The Making of the Modern Metropolis: Evidence from London

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  - Immense concentrations of economic activity (London : 8.4 million)
  - 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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- 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 ▸ pop-def

- 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) ▸ day-def
  - Historical business directories (1841 onwards)

- Rateable value data ▸ defn
  - 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
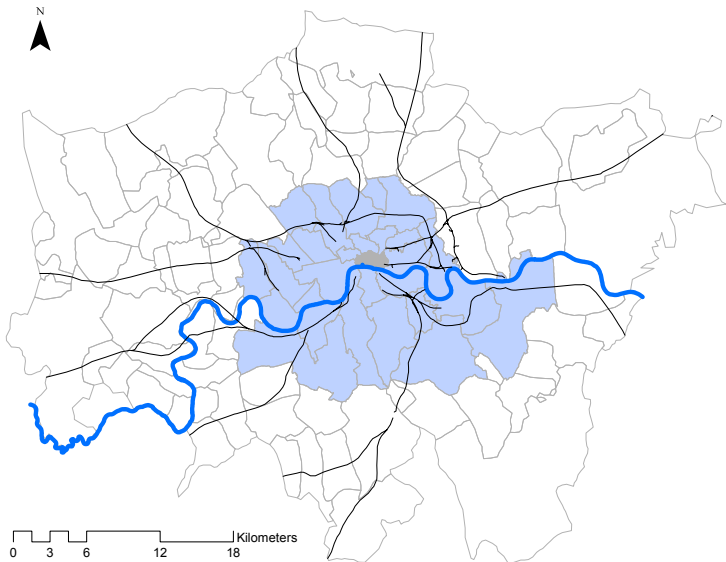
Administrative Units

- Home Counties 1921 (black), Greater London Authority (GLA) (red), London County Council (LCC) (purple) and City of London (green)
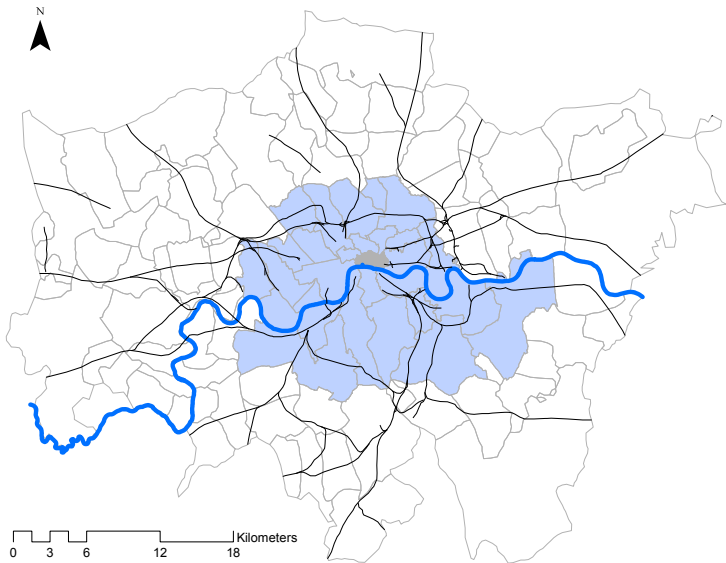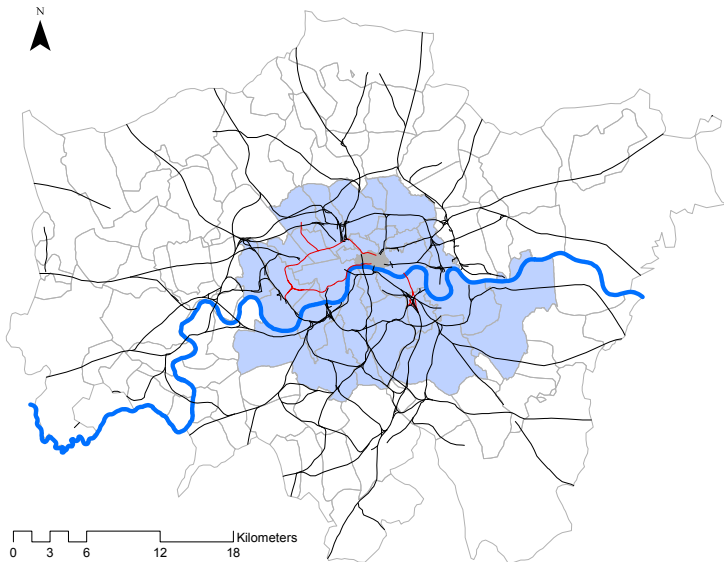- Borough and parish boundaries
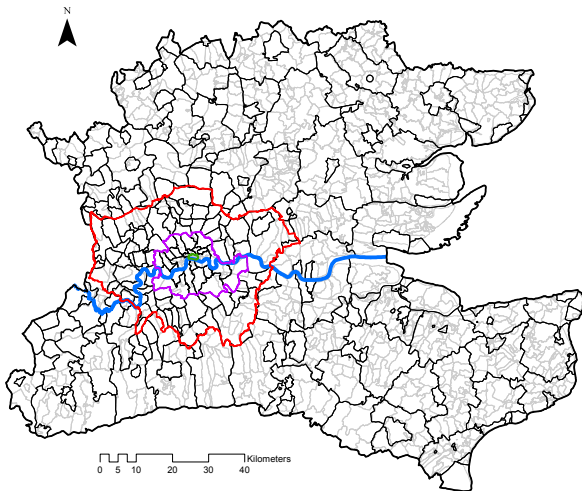
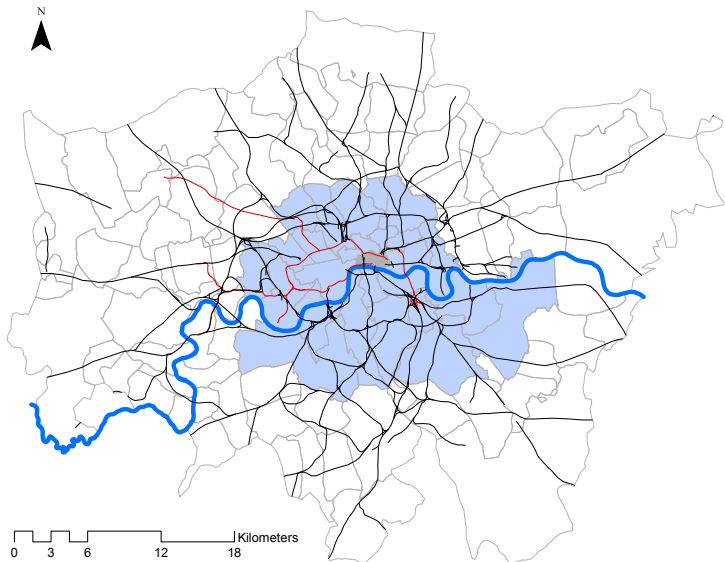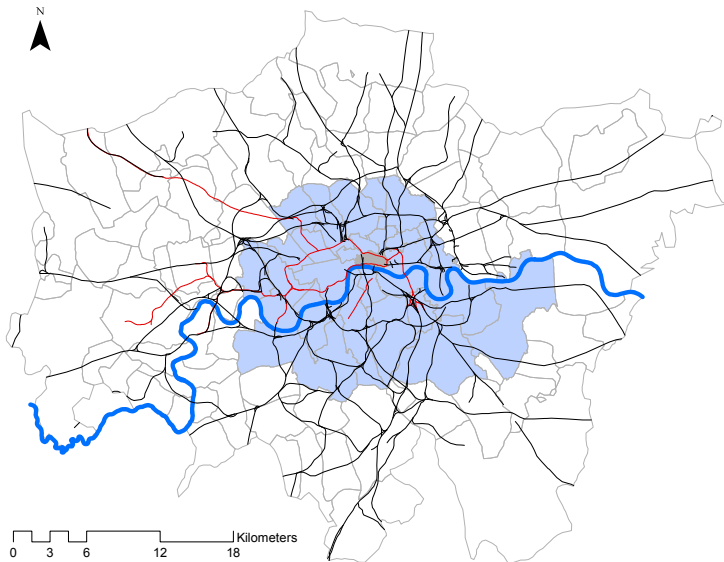Rail Network 1841
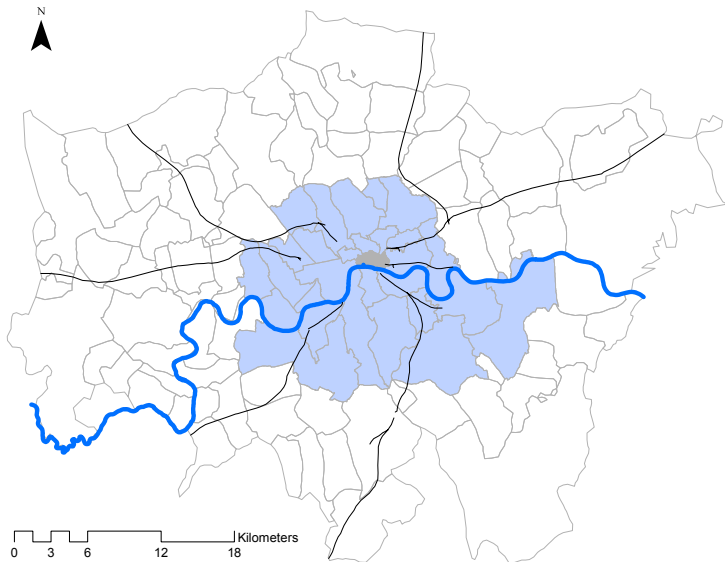
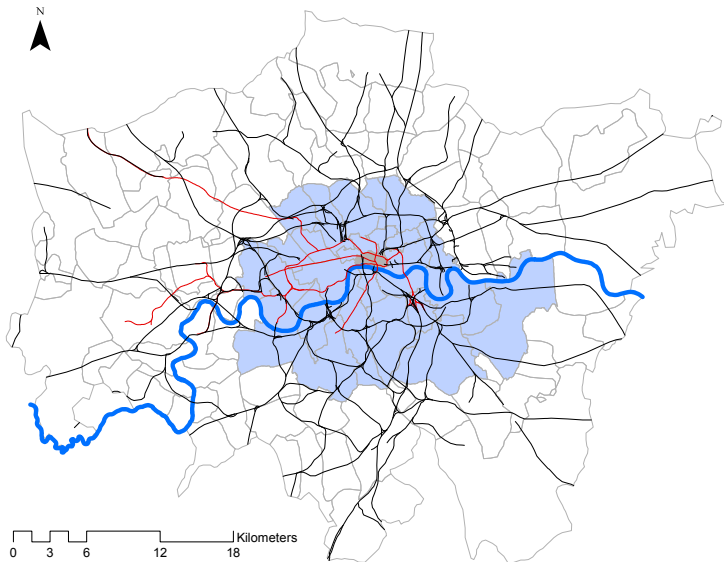# Rail Network 1851

Rail Network 1861

Rail Network 1871

Rail Network 1881

Rail Network 1891

Rail Network 1901

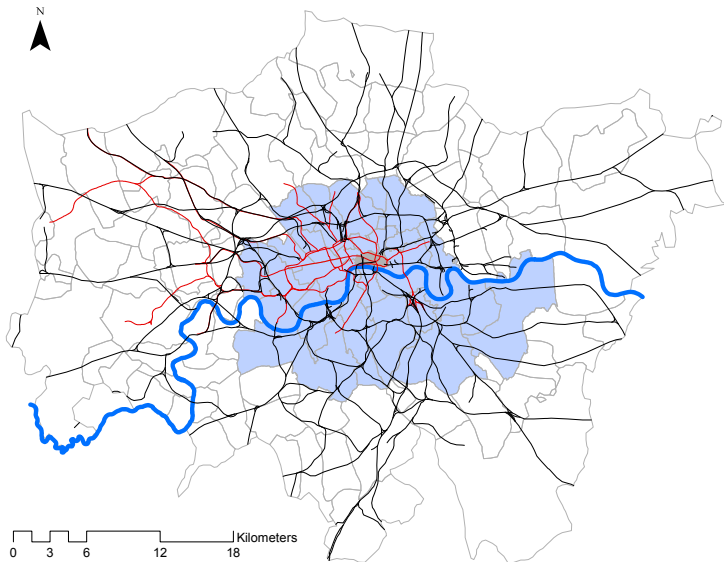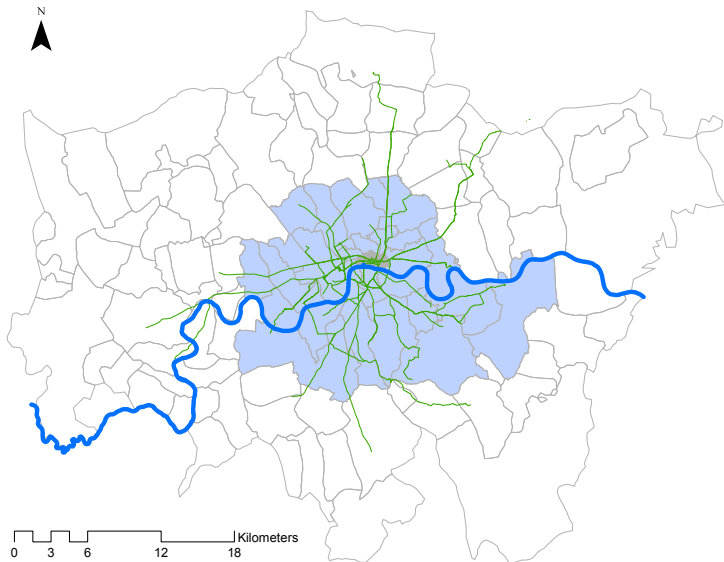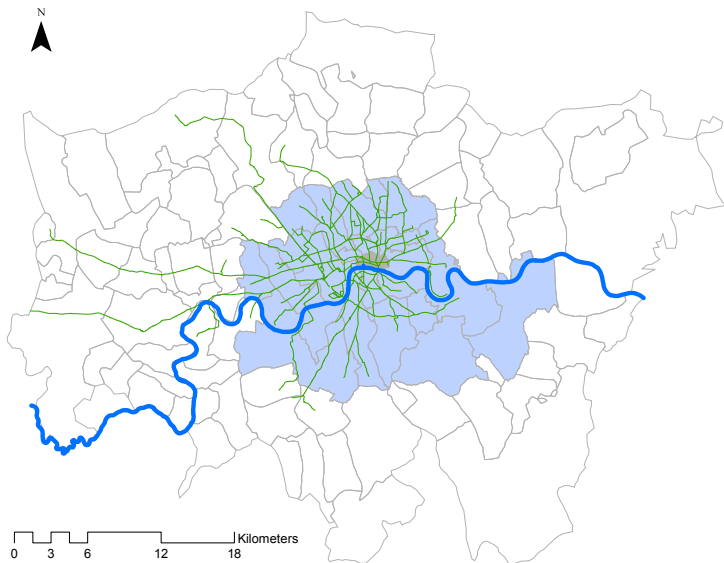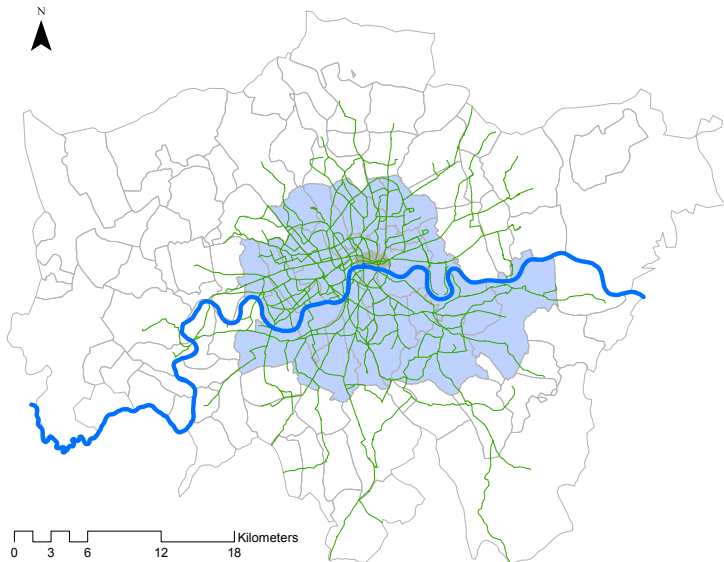# Rail Network 1911
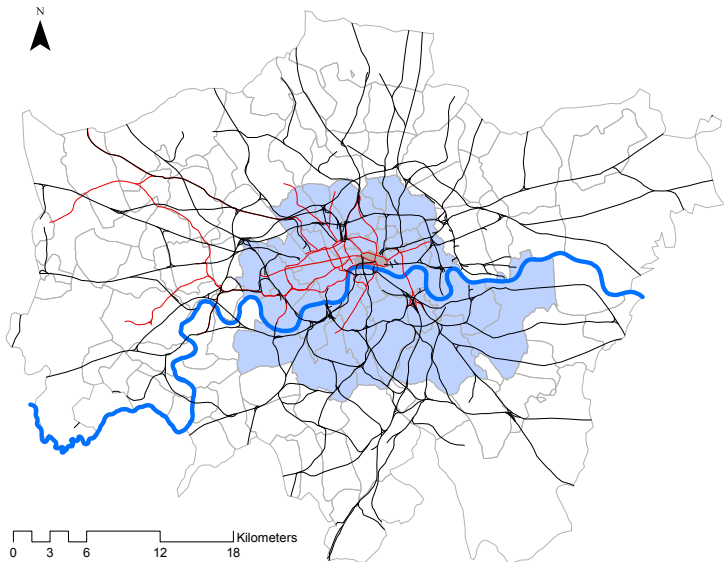
Rail Network 1921

Horse Omnibus Network 1839

Horse Omnibus/Tram Network 1881

Omnibus/Tram Network 1921

Outline

- Data

- Reduced-form evidence

- Quantitative Model

- Conclusions

Residential (Night) Population

City of London

Greater London Area

Year

Year
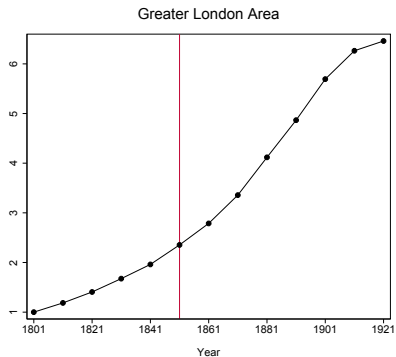
Day and Night Population

day-def   pop-def   usevidence
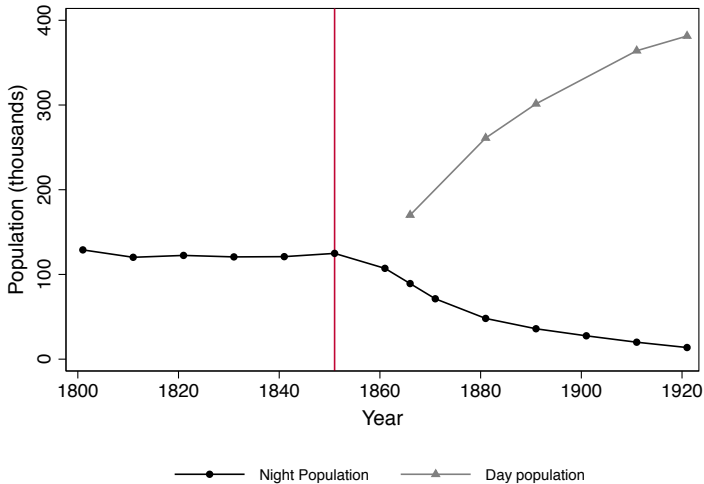
City's Share of GLA Rateable Value
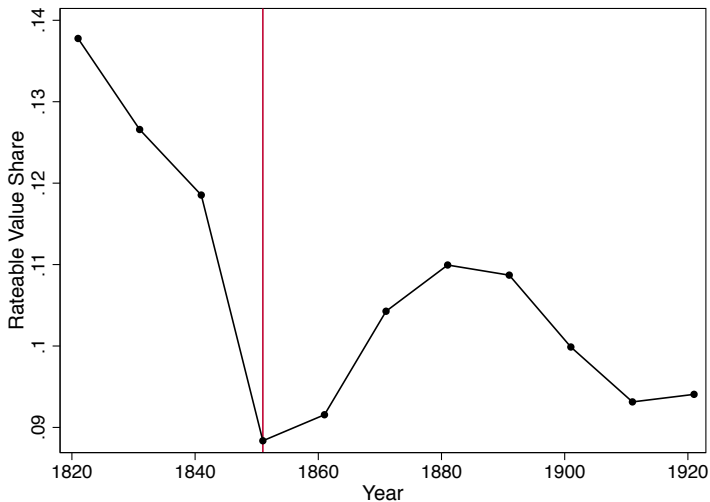
Difference-in-Differences Estimates

- 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 ▸ more

- 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
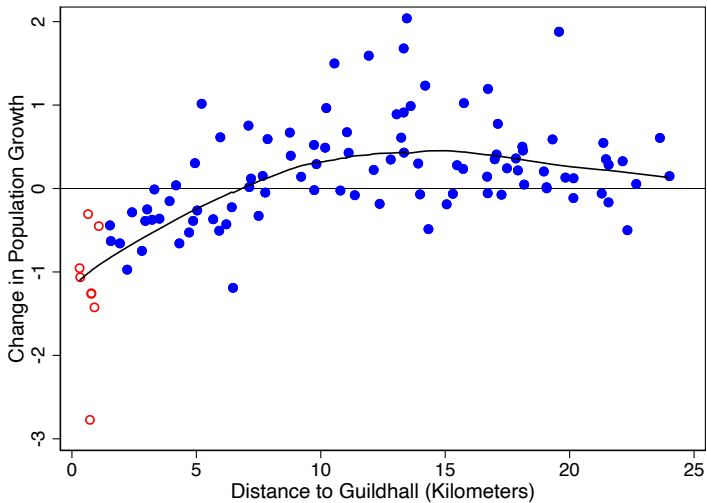
Model Outline

- 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_nH_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 ($\lambda_{nit|n}^{C}$, 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 $t = 1921$

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

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

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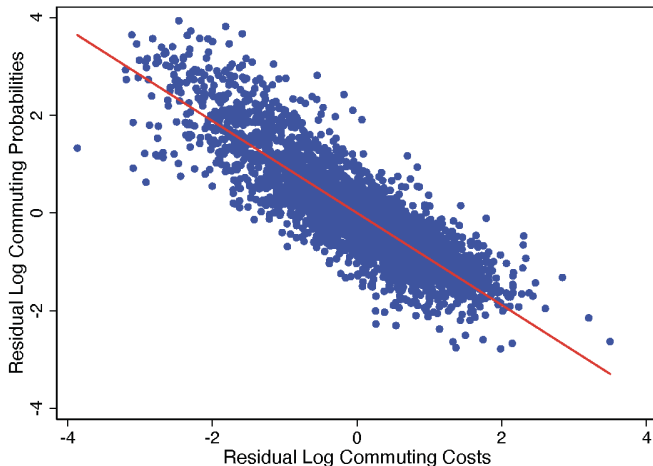
- Approx log linear relationship between commuting probabilities and commuting costs conditional on residence and workplace fixed effects

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

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

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

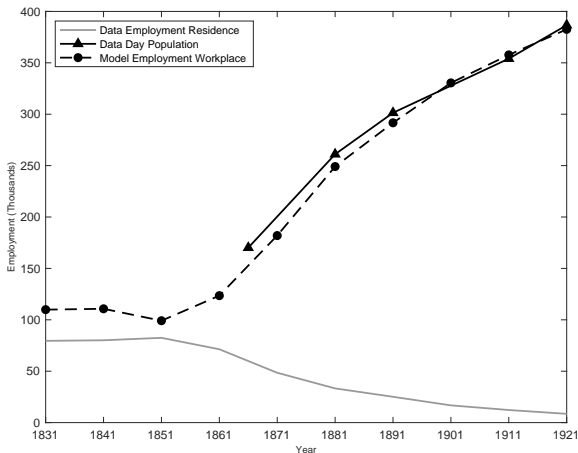## Estimating Historical Workplace Employment (Step 4)

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

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

- 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 ▸ Poole1861 ▸ Poole1901

Historical Workplace and Residence Employment
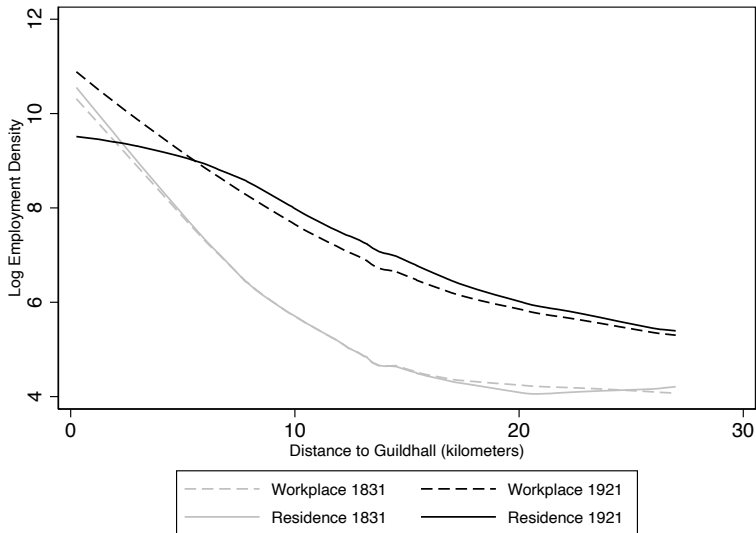
Productivity, Amenities and Agglomeration

- 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: $H_{nt} = h Q_{nt}^{\mu} K_n$

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

- 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
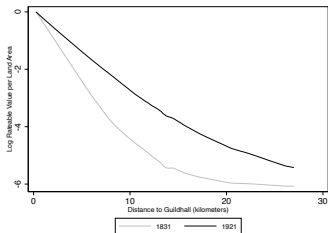
(a) Rateable Value per Land Area
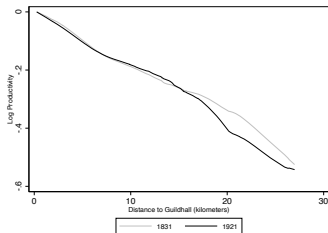
(b) Productivity
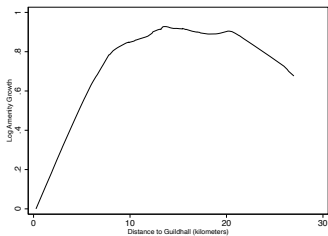
(c) Amenity Growth 1831-1921

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)
	$\ln \hat{\mathbb{A}}_{nt}^T$	$\ln \hat{\mathbb{B}}_{nt}$	$\ln \hat{\mathbb{A}}_{nt}^T$	$\ln \hat{\mathbb{B}}_{nt}$
$\ln \hat{L}_{nt}$	0.148^{***}	-	0.086^{**}	-
	(0.027)		(0.037)	
$\ln \hat{R}_{nt}$	-	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 (▸ more)
  - 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
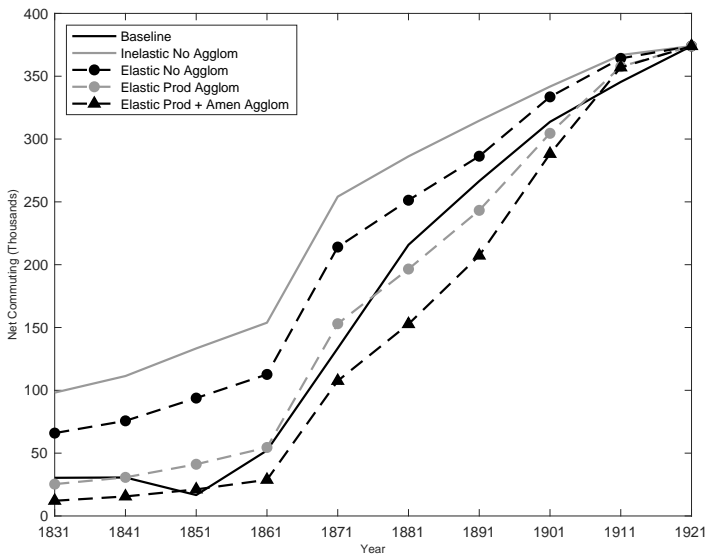
Underground Counterfactuals
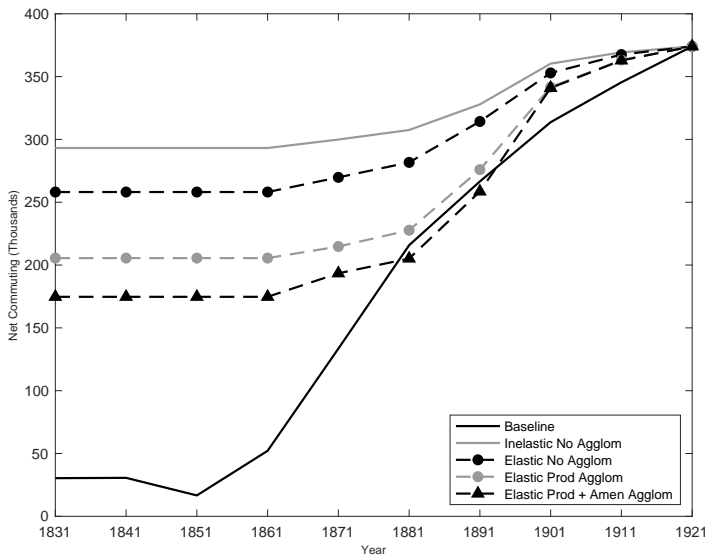
All Rail Counterfactual

	(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