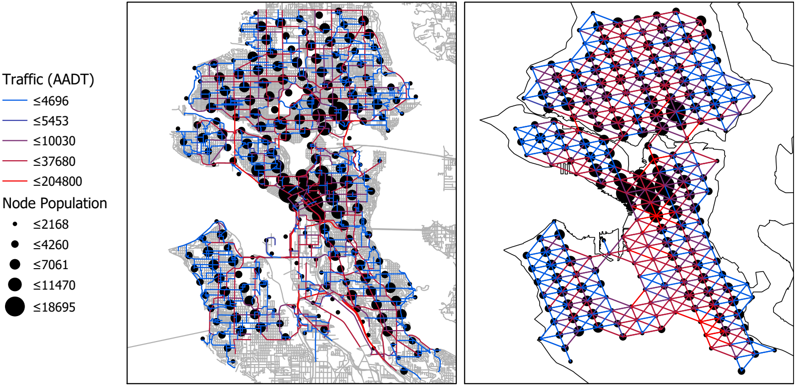
Why Seattle?

- The traffic in Seattle is bad.
  - Second highest commute times in the U.S.
  - No major public transportation system.
- The data in Seattle is good.
  - For roughly 1,500 miles of roads, we observe traffic, length, location, number of lanes, speed limit (HPMS)
  - Residential, workplace populations in each census block group (LODES).
  - Note: HPMS & LODES available throughout U.S.

Why Seattle?

- The traffic in Seattle is bad.
  - Second highest commute times in the U.S.
  - No major public transportation system.
- The data in Seattle is good.
  - For roughly 1,500 miles of roads, we observe traffic, length, location, number of lanes, speed limit (HPMS)
  - Residential, workplace populations in each census block group (LODES).
  - Note: HPMS & LODES available throughout U.S.
- The geography is interesting.
  - Water & bridges result in natural bottlenecks in road network.

The Seattle Road Network



Outline of Talk

Estimation overview

- To evaluate welfare impacts, only need to know four elasticities:
    1. Preference heterogeneity θ.
    2. Productivity spillover α.
    3. Amenity spillover β.
    4. Traffic congestion parameter λ.

Estimation overview

- To evaluate welfare impacts, only need to know four elasticities:

  1. Preference heterogeneity θ. $\leftarrow$ *We set* $\theta = 4$ *(Monte et al. '18).*
  2. Productivity spillover α.
  3. Amenity spillover β.
  4. Traffic congestion parameter λ.

Estimation overview

- To evaluate welfare impacts, only need to know four elasticities:

  1. Preference heterogeneity θ. $\leftarrow$ *We set* $\theta = 4$ *(Monte et al. '18).*
  2. Productivity spillover α. $\leftarrow$ *We set* $\alpha = 0.1$ *(Roca & Puga '17).*
  3. Amenity spillover β.
  4. Traffic congestion parameter λ.

Estimation overview

- To evaluate welfare impacts, only need to know four elasticities:

1. Preference heterogeneity θ. $\leftarrow$ *We set* $\theta = 4$ *(Monte et al. '18).*
2. Productivity spillover α. $\leftarrow$ *We set* $\alpha = 0.1$ *(Roca & Puga '17).*
3. Amenity spillover β. $\leftarrow$ *We set* $\beta = -0.3$ *(C-D share of housing).*
4. Traffic congestion parameter λ.

Estimation overview

- To evaluate welfare impacts, only need to know four elasticities:

  1. Preference heterogeneity θ. $\leftarrow$ *We set* $\theta = 4$ *(Monte et al. '18).*
  2. Productivity spillover α. $\leftarrow$ *We set* $\alpha = 0.1$ *(Roca & Puga '17).*
  3. Amenity spillover β. $\leftarrow$ *We set* $\beta = -0.3$ *(C-D share of housing).*
  4. Traffic congestion parameter λ. $\leftarrow$ *We estimate this.*

Estimation of Traffic Congestion

- Assume:
  1. Link costs increasing in travel time:

$$\ln t_{kl} = \delta_0 \ln time_{kl}$$

Estimation of Traffic Congestion

- Assume:
  1. Link costs increasing in travel time:

$$\ln t_{kl} = \delta_0 \ln time_{kl}$$

  2. Speed is decreasing in traffic (AADT) per lane-mile:

$$speed_{kl} = -\delta_1 \ln \left(\frac{\Xi_{kl}}{lanes_{kl}} \right) + \delta_{kl},$$

Estimation of Traffic Congestion

- Assume:
  1. Link costs increasing in travel time:

$$\ln t_{kl} = \delta_0 \ln time_{kl}$$

  2. Speed is decreasing in traffic (AADT) per lane-mile:

$$speed_{kl} = -\delta_1 \ln\left(\frac{\Xi_{kl}}{lanes_{kl}}\right) + \delta_{kl},$$

- Then:
  1. Consistent with theory, we have:

$$\ln t_{kl} = \underbrace{\delta_0 \ln distance_{kl} - \delta_0 \delta_1 lanes_{kl} - \delta_0 \delta_{kl}}_{\equiv \ln \bar{t}_{kl}} + \underbrace{\delta_0 \delta_1}_{\equiv \lambda} \ln \Xi_{kl}$$

    - Note: Constructing more lane-miles reduces $\bar{t}_{kl}$.

Estimation of Traffic Congestion

- Assume:
  1. Link costs increasing in travel time:

$$\ln t_{kl} = \delta_0 \ln time_{kl}$$

  2. Speed is decreasing in traffic (AADT) per lane-mile:

$$speed_{kl} = -\delta_1 \ln\left(\frac{\Xi_{kl}}{lanes_{kl}}\right) + \delta_{kl},$$

- Then:
  1. Consistent with theory, we have:

$$\ln t_{kl} = \underbrace{\delta_0 \ln distance_{kl} - \delta_0\delta_1 lanes_{kl} - \delta_0\delta_{kl}}_{\equiv \ln \bar{t}_{kl}} + \underbrace{\delta_0\delta_1}_{\equiv\lambda} \ln \Xi_{kl}$$

  - Note: Constructing more lane-miles reduces $\bar{t}_{kl}$.

  2. Simple estimating equation:

$$speed_{kl} = -\delta_1 \ln\left(\frac{\Xi_{kl}}{lanes_{kl}}\right) + \underbrace{\mathbf{X}_{kl}\beta + \varepsilon_{kl}}_{\equiv\delta_{kl}}$$

Estimation of Traffic Congestion (ctd.)

- Estimating equation from last slide:

$$speed_{kl} = -\delta_1 \ln\left(\frac{\Xi_{kl}}{lanes_{kl}}\right) + \underbrace{\mathbf{X}_{kl}\beta + \varepsilon_{kl}}_{\equiv \delta_{kl}}$$

Estimation of Traffic Congestion (ctd.)

- Estimating equation from last slide:

$$speed_{kl} = -\delta_1 \ln\left(\frac{\Xi_{kl}}{lanes_{kl}}\right) + \underbrace{\mathbf{X}_{kl}\beta + \varepsilon_{kl}}_{\equiv \delta_{kl}}$$

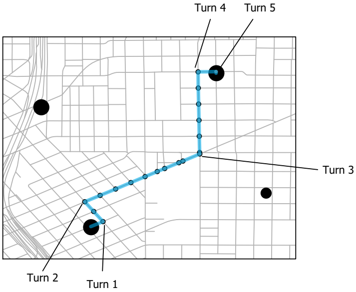
- Need an IV for traffic uncorrelated with free flow rate of speed.

Estimation of Traffic Congestion (ctd.)

- Estimating equation from last slide:

$$speed_{kl} = -\delta_1 \ln\left(\frac{\Xi_{kl}}{lanes_{kl}}\right) + \underbrace{\mathbf{X}_{kl}\beta + \varepsilon_{kl}}_{\equiv \delta_{kl}}$$

- Need an IV for traffic uncorrelated with free flow rate of speed.
  - *Solution*: Number of turns (conditional on number of intersections).



  - *Intuition*: Intersections uniformly costly, turns annoying.

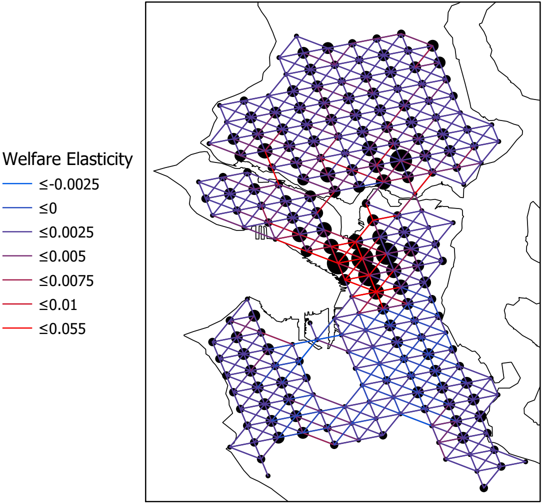
Table: Estimating the strength of traffic congestion

Travel Time Optimized	(1) OLS	(2) IV: 1st stage	(3) IV	(4) IV: 1st stage	(5) IV
AADT per Lane	-0.048***		0.118**		0.488*
	(0.007)		(0.048)		(0.278)
Turns along Route		-0.252***		-0.091**	
		(0.049)		(0.039)	
F-statistic	41.546	26.347	6.191	5.336	3.084
R-squared	0.766	0.721	-0.450	0.875	-2.757
Observations	1338	1338	1338	1338	1338
Start-location FE	Yes	Yes	Yes	Yes	Yes
End-location FE	Yes	Yes	Yes	Yes	Yes
No. of Intersections	No	Yes	Yes	Yes	Yes
Bilateral Route Quality	No	No	No	Yes	Yes

- Implies $\lambda = 0.11$.

Outline of Talk

Welfare elasticities $\left(\frac{\partial \ln W}{\partial \ln \bar{t}_{kl}}\right)$ of improving each link



- ~ 10% of links are welfare *reducing* (Braess paradox in action!)

Calculating the Returns on Investment

- Calculate the annual return on investment for an additional lane-mile on every segment.

Calculating the Returns on Investment

- Calculate the annual return on investment for an additional lane-mile on every segment.

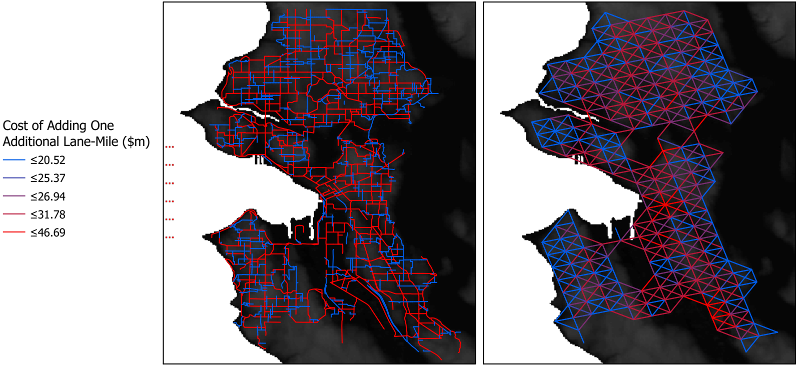
- *Benefits*:

$$\frac{\partial \ln W}{\partial \ln lanes_{kl}} = \delta_0 \delta_1 \times \frac{\partial \ln W}{\partial \ln \bar{t}_{kl}}$$

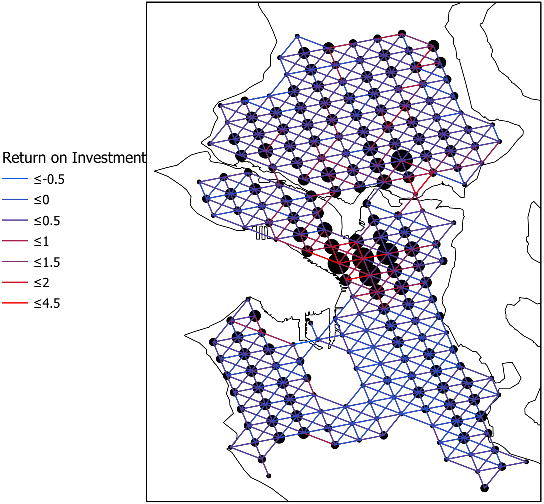
Calculating the Returns on Investment

- Calculate the annual return on investment for an additional lane-mile on every segment.
- *Benefits*:
$$\frac{\partial \ln W}{\partial \ln lanes_{kl}} = \delta_0 \delta_1 \times \frac{\partial \ln W}{\partial \ln \bar{t}_{kl}}$$
- *Costs*: Latest estimates from Federal Highway Administration (FHWA) by road type & location. Assume 10 year linear depreciation.

Estimated Annualized cost of an Additional Lane-mile

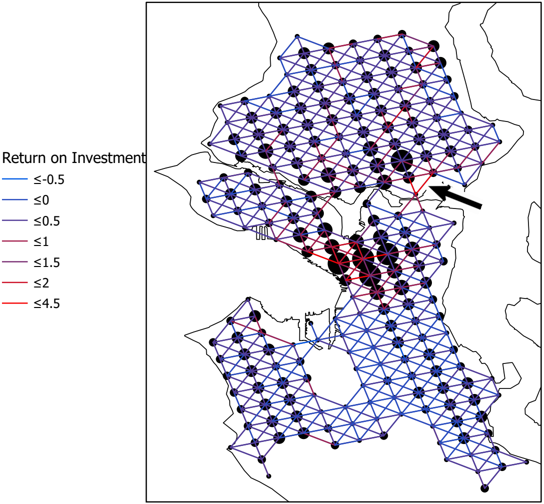


Return on Investment of Infrastructure Investment



- Huge heterogeneity in ROI: Mean: 17%, Median: 8%, SD: 37%.

Return on Investment of Infrastructure Investment



- Huge heterogeneity in ROI: Mean: 17%, Median: 8%, SD: 37%.

Return on Investment of Infrastructure Investment

Seattle City Council won't back second Montlake Bridge

Posted on **Wednesday, September 25, 2019 - 7:00 am** by **jseattle**

— A 10-year-old rendering of what a second Montlake Bridge could look like — via Madison Park Blogger

The state has the funds to build it but the **Seattle City Council** won't — yet — back a resolution supporting a second bascule bridge connecting through the transit chokepoint between Montlake and light rail at Husky Stadium.

Conclusion

- To bolster the quantitative revolution, introduce new urban framework with traffic congestion:
  - Same analytical tractability, close marriage between theory and data.
  - New implications for welfare impacts of road construction.

Conclusion

- To bolster the quantitative revolution, introduce new urban framework with traffic congestion:
  - Same analytical tractability, close marriage between theory and data.
  - New implications for welfare impacts of road construction.
- Future work could leverage wide-spread availability of traffic data to better design infrastructure networks in locations where commuting data is scarce (e.g. in developing countries).