The Economics of Space 433: Lectures 15 and 16

Routing, Traffic and the Infrastructure Network

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Traffic

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  - Not a very hard topic to motivate
  - What are the economic routes of the problem? What are the solutions?

Routing and Traffic

- We have studied a solution of the routing problem that yields a specific solution of the trade costs τ_{ij} as a function of the spatial connections $\bar{t}_{ij}$
  - We now have to add traffic congestion in the mix
  - It affects the cost of using each of the links of the network

- We also want to delve into understanding how changes
  1. in the infrastructure network will affect those costs
  2. other urban planning measure can deal with traffic congestion

Roadmap

- **Traffic Congestion**
- Traffic Congestion and Traffic Externalities
- Routing Improvements and Traffic Congestion
- Urban Planning and Traffic Congestion

Traffic Congestion

- In our analysis, so far, we ignored intentionally the feedback between economic activity and the efficiency of the network
  - **Traffic** is the amount of transportation that passes through each transportation link each given amount of time
  - **Traffic congestion** of the transportation system happens if the flows of goods or people or other endogenous variables affect the intensity/cost of the link

- In our mathematical language we will say that now $\tau_{ij}\left(\bar{t}_{11}, \bar{t}_{12}, ..., \bar{t}_{NN}, \Xi_{11}, \Xi_{12}, ..., \Xi_{NN}\right)$ where Ξ_{ij} is the traffic for a given link in the network
  - ie. the cost of trade between two locations depends on the network and on the level of traffic itself
  - Of course traffic, ultimately depends on the economic activity, i.e. trade or commuting etc.

Next step: Incorporating Congestion

- Following Vickrey '67 (and a large literature thereafter) suppose that:

$$\ln \text{speed}_{ij} = \alpha_0 - \alpha_1 \ln \left(\frac{\text{traffic}_{ij}}{\text{lanes}_{ij}} \right)$$

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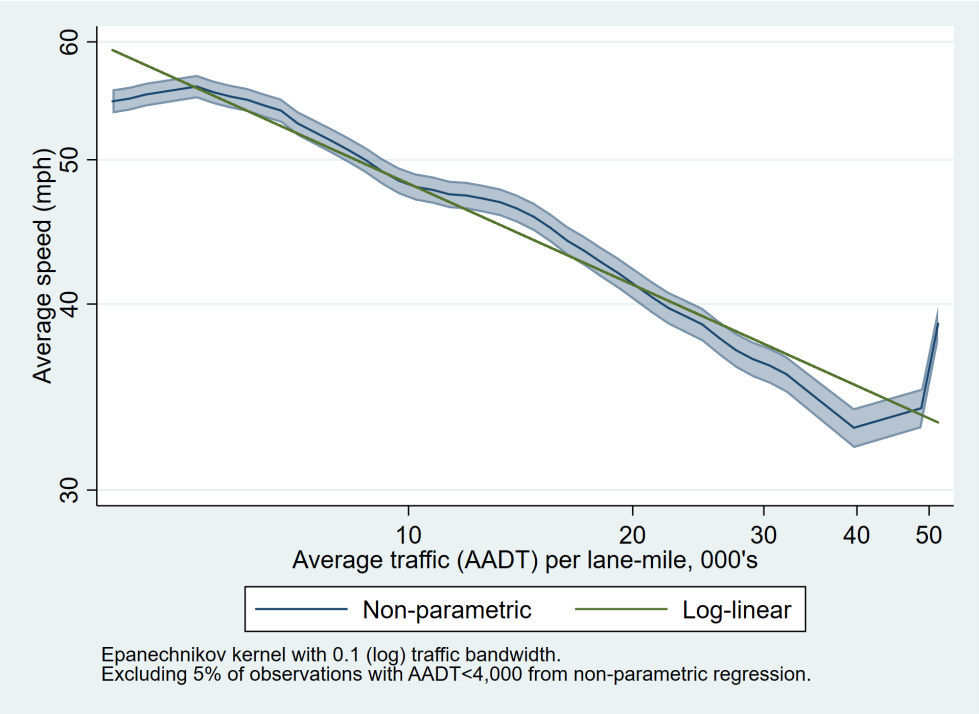
- Log-linear relationship holds very well in data (with $\alpha_1 = 0.226$)



- Speed of travel: API. Traffic: AADT, US Department of Transportation

Costs of Congestion

- Congestion creates various externalities
  - Pollution, time delays, vehicle capital depreciation, accidents are primary examples of this
  - Quantification of these costs are difficult. We will look at a meta analysis of the literature by Small and Verhoef '07

Private and Social Costs of Driving

- Costs of driving are numerous. Bared by individuals and the society
  - Cost of Congestion estimated at 10-20% of overall costs
  - Congestion also generates additional negative externalities due to pollution etc.

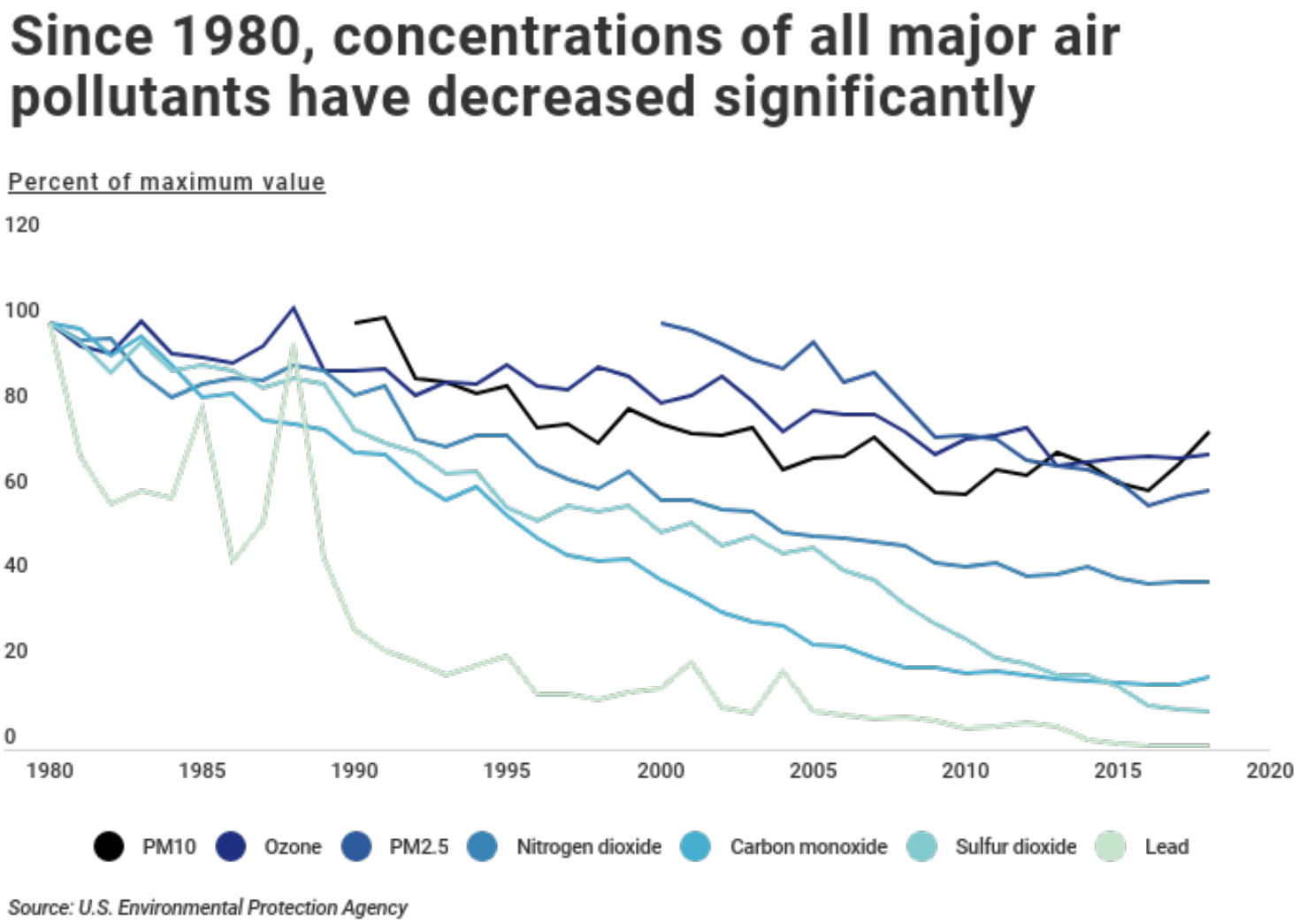
Type of cost	*Private*	*Social*	
	Average [1]	*Average*	*Marginal*
Variable costs			
Cost borne mainly by highway users in aggregate			
(1) Operating and maintenance	0.088	0.088	0.088
(2) Vehicle capital	0.106	0.106	0.106
(3) Travel time	0.189	0.189	0.241
(4) Schedule delay and unreliability	0.058	0.058	0.107
Costs borne substantially by non-users			
(5) Accidents	0.073	0.087	0.111
(6) Government services	0.003	0.011	0.011
(7) Environmental externalities	0	0.009	0.009
Short-run variable costs		0.034	
Fixed costs			
(8) Roadway	0.009	0.034	
(9) Parking	0.014	0.21	
Short-run fixed costs			
Total costs	0.531	0.76	0.675

Notes: All costs in US dollar per vehicle-km. Taken from Kenneth and Erik Table 3.3.
1. If increased vehicle requires a proportionate expansion of the car fleet, then private marginal cost is approximately the same as private average cost (including average fixed cost). In the opposite case where increased travel occurs solely in the form of longer trips, then the following items should be excluded from private marginal cost because they are fixed in the short run: 60% of (2) and all of (6) and (9). The intermediate case, where increased travel occurs using the same vehicle fleet but in the form of more rather than longer trips, is like this second extreme except some private parking cots in (9) become variable to the extent that the additional trips are to locations with parking fees. We arbitrarily allocate user fees among private cost categories as follows: vehicle and licence fees count toward government services and fuel taxes toward roadway capital: hence, for private average cost, item (8) is actually variable rather than fixed.

Traffic and Air Pollution

- Heavy traffic generates two other important health externalities worth discussing
- Poor air quality. Usually measured by fine particulate matter. Alert level $>$ 25-35 $\mu g/m^3$.
  - Estimates from health studies indicate that living within $50m - 100m$ of a major road significantly increases disease health risk and mortality
    - Measured in years of increased mortality
  - See Brugge, Durant, Rioux '07 for a review

Pollutant Levels over the Years



Traffic and Noise Pollution

- Another externality is extreme noise levels
  - Alert levels >65-80 dB. Oftentimes measured at 90+ dB (close to a mower)
- A positive effects of the recent technological advancements (e.g. elimination of lead in gas, catalysts, better combustion engines, electrical cars) is cleaner air and lower noise levels in big cities
  - Important factor in re-population of major cities
  - However, ought to be vigilant. Reversal may happen when regulations relax

Roadmap

- Traffic Congestion
- **Traffic Congestion and Traffic Externalities**
- Routing Improvements and Traffic Congestion
- Urban Planning and Traffic Congestion

Traffic in a Simple Model

- Consider N travelers
  - Two routes available n_1, n_2 such that $n_1 + n_2 = N$
  - The cost of each route is linear

$$C_i(n_i) = \alpha_i + \underbrace{\beta_i}_{\text{marginal cost}} n_i$$

- In equilibrium, changing a route is not optimal, i.e.

$$C_1 = \alpha_1 + \beta_1 n_1 = \alpha_2 + \beta_2 \left(\underbrace{N - n_1}_{n_2} \right) = C_2 \iff$$

$$n_1 = \frac{\alpha_2 - \alpha_1}{\beta_1 + \beta_2} + \frac{\beta_2}{\beta_1 + \beta_2} N$$

Traffic and the Social Optimum

- A social optimum requires that we minimize total cost

$$n_1 C_1(n_1) + n_2 C_2(n_2)$$

i.e. minimize the function (recall that $n_2 = N - n_1$)

$$f(n_1) = n_1\alpha_1 + n_1^2\beta_1 + (N - n_1)\alpha_2 + (N - n_1)^2\beta_2$$

- Taking the derivative of this function. We obtain

$$\alpha_1 + 2n_1\beta_1 - \alpha_2 - 2(N - n_1)\beta_2 = 0 \iff$$

$$n_1 = \frac{1}{2}\frac{\alpha_2 - \alpha_1}{\beta_1 + \beta_2} + \frac{2\beta_2}{2(\beta_1 + \beta_2)}N$$

  - Difference with previous expression: marginal cost replaced by $2\beta_i$
  - In other words the planner, internalizing all players actions and effects, associates a higher marginal cost to congestion

Dealing with Traffic

- How can you deal with traffic?
  - We can put a countervailing toll on the marginal usage

$$C_i(n_i) = \alpha_i + \underbrace{2\beta_i}_{\text{marginal cost}} n_i$$

- In equilibrium, changing a route is not optimal, i.e.

$$C_1 = \alpha_1 + 2\beta_1 n_1 = \alpha_2 + 2\beta_2 \left(\underbrace{N - n_1}_{n_2} \right) = C_2 \iff$$

$$n_1 = \frac{1}{2} \frac{\alpha_2 - \alpha_1}{(\beta_1 + \beta_2)} + \frac{2\beta_2}{2(\beta_1 + \beta_2)} N$$

  - Thus, traffic is an externality that can be ''corrected'' with a tax

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Traffic Congestion

- As someone could imagine, building more roads is not a panacea for traffic
  - May lead to reallocation of economic activity as a result
- You can plausibly assume that people could start using more cars exactly where the road improves
  - Also people could relocate to regions with better infrastructure

Traffic Congestion and Road Investment

- Duranton Turner '11 study this relationship
  - Vehicle-kilometers traveled (VKT) regressed on interstate highway Interstate Highway lane km
  - Using AADT data for traffic and lane-kilometers

Traffic Congestion and Road Investment

- Duranton Turner '11 study this relationship
  - Vehicle-kilometers traveled (VKT) regressed on interstate highway Interstate Highway lane km
  - Using AADT data for traffic and lane-kilometers
  - Result: the Law of Road Congestion!
- They find almost a one-to-one relationship between traffic and capacity improvement
  - As lane-km increase in an area, VKT increases almost one-to-one
- Estimates by Allen Arkolakis '22 are much smaller, an elasticity of 0.4
  - Substantially different empirical methodologies (i.e. instruments)

Traffic and Road Investment

Year:	1983	1993	2003
Mean daily VKT (IH, '000 km)	7,777	11,905	15,961
	(16,624)	(24,251)	(31,579)
Mean AADT (IH)	4,832	7,174	9,361
	(2,726)	(3,413)	(4,092)
Mean lane km (IH)	1,140	1,208	1,280
	(1,650)	(1,729)	(1,858)
Mean lane km (IH, per 10,000 population)	26.7	24.3	22.1
	(26.9)	(20.9)	(16.4)
Mean daily VKT (MRU, '000 km)	14,553	22,450	31,242
	(36,303)	(49,132)	(70,692)
Mean AADT (MRU)	3,146	3,646	3,934
	(847)	(947)	(1,059)
Mean lane km (MRU)	3,885	5,071	6,471
	(7,926)	(9,119)	(12,426)
Mean VKT share urbanized (IHU/IH)	0.38	0.44	0.48
Mean lane km share urbanized (IHU/IH)	0.29	0.36	0.40
Mean share truck AADT (IH)	0.11	0.12	0.13
Peak service large buses per 10,000 population	1.20	1.09	1.34
	(1.02)	(0.98)	(0.98)
Peak service large buses	169	165	217
	(563)	(562)	(742)
Number MSAs	228	228	228
Mean MSA population	753,726	834,290	950,054

Notes: Cross MSA means and standard deviations in parentheses. IH denotes interstate highways for the entire MSA. IHU denotes interstate highways for the urbanized areas within an MSA. MRU denotes major roads for the urbanized areas within an MSA.

Traffic and Road Investment

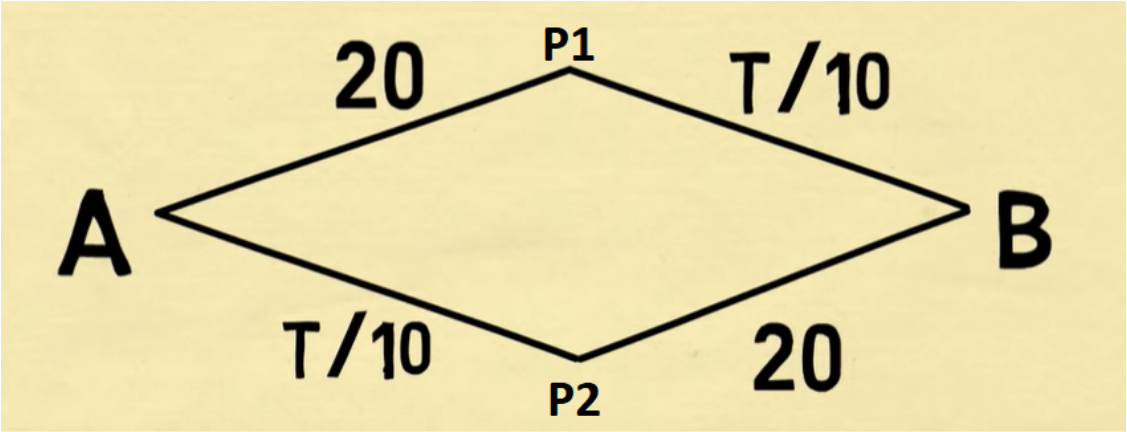
MSA sample	All (1)	All (2)	All (3)	All (4)	All (5)	Lane ↑ (6)	Lane ↑ (7)	Lane ↓ (8)	All (9)	All (10)
Panel A. Dependent variable: Δln VKT for interstate highways, entire MSAs, OLS										
Δln (IH lane km)	1.04***	1.05***	1.02***	1.00***	0.93***	1.09***	0.90***	0.82***	1.03***	1.03***
	(0.05)	(0.05)	(0.04)	(0.04)	(0.04)	(0.06)	(0.06)	(0.09)	(0.05)	(0.05)
Δln (population)		0.34***	0.40***	0.44***	0.39***	0.31*	0.45**	0.16		0.51**
		(0.10)	(0.10)	(0.11)	(0.13)	(0.17)	(0.21)	(0.22)		(0.20)
ln (initial VKT)			−0.047***	−0.057***	−0.12***		−0.15***	−0.13***		
			(0.006)	(0.007)	(0.02)		(0.03)	(0.04)		
Geography				Y	Y		Y	Y		
Census divisions				Y	Y		Y	Y		
Socioeconomic characteristics					Y		Y	Y		
Past populations					Y		Y	Y		
MSA fixed effects									Y	Y
R^2	0.87	0.87	0.89	0.90	0.91	0.91	0.94	0.69	0.91	0.94
Panel B. Dependent variable: Δln VKT for interstate highways, entire MSAs, TSLS										
Δln (IH lane km)		1.05***	1.02***	1.00***	0.92***	1.07***	0.90***	0.82***		1.03***
		(0.05)	(0.04)	(0.04)	(0.04)	(0.06)	(0.05)	(0.09)		(0.03)
Δln (population)		0.093	0.34**	0.45	1.02**	−0.16	1.14	1.50		0.62*
		(0.18)	(0.16)	(0.32)	(0.45)	(0.29)	(0.72)	(1.45)		(0.37)
First stage statistic		63.3	54.3	29.2	23.9	45.7	12.3	4.05		20.1

Notes: All regressions include a constant and decade effects. Robust standard errors clustered by MSA in parentheses. 456 observations for each regression in columns 1–5 and 9–10, 205 in columns 6–7 which consider only increases in lane kilometers of more than 5 percent, and 115 in column 8 which considers declines in lane kilometers greater than 5 percent. Instrument for Δln (population) is expected population growth based on initial composition of economic activity.

Braess's Paradox

- In fact, investing on roads may even sometimes **increase** traffic
  - Let us see this by building on our earlier example

- Example: suppose 200 drivers want to drive from point A to point B
  - Road segments A-P1 and P2-B take a fixed amount of time to traverse (20 min)
  - Road segments P1-B, A-P2 take $\frac{T}{10}$ minutes to traverse (T is number of drivers)

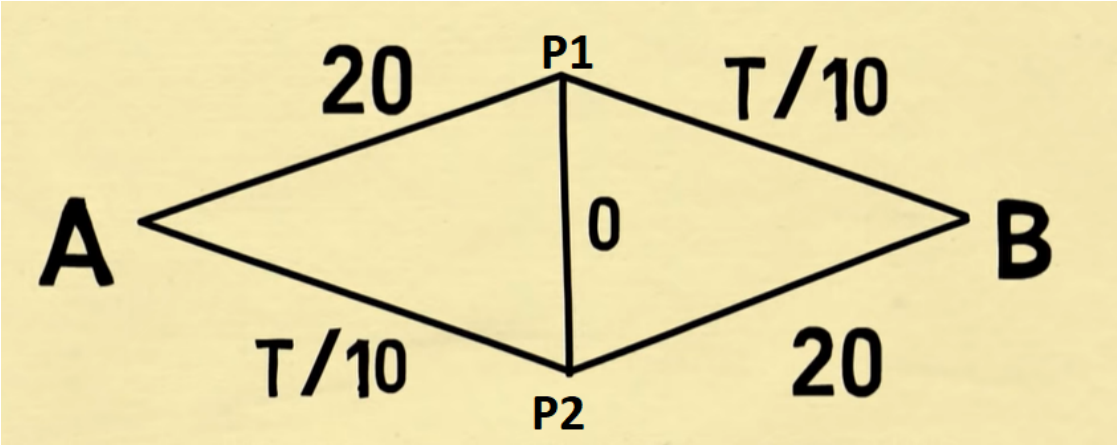


Source: MindYourDecisions (YouTube channel)

- Nash Equilibrium: half of drivers take path A-P1-B and other half take A-P2-B
  - Total travel time: $t_0 = 20 + \frac{100}{10} = \frac{100}{10} + 20 = 30$ minutes

Braess's Paradox

- What if a new road is built to connect the two mid-points P1 and P2?
  - Assume new road can be traversed instantly (in 0 minutes)



Source: MindYourDecisions YouTube channel

- Note that $\frac{T}{10} \leq 20$ for sure because there are only 200 drivers
  - Using segments A-P2 and P1-B is a (weakly) dominant strategy for all drivers

- New Nash equilibrium: all drivers use path A-P2-P1-B
  - Total travel time: $t_1 = \frac{200}{10} + \frac{200}{10} = 40$ minutes
  - Travel time is higher than before the new road was built!

Roadmap

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- **Urban Planning and Traffic Congestion**

Countermeasures

- As we discussed, congestion has been viewed by economists as negative externality
- Negative effects on economic activity not priced by market. Countermeasures:
  - ''Use'' tax that can be dedicated to subsidize measures that alleviate traffic.

Congestion Pricing

- This form of tax is called ‘‘congestion’’ pricing
- It be used to provide benefits to those affected by externalities:
  - Improve public transportation, road infrastructure
- New York has voted to implement congestion pricing as early as end of 2023
  - $23 for entering lower Manhattan
  - Provide a revenue stream for Metro Transit Autoriry

Long Term Solutions for Traffic

- Long term solution to traffic involves a variety of other measures
  - Congestion tax is oftentimes unpopular
- Urban planning (e.g. zoning, road rerouting) used to reroute economic activity
  - E.g. in different parts of the city or at different times etc
- Massive infrastructure projects have been employed to deal with congestion
  - Oftentimes simply to end up accommodating a proportional increase in economic activity and traffic (see Duranton Turner '11)
- Combination of urban planning, public transit, congestion taxes led to success
  - Such a coordinated response to traffic has been particularly difficult to implement in decentralized administrative systems
  - E.g. New York had struggled for decades to implement a serious response to increased traffic
  - Postponed congestion price for at least a year
  - Reasons: massive building costs (lack of unique planning authority), congestion tax unpopular to voters, difficult to reroute traffic (land use restrictions)

Traffic Congestion and Investment in Infrastructure

- Investment in the presence of traffic congestion is more complicated
  - Subject to Braess paradox, Duranton Turner law of congestion, feedback effects etc

- One way to capture the impact of congestion is to write the cost of passing through a link as

$$t_{ij} = \bar{t}_{ij} \times f^{\Xi}\left(\Xi_{ij}\right)$$

  where Ξ_{ij} is traffic that passes through the link and f^{Ξ} is some increasing function
  - $\bar{t}_{ij}$ is the geographic cost of the link (e.g. terrain, quality of road etc)

Measuring Traffic Congestion in Theory and Data

- This representation leaves two question to answer
  - How is Ξ_{ij} related to geography in the data
  - How is Ξ_{ij} related to economic activity

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- Recall that we can establish an empirical relationship in the data

$$t_{ij} = \bar{t}_{ij} \times f^{\Xi}\left(\Xi_{ij}\right)$$

  - Think of t_{ij} as inversely related to speed i.e. $s_{ij} = t_{ij}^{-1}$.
  - Also $\bar{t}_{ij}$ as inversely related to geography and road quality

- In other words this relationship is the analog of the Vickrey

$$-\ln s_{ij} = \ln \bar{t}_{ij} + \ln f^{\Xi}\left(\Xi_{ij}\right) \iff \ln s_{ij} = \underbrace{-\ln \bar{t}_{ij}}_{\text{geography/road quality}} - \ln f^{\Xi}\left(\Xi_{ij}\right)$$

Traffic and Geography

- How is Ξ_{ij} related to economic activity and geography?
- Here we have some empirical guidance from the Vickrey relationship

$$\ln \text{speed}_{ij} = \alpha_0 - \alpha_1 \ln \left(\frac{\text{traffic}_{ij}}{\text{lanes}_{ij}} \right)$$

  - Log-linear relationship holds very well in data with $\alpha_1 = 0.226$.
  - α_0 could be considered as the maximum speed that can be attained in a road

Traffic and Economic Activity

- There is a relationship between traffic and economic activity...
  - ...but it is complicated :)

$$\Xi_{ij} = \sum_{k \in \mathcal{N}} \sum_{l \in \mathcal{N}} \pi_{kl}^{ij} X_{kl}$$

π_{kl}^{ij} can be thought of as the probability of using segment ij when traveling from k to l, X_{kl} total number of shipments (trade, commuting trips etc) from k to l

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- Very hard problem to characterize
  - Fagjelbaum Schaal '20 circumvent it by using optimal transport tools
  - Allen Arkolakis '21 show that it can be written (under strong assumptions) as

$$\Xi_{ij} \propto t_{ij}^{-\varepsilon} \times P_i^{-\varepsilon} \Pi_j$$

for some constant $\varepsilon > 0$

  - Larger consumer/producer access $\Longrightarrow$ more traffic

Traffic and Economic Activity

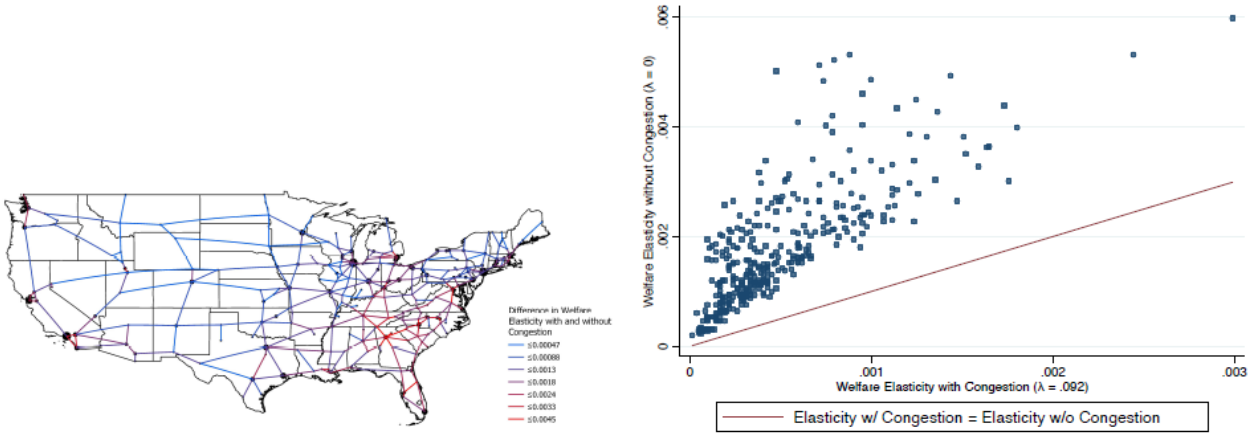
- We combine this with the traffic equation (and measurements a la Vickrey thereof)

$$\Xi_{ij} \propto \left[\bar{t}_{ij} \times f^{\Xi}\left(\Xi_{ij}\right)\right]^{-\varepsilon} \times P_i^{-\varepsilon} \Pi_j$$

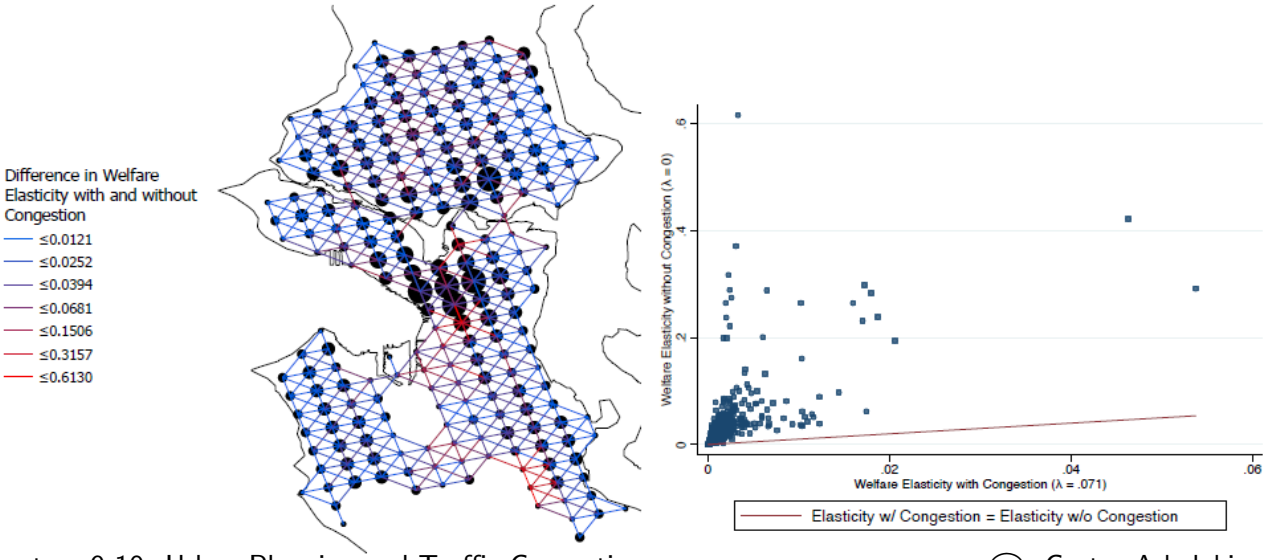
  - We need to consider the impact of policy. For a given change in $\bar{t}_{ij}$
    - take into account changes in market access P_i, Π_j and find the new Ξ_{ij}
    - find new economic outcomes and benefits from investment and compare to costs

Welfare Elasticities with and without Congestion

(a) U.S. Highway Network



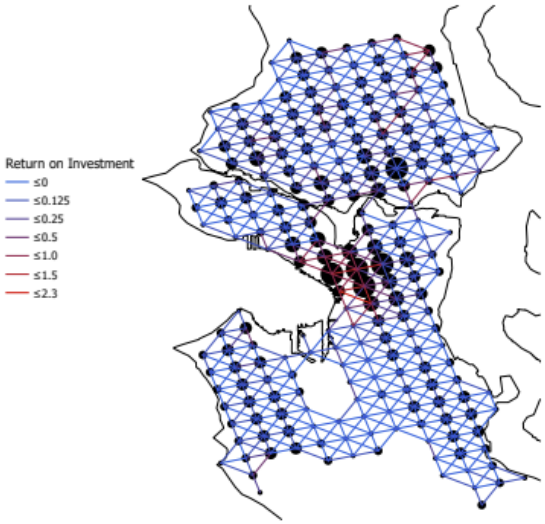
(b) Seattle Road Network



Return-of-Investment with and without Congestion

(a) U.S. Highway Network

(b) Seattle Road Network



Notes: This figure presents the return on investment of improving links in the Interstate Highway System (Panel A) and the Seattle road network (Panel B). Return on investment is annual and in decimals of the initial investment (i.e. 0.75 means a 75% return on initial investment per annum). The color ramps goes from blue (negative returns) to red (high positive returns). Nodes in the network are marked by the black circles, which are increasing the population size of the node.

Extending the Analysis

- We can extend this analysis of in a variety of circumstances
  - Multimodal transportation (Fan, Lu, Luo '21). E.g. multiple choices of highways, different modes
  - International trade through shipping (Fong, Ganapati, Ziv '21, Heiland, Moxnes, Ulltveit-Moe, Zi '21)
  - Containerization (Ducruet, Juhasz, Nagy, Steinwender '21)

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