The Making of the Modern Metropolis: Evidence from London

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  - Transport millions of people each day between their residence and workplace (London underground : 3.5 million journeys each day)

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- Basic idea: Steam railways made possible the first large-scale separation of workplace and residence
  - Previously, given the limitations of human/horse transport technology, most people lived close to work

Empirical Setting

- 19th-century London is the poster child for large metropolitan areas
  - In 1801, around 1 million people, and a walkable city 5 miles E-W
  - By 1901, over 6.5 million people, 17 miles from E-W, and the metropolis that we would recognize today

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  - Observe historical data on employment by residence and land values
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- Our quantitative analysis has a recursive structure
  - In initial steps, predictions for employment by workplace use only gravity and commuter and land market clearing
  - In later steps, use more of the model's structure to recover productivity, amenities and floor space and undertake counterfactuals

Related Literature

- Size and internal structure of cities
  - Alonso-Mills-Muth, Fujita-Ogawa (1982), Fujita-Krugman (1995), Lucas-Rossi-Hansberg (2002), Ahlfeldt-Redding-Sturm-Wolf (2015), Allen-Arkolakis-Li (2016), Owens-Rossi-Hansberg-Sarte (2017)
- Agglomeration economies
  - Henderson (1974), Fujita-Krugman-Venables (1999), Davis-Weinstein (2002), Duration-Puga (2004), Rosenthal-Strange (2004), Moretti (2004), Rossi-Hansberg (2005), Combes-Duranton-Gobillon (2010), Kline-Moretti (2014), Allen-Arkolakis (2014), Monte-Redding-Rossi-Hansberg (2016)
- Transport infrastructure and development
  - McDonald-Osuji (1995), Baum-Snow-Kahn (2005), Gibbons-Machin (2005), Baum-Snow(2007), Michaels (2008), Donaldson (2014), Duranton-Turner (2011, 2012), Donaldson-Hornbeck (2016), Faber (2014), Fajgelbaum-Redding (2014), Baum-Snow (2016)
- Historical city development
  - Ball-Sunderland (2001), Barker-Robbins (1976), Kynaston (2011), Porter (1995), White (2007, 2008, 2012), Masucci-Stanilov-Batty (2013)

Outline

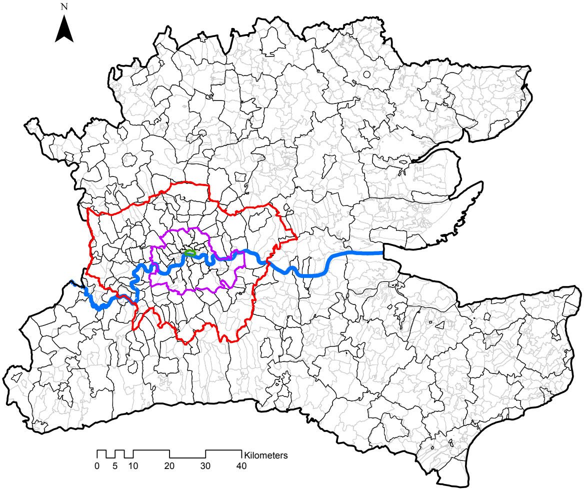
- Data
- Reduced-form evidence
- Quantitative Model
- Conclusions

Data

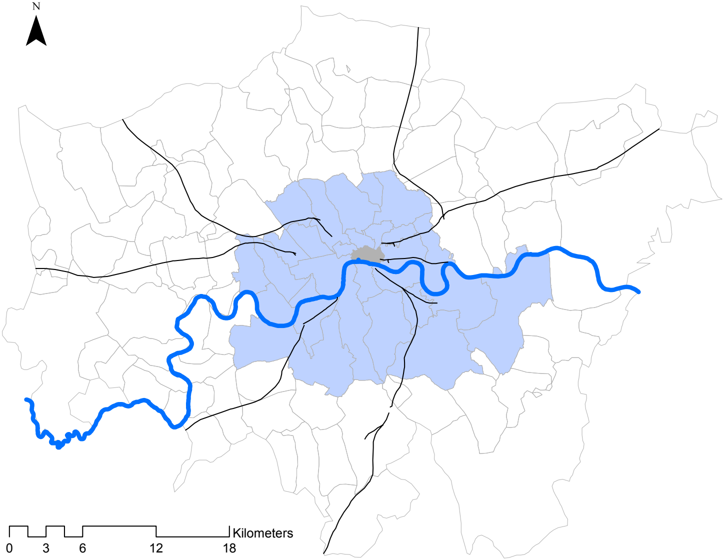
- Population Census data
  - Parishes (285 in GLA) and metropolitan boroughs (99 in GLA)
  - Population by residence from 1801-1921
- Commuting Data
  - Bilateral commuting between boroughs, employment by workplace and employment by residence for 1921
  - Employment by workplace not available before 1921 except for City of London from Day Censuses (from 1866)
  - Historical business directories (1841 onwards)
- Rateable value data
  - Rateable value data by parish from 1815-1921
  - Market rental value of land and buildings after deducting expenses for repair and maintenance
- Transport network data
  - In particular, overground and underground rail by year

Administrative Units

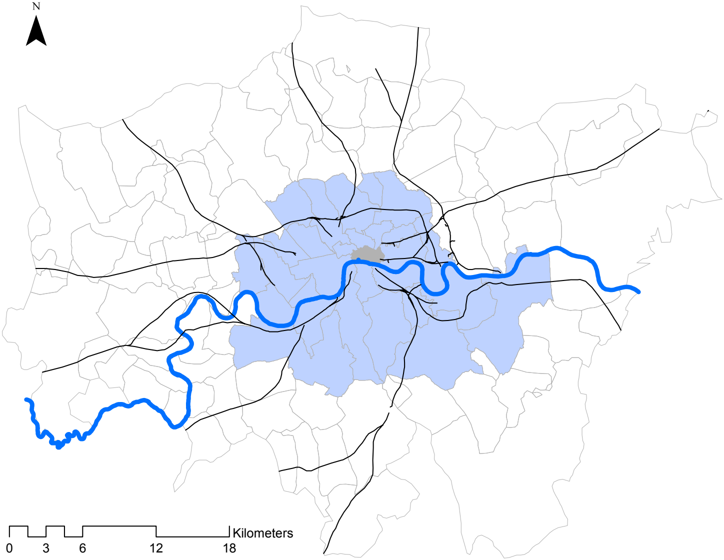
- Home Counties 1921 (black), Greater London Authority (GLA) (red), London County Council (LCC) (purple) and City of London (green)
- Borough and parish boundaries



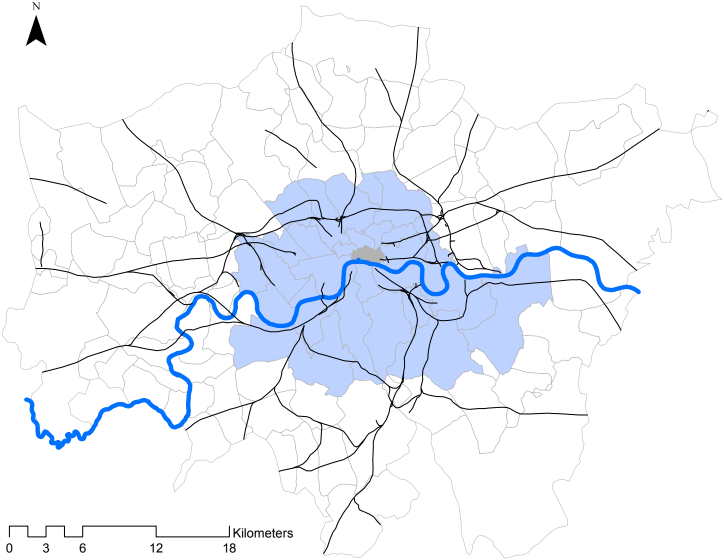
Rail Network 1841



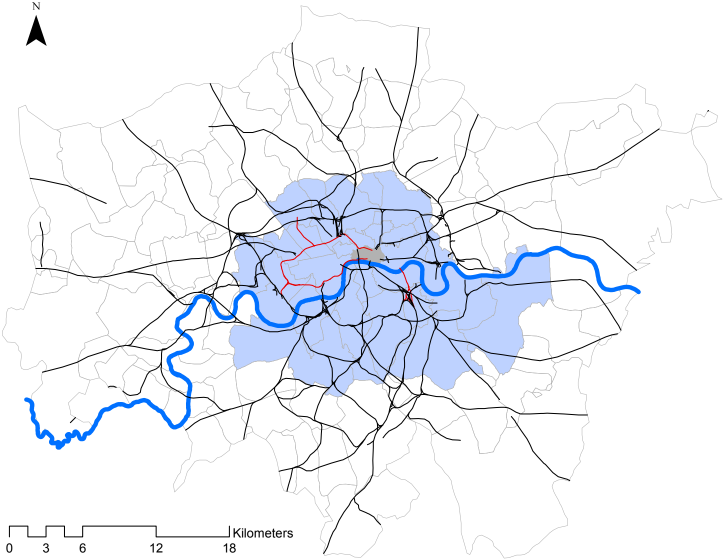
Rail Network 1851



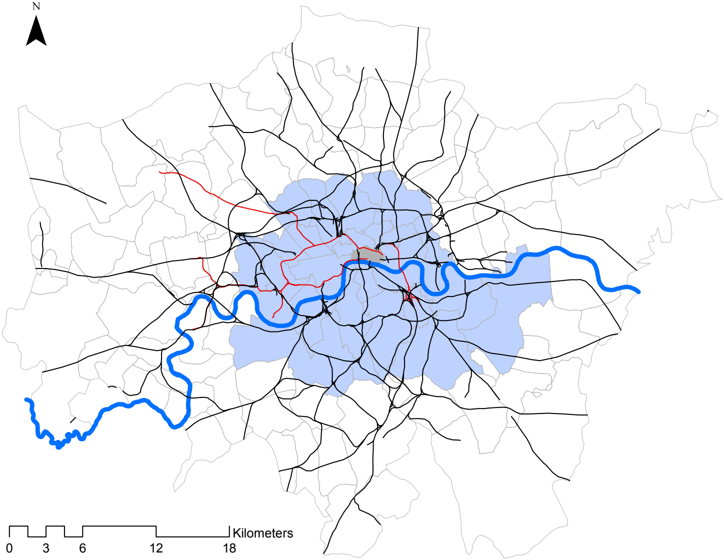
Rail Network 1861



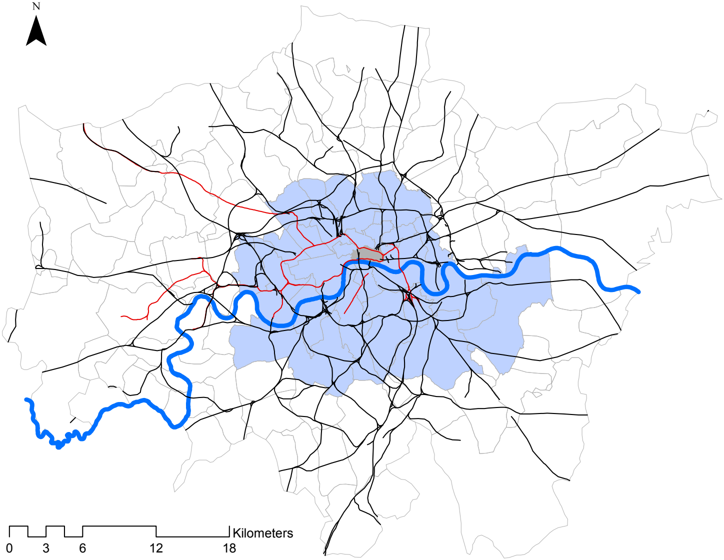
Rail Network 1871



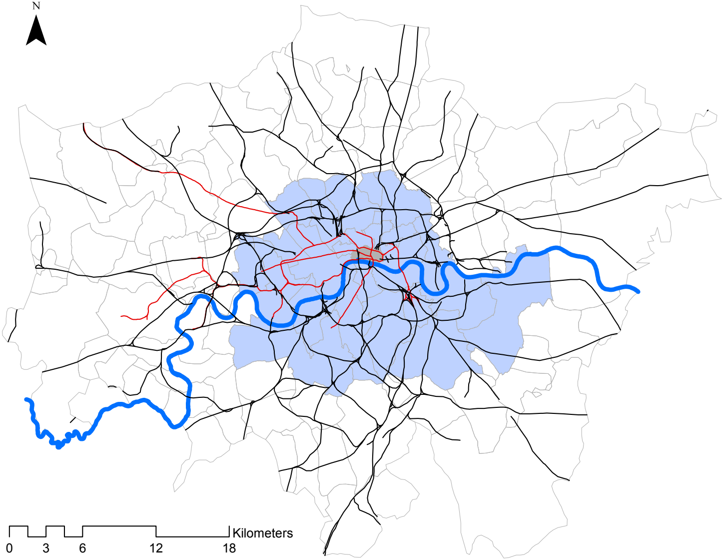
Rail Network 1881



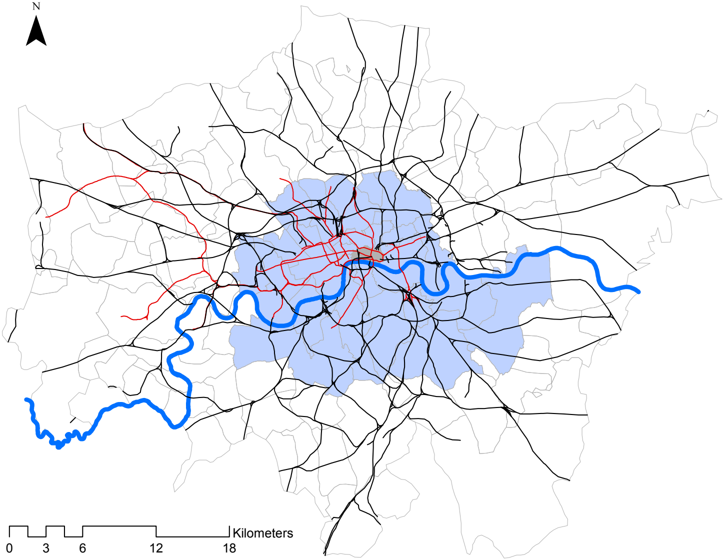
Rail Network 1891



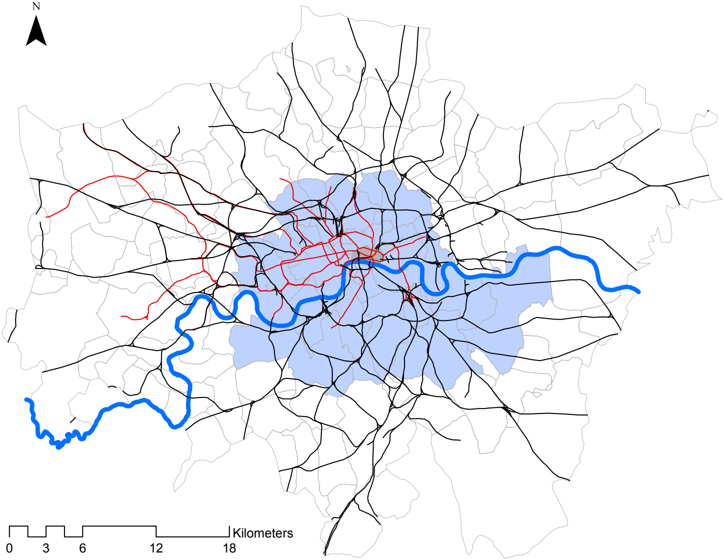
Rail Network 1901



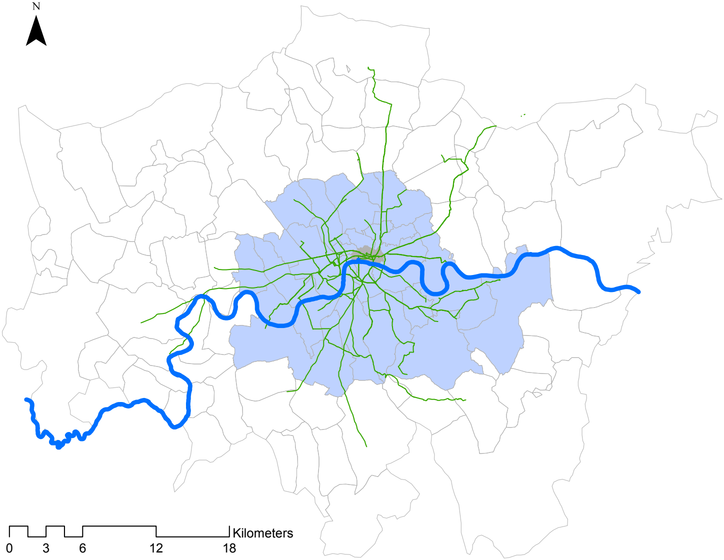
Rail Network 1911



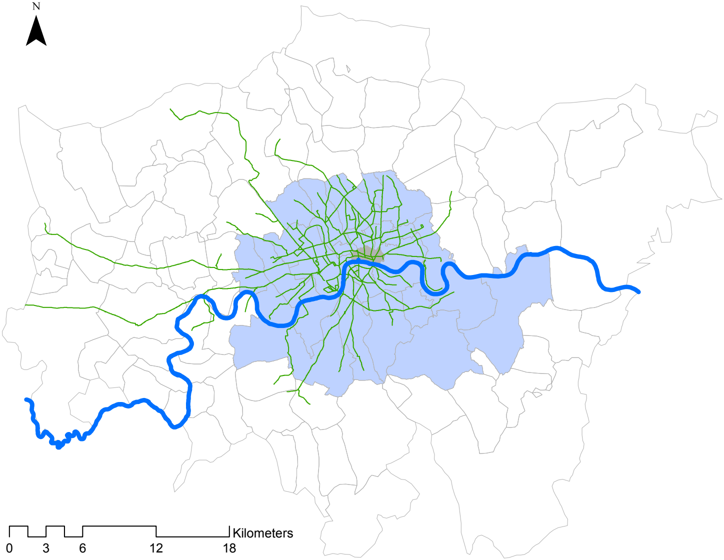
Rail Network 1921



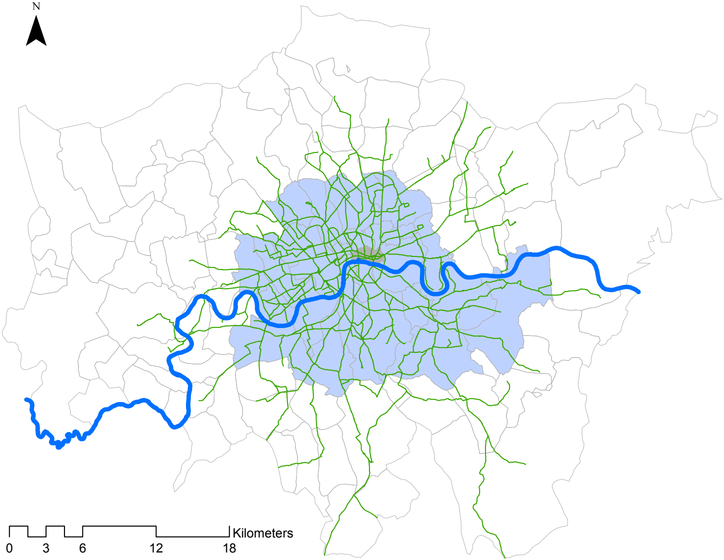
Horse Omnibus Network 1839



Horse Omnibus/Tram Network 1881



Omnibus/Tram Network 1921



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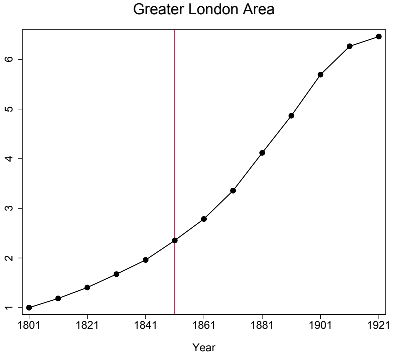
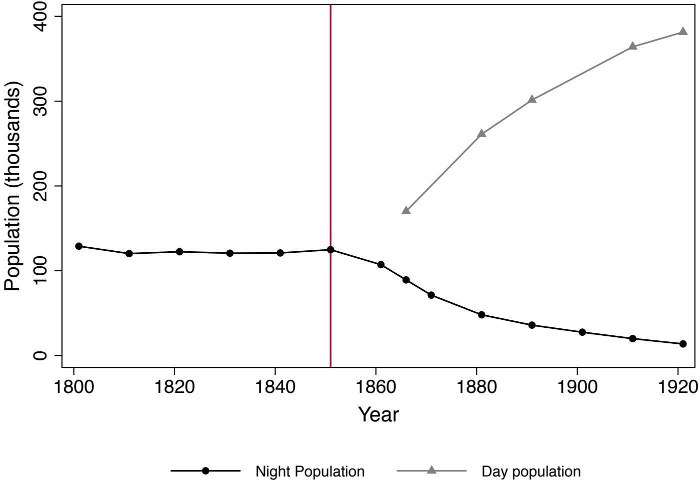
Residential (Night) Population



Day and Night Population

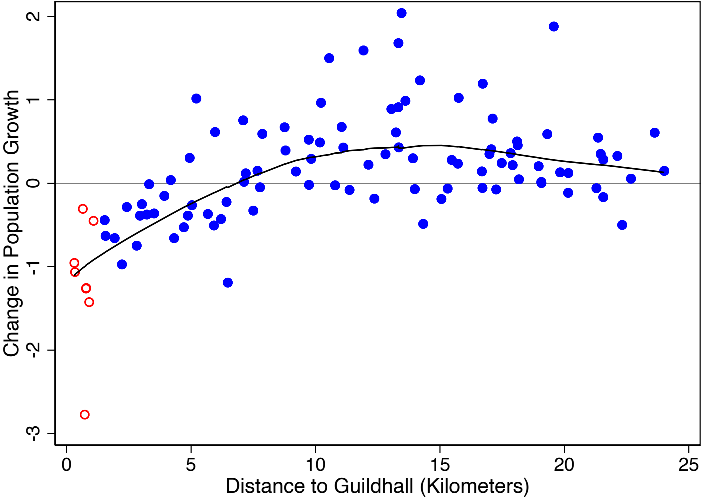


City's Share of GLA Rateable Value

Difference-in-Differences Estimates

- Provide additional reduced-form evidence in the paper
- Using our parish-level data, we can examine changes in (night) population growth before and after the arrival of an overground or underground railway station
- Parishes are connected to the railway network in different years
- We first compute parish log population relative to its mean in Greater London in each year (takes out common year effects)
- We next compute the difference in parish population growth rates between the 30 years before and after the arrival of a railway station
- This approach implicitly controls for parish fixed effects and parish-specific linear time trends in log population

Treatment Heterogeneity



Model Outline

- Each worker ω is geographically mobile and chooses a residence n and workplace i within Greater London from a set of locations $L_{\mathbb{N}} \subset L_{\mathbb{M}}$
- Utility for worker ω residing in n and working in i is

$$U_{ni}(\omega) = \frac{B_{ni} z_{ni}(\omega) w_i}{\kappa_{ni} P_n^{\alpha} Q_n^{1-\alpha}}, \qquad G_n(z) = e^{-z^{-\epsilon}},$$

- with common amenity B_{ni}, idiosyncratic amenity $z_{ni}(\omega)$, wage w_i, consumption price P_n, floor space price Q_n, and commuting costs κ_{ni}
- Probability that a worker chooses to live in n and work in i

$$\lambda_{ni} = \frac{L_{ni}}{L_{\mathbb{N}}} = \frac{(B_{ni} w_i)^{\epsilon} \left(\kappa_{ni} P_n^{\alpha} Q_n^{1-\alpha}\right)^{-\epsilon}}{\sum_{r \in \mathbb{N}} \sum_{\ell \in \mathbb{N}} (B_{r\ell} w_{\ell})^{\epsilon} \left(\kappa_{r\ell} P_r^{\alpha} Q_r^{1-\alpha}\right)^{-\epsilon}}.$$

- Expected utility equalized across residence-workplace pairs

$$\bar{U} \left(\frac{L_{\mathbb{N}}}{L_{\mathbb{M}}}\right)^{\frac{1}{\epsilon}} = \delta \left[\sum_{r \in \mathbb{N}} \sum_{\ell \in \mathbb{N}} (B_{r\ell} w_{\ell})^{\epsilon} \left(\kappa_{r\ell} P_r^{\alpha} Q_r^{1-\alpha}\right)^{-\epsilon}\right]^{\frac{1}{\epsilon}}.$$

- Cobb-Douglas production using labor and commercial floor space
- Total payments for floor space ($Q_n H_n$) equal rateable value ($\mathbb{Q}_n$)

Isomorphisms

- The framework outlined above encompasses a number of different approaches to modelling consumption, production and transport costs
  - Classical urban model (one good and no trade costs)
  - Extension of classical urban model (traded and non-traded goods)
  - Eaton-Kortum model (multiple goods and trade costs)
  - Armington model (goods differentiated by origin and trade costs)
  - Dixit-Stiglitz (horizontally-differentiated varieties and trade costs)

- Each of these models involves different assumptions about P_n and how revenue is generated

- For our basic quantitative analysis, we do not have to take a stance as to which of these models is the right model of cities
  - Gravity in commuting
  - Land market clearing
  - Payments for commercial and residential floor space are constant shares of workplace and residential income respectively

- For counterfactuals, we focus on extension of classical urban model

Quantitative Analysis (Steps 1-2)

- Step 1 : Compute commuting probabilities and employment ($\lambda^C_{nit|n}$, R_{nt}, L_{nt}) in year $t = 1921$

- Step 2 : Solve for wages (w_{nt}) and expected residential income (v_{nt}) in initial equilibrium in year $t = 1921$

$$RV_{nt} = (1-\alpha) v_{nt} R_{nt} + \frac{1-\beta}{\beta} w_{nt} L_{nt},$$

$$RV_{nt} = (1-\alpha) \left[\sum_{i \in \mathbb{N}} \lambda^C_{nit|n} w_{it} \right] R_{nt} + \frac{1-\beta}{\beta} w_{nt} L_{nt},$$

Estimate Commuting Parameters (Step 3)

- Discretize Greater London into a raster of grid points
- Distinguish four transport networks based on average travel speeds

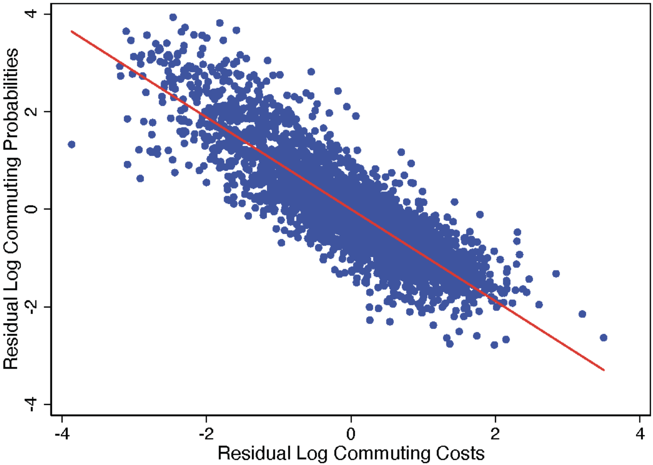
overground railways	21 mph	1
underground railways	15 mph	1.4=21/15
omnibuses and trams	6 mph	3.5=21/6
walking	3 mph	7=21/3

- Compute lowest-weighted-cost distance (d_{nit}^{W}) between boroughs
- Estimate gravity equation for log commuting probabilities

$$\log \lambda_{nit} = \xi_{it} + \zeta_{nt} - \epsilon\phi \log d_{nit}^{W} + u_{nit}$$

- Instrument weighted distance using
  - Log straight-line distance
  - Square of log straight-line distance
- Estimate $\epsilon\phi = 5.20$

Cross-Section Fit (Step 3)



- Approx log linear relationship between commuting probabilities and commuting costs conditional on residence and workplace fixed effects

Estimating Historical Workplace Employment (Step 4)

- Use DEK (2007) "exact-hat algebra" ($\hat{x}_t = x_\tau / x_t$) to generate model predictions for years $\tau < t$ starting from $t = 1921$

- Solve for changes in wages ($\hat{w}_{it}$) for $\tau < t$ from commuter and land market clearing

$$\hat{\mathbb{Q}}_{nt}\mathbb{Q}_{nt} = (1-\alpha)\left[\sum_{i\in\mathbb{N}} \frac{\lambda^C_{nit|n}\hat{w}^\epsilon_{it}\hat{\kappa}^{-\epsilon}_{nit,\tau}}{\sum_{\ell\in\mathbb{N}}\lambda^C_{n\ell t|n}\hat{w}^\epsilon_{\ell t}\hat{\kappa}^{-\epsilon}_{n\ell t,\tau}}\hat{w}_{it}w_{it}\right]\hat{R}_{nt}R_{nt} + \left(\frac{1-\beta}{\beta}\right)\hat{w}_{nt}w_{nt}\left[\sum_{i\in\mathbb{N}} \frac{\lambda^C_{nit|n}\hat{w}^\epsilon_{it}\hat{\kappa}^{-\epsilon}_{nit,\tau}}{\sum_{\ell\in\mathbb{N}}\lambda^C_{n\ell t|n}\hat{w}^\epsilon_{\ell t}\hat{\kappa}^{-\epsilon}_{n\ell t,\tau}}\hat{R}_{nt}R_{nt}\right],$$

- where we determined w_{it} and $\hat{\kappa}^\epsilon_{nit,\tau}$ above

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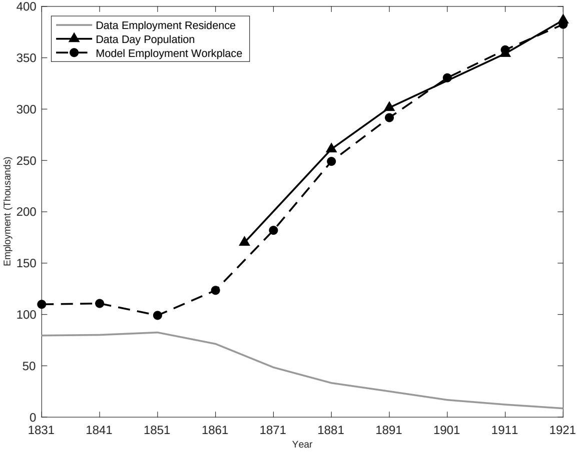
- where we determined w_{it} and $\hat{\kappa}^{\epsilon}_{nit,\tau}$ above
- Using these solutions ($\hat{w}_{it}$), we can determine changes in employment by workplace ($\hat{L}_{it}$) for $\tau < t$ from commuter market clearing

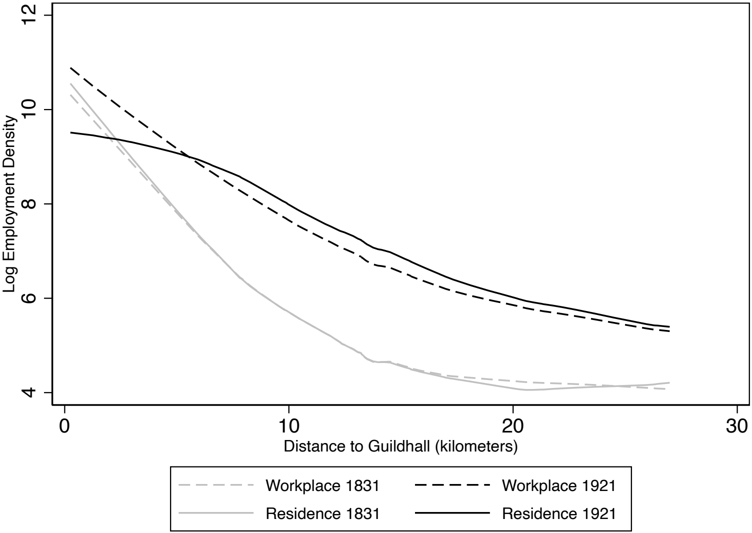
$$\hat{L}_{it}L_{it} = \sum_{n\in\mathbb{N}} \frac{\lambda^C_{nit|n}\hat{w}^{\epsilon}_{it}\hat{\kappa}^{-\epsilon}_{nit,\tau}}{\sum_{\ell\in\mathbb{N}}\lambda^C_{n\ell t|n}\hat{w}^{\epsilon}_{\ell t}\hat{\kappa}^{-\epsilon}_{n\ell t,\tau}}\hat{R}_{nt}R_{nt}.$$

Workplace Employment (Step 4)



- Calibrate $\kappa = 5.25$ by minimizing sum of squared deviations in day population in model and data for 1881, 1891 and 1991
- Model captures historical commuting patterns

Historical Workplace and Residence Employment



Productivity, Amenities and Agglomeration

- Baseline quantitative analysis holds in an entire class of models
- Now consider extension canonical urban model to recover productivity and amenities and estimate agglomeration forces
  - Freely traded and non-traded consumption goods
  - Perfect competition and Cobb-Douglas preferences and technologies
- Supply of floor space: $H_{nt} = hQ_{nt}^{\mu}K_n$

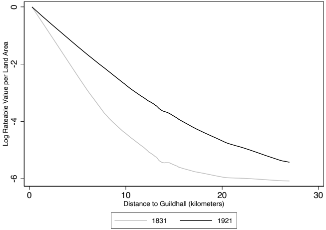
$$Q_{nt} = \left(\frac{\mathbb{Q}_{nt}}{hK_n}\right)^{\frac{1}{1+\mu}}, \qquad H_{nt} = hK_n\left(\frac{\mathbb{Q}_{nt}}{hK_n}\right)^{\frac{\mu}{1+\mu}}.$$

- Composite traded productivity and composite amenities

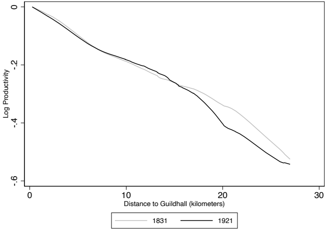
$$\mathbb{A}_{nt}^{T} = w_{nt}^{\beta^L} Q_{nt}^{\beta^H},$$

$$\hat{\lambda}_{nt}^{R}\lambda_{nt}^{R} = \frac{\lambda_{nt}^{R}\hat{\mathbb{B}}_{nt}^{\epsilon}\hat{Q}_{nt}^{-\epsilon(1-\alpha)}\widehat{RMA}_{nt}^{\epsilon}}{\sum_{k\in\mathbb{N}}\lambda_{kt}^{R}\hat{\mathbb{B}}_{kt}^{\epsilon}\hat{Q}_{kt}^{-\epsilon(1-\alpha)}\widehat{RMA}_{kt}^{\epsilon}}, \quad \widehat{RMA}_{nt} = \left[\sum_{\ell\in\mathbb{N}}\lambda_{n\ell t|n}^{R}\hat{w}_{\ell t}^{\epsilon}\hat{\kappa}_{n\ell}^{-\epsilon}\right]^{\frac{1}{\epsilon}}.$$

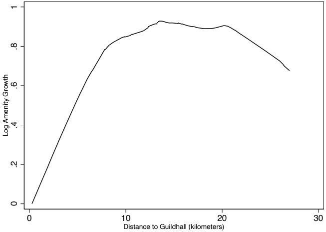
Productivity and Amenities



(a) Rateable Value per Land Area



(b) Productivity



(c) Amenity Growth 1831-1921

Estimating Agglomeration Forces

$$\ln \hat{\mathbb{A}}_{nt}^{T} = \varsigma^{L} + \eta^{L} \ln \hat{L}_{nt} + \ln \hat{a}_{nt},$$
$$\ln \hat{\mathbb{B}}_{nt} = \varsigma^{R} + \eta^{R} \ln \hat{R}_{nt} + \ln \hat{b}_{nt},$$

	(1)	(2)	(3)	(4)
	$\ln \widehat{\mathbb{A}}_{nt}^{T}$	$\ln \widehat{\mathbb{B}}_{nt}$	$\ln \widehat{\mathbb{A}}_{nt}^{T}$	$\ln \widehat{\mathbb{B}}_{nt}$
$\ln \widehat{L}_{nt}$	0.148^{***}	-	0.086^{**}	-
	(0.027)		(0.037)	
$\ln \widehat{R}_{nt}$	-	0.248^{***}	-	0.172^{***}
		(0.023)		(0.031)
$\ln L_{nt}$	0.029^{*}	-	0.011	-
	(0.017)		(0.017)	
$\ln R_{nt}$	-	0.033	-	-0.015
		(0.024)		(0.027)
$\ln K_{n}$	0.078^{***}	-0.067	0.092^{***}	-0.056
	(0.020)	(0.042)	(0.023)	(0.038)
$\mathbb{I}_{n}^{\text{LCC}}$	-0.112^{**}	0.085	-0.033	0.252^{***}
	(0.048)	(0.074)	(0.060)	0.089
First-stage F-statistic	-	-	11.26	12.76
Kleibergen-Paap (p-value)	-	-	0.000	0.000
Hansen-Sargen (p-value)	-	-	0.416	0.483
Estimation	OLS	OLS	IV	IV
Observations	99	99	99	99
R-squared	0.428	0.648	-	-

Counterfactuals

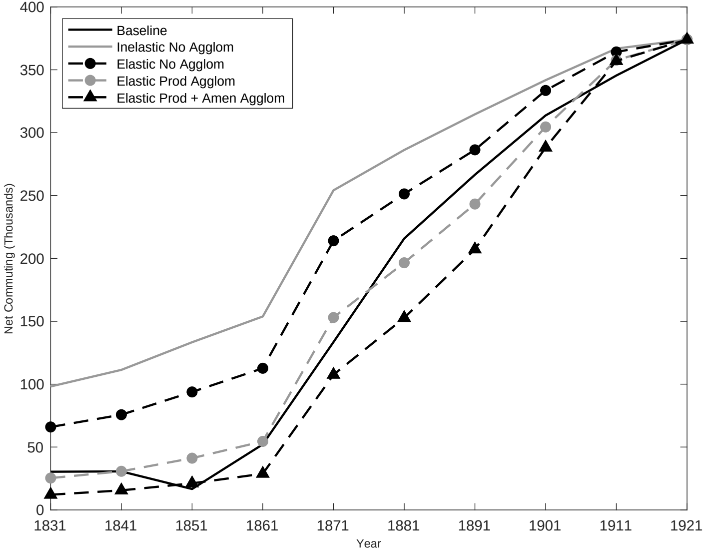
- Undertake counterfactuals
  - Removal of entire railway network
  - Removal of underground railway network
  - Removal railway lines constructed from 1911-1921

- We undertake these counterfactuals under a range of assumptions about the floor space supply elasticity and agglomeration forces

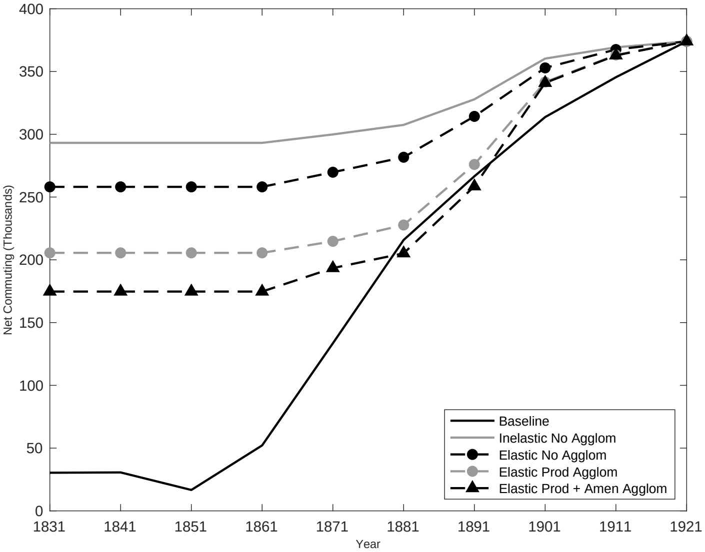
- Assume population mobility with the rest of the economy with elasticity of labor supply determined by ϵ

- We compare the change in the net present value of land and buildings to historical estimates of construction costs
  - Overground railways: £60,000 per mile
  - Cut-and-cover underground railways: £355,000 per mile
  - Bored-tube underground railways: £555,000 per mile

Rail Counterfactuals



Underground Counterfactuals



All Rail Counterfactual

	(1)	(2)	(3)	(4)
Floor Space Supply Elasticity	$\mu = 0$	$\mu = 1.83$	$\mu = 1.83$	$\mu = 1.83$
Production Agglomeration Force	$\eta^L = 0$	$\eta^L = 0$	$\eta^L = 0.086$	$\eta^L = 0.086$
Residential Agglomeration Force	$\eta^R = 0$	$\eta^R = 0$	$\eta^R = 0$	$\eta^R = 0.172$
Removing the Entire Overground and Underground Railway Network				
Economic Impact				
Rateable Value	$-£8.24$m	$-£15.55$m	$-£20.78$m	$-£35.07$m
NPV Rateable Value (3 percent)	$-£274.55$m	$-£518.26$m	$-£692.76$m	$-£1,169.05$m
NPV Rateable Value (5 percent)	$-£164.73$m	$-£310.96$m	$-£415.66$m	$-£701.43$m
Construction Costs				
Cut-and-Cover Underground	$-£9.96$m			
Bored-tube Underground	$-£22.90$m			
Overground Railway	$-£33.19$m			
Total All Railways	$-£66.05$m			
Ratio Economic Impact / Construction Cost				
$\frac{\text{NPV Rateable Value (3 percent)}}{\text{Construction Cost}}$	4.16	7.85	10.49	17.70
$\frac{\text{NPV Rateable Value (5 percent)}}{\text{Construction Cost}}$	2.49	4.71	6.29	10.62

Underground Rail Counterfactual

Removing the Entire Underground Railway Network				
Economic Impact				
Rateable Value	$-£2.65$m	$-£6.21$m	$-£8.22$m	$-£14.16$m
NPV Rateable Value (3 percent)	$-£88.46$m	$-£206.87$m	$-£274.05$m	$-£471.85$m
NPV Rateable Value (5 percent)	$-£53.08$m	$-£124.12$m	$-£164.43$m	$-£283.11$m
Construction Costs				
Cut-and-Cover Underground		$-£9.96$m		
Bored-tube Underground		$-£22.90$m		
Total All Underground		$-£32.86$m		
Ratio Economic Impact / Construction Cost				
$\frac{\text{NPV Rateable Value (3 percent)}}{\text{Construction Cost}}$	2.69	6.30	8.34	14.36
$\frac{\text{NPV Rateable Value (5 percent)}}{\text{Construction Cost}}$	1.62	3.78	5.00	8.62

Conclusion

- Modern metropolitan areas involve immense concentrations of economic activity and the transport of millions of people each day
- We provide evidence on the role of the separation of workplace and residence for these large metropolitan areas using the innovation of steam railways and disaggregated data for London from 1801-1921
- We show that our model is able to account quantitatively for the observed changes in the spatial organization of economic activity
  - Observed reorganization of economic activity implies substantial agglomeration forces in production and residence
- Undertaking counterfactuals for removing the entire railway network and only the underground network, we find
  - Substantial effects of the change in commuting costs alone
  - Commuting into City of London falls from $> 370,000$ to $< 100,000$
  - With endogenous supply of floor space and agglomeration forces, railway accounts for around half of Greater London's population growth
  - Changes in rateable values exceed construction costs

Thank You