Quantitative Urban Models

Stephen J. Redding
Princeton University, NBER and CEPR

Motivation

- Complexity of modelling spatial interactions implies that theoretical urban literature has traditionally focused on stylized settings
  - Monocentric city
  - Symmetric locations
  - Hard to connect directly with observed data

Motivation

- Complexity of modelling spatial interactions implies that theoretical urban literature has traditionally focused on stylized settings
  - Monocentric city
  - Symmetric locations
  - Hard to connect directly with observed data

- More recent research has developed quantitative urban models
  - Capture first-order features of the data, such as many locations, heterogeneous productivity and amenities, and transport networks
  - Small number of structural parameters to estimate
  - Sufficiently tractable to permit realistic policy counterfactuals (e.g. construction of a new subway line between one location and another)

Motivation

- Complexity of modelling spatial interactions implies that theoretical urban literature has traditionally focused on stylized settings
  - Monocentric city
  - Symmetric locations
  - Hard to connect directly with observed data

- More recent research has developed quantitative urban models
  - Capture first-order features of the data, such as many locations, heterogeneous productivity and amenities, and transport networks
  - Small number of structural parameters to estimate
  - Sufficiently tractable to permit realistic policy counterfactuals (e.g. construction of a new subway line between one location and another)

- Focus today on quantitative urban models of internal city structure
  - Part of a larger literature on quantitative trade and spatial models (e.g. models of systems of cities)

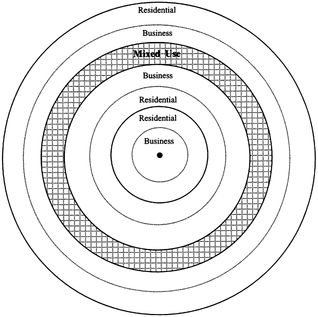
Traditional Theoretical Literature

- Alonso-Muth-Mills monocentric city model is the traditional theoretical model of internal city structure
  - All employment concentrated in Central Business District (CBD)

Traditional Theoretical Literature

- Alonso-Muth-Mills monocentric city model is the traditional theoretical model of internal city structure
  - All employment concentrated in Central Business District (CBD)

- Path-breaking theoretical models of non-monocentric cities
  - Fujita and Ogawa (1982) (linear city)
  - Lucas and Rossi-Hansberg (2002) (symmetric circular city)



Quantitative Urban Model

- Tractable model of the equilibrium distribution of residents, workers and land rents across locations within a city

- Rationalize observed data on thousands of city blocks
  - Employment by workplace and by residence
  - Or data on bilateral commuting flows
  - Land rents
  - Bilateral transport network and travel times

- Capture empirically relevant differences across locations in
  - Productivity
  - Amenities
  - Supply of floor space
  - Transportation infrastructure

- Endogenous agglomeration and dispersion forces
  - Production externalities
  - Residential externalities
  - Supply of floor space
  - Commuting costs

Applications

- Consider two different applications of quantitative urban models
- Structural estimation of agglomeration and dispersion forces
  - Ahlfeldt, Gabriel, Stephen Redding, Daniel Sturm and Nikolaus Wolf (2015) "The Economics of Density: Evidence from the Berlin Wall," *Econometrica*, 83(6), 2015, 2127-2189.
- Quantify the impact on transport infrastructure on the spatial distribution of economic activity within cities
  - Heblich, Stephan, Stephen Redding and Daniel Sturm (2020) "The Making of the Modern Metropolis: Evidence from London," *Quarterly Journal of Economics*, forthcoming.

Applications

- Consider two different applications of quantitative urban models
- Structural estimation of agglomeration and dispersion forces
  - Ahlfeldt, Gabriel, Stephen Redding, Daniel Sturm and Nikolaus Wolf (2015) "The Economics of Density: Evidence from the Berlin Wall," *Econometrica*, 83(6), 2015, 2127-2189.
- Quantify the impact on transport infrastructure on the spatial distribution of economic activity within cities
  - Heblich, Stephan, Stephen Redding and Daniel Sturm (2020) "The Making of the Modern Metropolis: Evidence from London," *Quarterly Journal of Economics*, forthcoming.
- Model of goods trade and commuting within and across cities
  - Monte, Ferdinando, Stephen Redding and Esteban Rossi-Hansberg (2018) "Commuting, Migration and Local Employment Elasticities," *American Economic Review*, 108(12), 3855-3890.

The Economics of Density: Evidence from the Berlin Wall

Motivation

- Economic activity is highly unevenly distributed across space:
  - The existence of cities (e.g. 19 cities worldwide had a population greater than 10 million in 2007)
  - Concentrations of economic functions within cities (e.g. advertising agencies in mid-town Manhattan)

- A key research objective is determining the strength of agglomeration and dispersion forces
  - Agglomeration: increasing returns
  - Dispersion: land scarcity and commuting costs

- Determining the magnitude of these forces is central to a host of economic and policy issues:
  - Productivity advantages of cities
  - Cost-benefit analyzes of transport infrastructure
  - Effects of property taxation and regional policy

Empirical Challenges

- Economic activities often cluster together because of shared locational fundamentals
  - What are the roles of agglomeration/dispersion forces versus shared natural advantages?
  - Historical natural advantages can have long-lived effects through for example sunk costs or coordination effects
- One approach regresses productivity, wages or employment on the density of economic activity
  - Third variables can affect both productivity and wages and density
  - Difficult to find instruments that only affect productivity or wages through density (with a few exceptions)
- Little evidence on the spatial scale of agglomeration forces or separating them from congestion forces
- Difficult to find sources of exogenous variation in the surrounding concentration of economic activity

This Paper

- We develop a quantitative model of city structure to determine agglomeration and dispersion forces, while also allowing empirically-relevant variation in:
  - Production locational fundamentals
  - Residential locational fundamentals
  - Transportation infrastructure

- We combine the model with data for thousands of city blocks in Berlin in 1936, 1986 and 2006 on:
  - Land prices
  - Workplace employment
  - Residence employment

- We use the division of Berlin in the aftermath of the Second World War and its reunification in 1989 as a source of exogenous variation in the surrounding concentration of economic activity

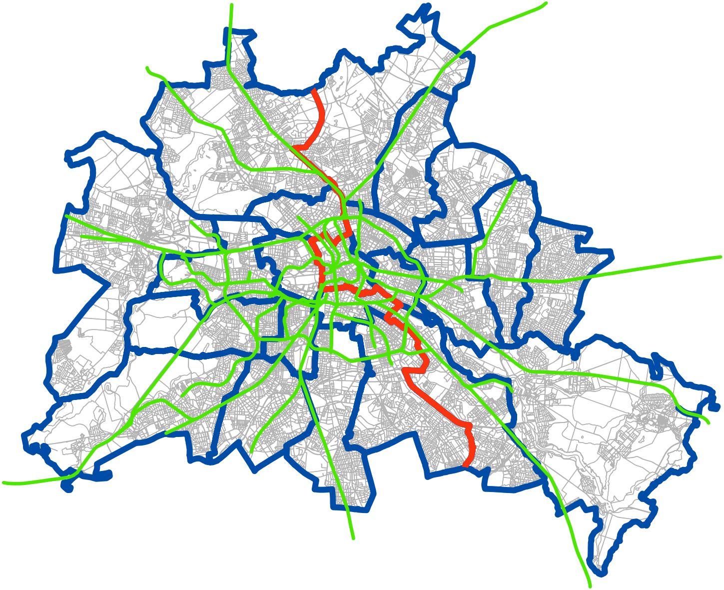
Road Map

- Historical Background
- Theoretical Model
- Data
- Reduced-Form Evidence
- Structural Estimation

Historical Background

- A protocol signed during the Second World War organized Germany into American, British, French and Soviet occupation zones
- Although 200km within the Soviet zone, Berlin was to be jointly occupied and organized into four occupation sectors:
  - Boundaries followed pre-war district boundaries, with the same East-West orientation as the occupation zones, and created sectors of roughly equal pre-war population (prior to French sector)
  - Protocol envisioned a joint city administration ("Kommandatura")
- Following the onset of the Cold War
  - East and West Germany founded as separate states and separate city governments created in East and West Berlin in 1949
  - The adoption of Soviet-style policies of command and control in East Berlin limited economic interactions with West Berlin
  - To stop civilians leaving for West Germany, the East German authorities constructed the Berlin Wall in 1961

The Division of Berlin



Model Setup

- We consider a city embedded within a larger economy, which provides a reservation level of utility $(\bar{U})$
- The city consists of a set of discrete blocks indexed by i, with supply of floor space depending on the density of development (φ_i)
- There is a single final good which is costlessly traded and is chosen as the numeraire
- Markets are perfectly competitive
- Workers choose a block of residence, a block of employment, and consumption of the final good and floor space to max utility
- Firms choose a block of production and inputs of labor and floor space to max profits
- Floor space within each block optimally allocated between residential and commercial use
- Productivity depends on fundamentals (a_i) & spillovers (Υ_i)
- Amenities depend on fundamentals (b_i) & spillovers (Ω_i)
- Workers face commuting costs

Consumption

- Utility for worker ω residing in block i and working in block j:

$$U_{ij\omega} = \frac{B_i z_{ij\omega}}{d_{ij}} \left(\frac{c_{ij}}{\beta}\right)^{\beta} \left(\frac{\ell_{ij}}{1-\beta}\right)^{1-\beta}, \qquad 0 < \beta < 1,$$

  - Consumption of the final good (c_{ij}), chosen as numeraire ($p_i = 1$)
  - Residential floor space (ℓ_{ij})
  - Residential amenity B_i
  - Commuting costs d_{ij}
  - Idiosyncratic shock $z_{ij\omega}$ that captures idiosyncratic reasons for a worker living in block i and working in block j
- Indirect utility

$$U_{ij\omega} = \frac{z_{ij\omega} B_i w_j Q_i^{\beta-1}}{d_{ij}},$$

- The idiosyncratic shock to worker productivity is drawn from a Fréchet distribution:

$$F(z_{ij\omega}) = e^{-T_i E_j z_{ij\omega}^{-\epsilon}}, \qquad T_i, E_j > 0, \ \epsilon > 1,$$

Commuting Decisions

- Probability worker chooses to live in block i and work in block j is:

$$\pi_{ij} = \frac{T_i E_j \left(d_{ij} Q_i^{1-\beta} \right)^{-\epsilon} \left(B_i w_j \right)^{\epsilon}}{\sum_{r=1}^{S} \sum_{s=1}^{S} T_r E_s \left(d_{rs} Q_r^{1-\beta} \right)^{-\epsilon} \left(B_r w_s \right)^{\epsilon}} \equiv \frac{\Phi_{ij}}{\Phi}.$$

- Residential and workplace choice probabilities

$$\pi_{Ri} = \sum_{j=1}^{S} \pi_{ij} = \frac{\sum_{j=1}^{S} \Phi_{ij}}{\Phi}, \qquad \pi_{Mj} = \sum_{i=1}^{S} \pi_{ij} = \frac{\sum_{i=1}^{S} \Phi_{ij}}{\Phi}.$$

- Conditional on living in block i, the probability that a worker commutes to block j follows a gravity equation:

$$\pi_{ij|i} = \frac{E_j \left(w_j / d_{ij} \right)^{\epsilon}}{\sum_{s=1}^{S} E_s \left(w_s / d_{is} \right)^{\epsilon}},$$

Commuting Market Clearing

- In the model, workplace employment in block j equals the sum across all blocks i of residence employment times the probability of commuting from i to j:

$$H_{Mj} = \sum_{i=1}^{S} \frac{\left(w_j / d_{ij}\right)^{\epsilon}}{\sum_{s=1}^{S} \left(w_s / d_{is}\right)^{\epsilon}} H_{Ri}, \qquad d_{ij} = e^{\kappa \tau_{ij}}.$$

- In our data, we observe workplace employment (H_{Mj}), residence employment (H_{Ri}) and bilateral travel times (τ_{ij} and hence d_{ij})
- Given these observed data, we can solve for the wages for which the observed values of workplace and residence employment are an equilibrium of the model
- Commuting equilibrium above provides a system of S equations that determines unique values of the S unknown wages $\{w_j\}$

Consumer Equilibrium

- Expected utility

$$\mathbb{E}\left[U\right] = \gamma \left[\sum_{r=1}^{S} \sum_{s=1}^{S} T_r E_s \left(d_{rs} Q_r^{1-\beta}\right)^{-\epsilon} \left(B_r w_s\right)^{\epsilon}\right]^{1/\epsilon} = \bar{U},$$

- Residential amenities (B_i) from residential choice probabilities:

$$\frac{B_i T_i^{1/\epsilon}}{\bar{U}/\gamma} = \left(\frac{H_{Ri}}{H}\right)^{\frac{1}{\epsilon}} \frac{Q_i^{1-\beta}}{W_i^{1/\epsilon}},$$

$$W_i = \sum_{s=1}^{S} E_s \left(w_s / d_{is}\right)^{\epsilon}, \qquad d_{is} = e^{\kappa \tau_{is}}.$$

- Residential amenities are influenced by both fundamentals (b_i) and spillovers (Ω_i)

$$b_i = B_i \Omega_i^{-\eta}, \qquad \Omega_i \equiv \left[\sum_{s=1}^{S} e^{-\rho \tau_{is}} \left(\frac{H_{Rs}}{K_s}\right)\right].$$

Production

- A single final good (numeraire) is produced under conditions of perfect competition, constant returns to scale and zero trade costs with a larger economy:

$$X_j = A_j \left(H_{Mj}\right)^{\alpha} \left(\theta_j L_j\right)^{1-\alpha}, \qquad 0 < \alpha < 1,$$

- H_{Mj} is workplace employment
- L_j is total floor space
- θ_j is the fraction of floor space allocated to commercial use
- Productivity (A_j) depends on fundamentals (a_j) and spillovers (Υ_j):

$$A_j = a_j \Upsilon_j^{\lambda}, \qquad \Upsilon_j \equiv \left[\sum_{s=1}^{S} e^{-\delta \tau_{is}} \left(\frac{H_{Ms}}{K_s} \right) \right],$$

- δ is the rate of decay of spillovers
- λ captures the relative importance of spillovers

Producer Equilibrium

- Firms choose a block of production, effective employment and commercial land use to maximize profits taking as given goods and factor prices, productivity and the locations of other firms/workers
- Productivity (A_j) from profit maximization and zero profits:

$$q_j = (1-\alpha)\left(\frac{\alpha}{w_j}\right)^{\frac{\alpha}{1-\alpha}} A_j^{\frac{1}{1-\alpha}}.$$

- Production fundamentals (a_j) and spillovers (Υ_j) follow from the production technology:

$$a_j = A_j \Upsilon_j^{-\lambda}, \qquad \Upsilon_j \equiv \left[\sum_{s=1}^{S} e^{-\delta\tau_{is}}\left(\frac{H_{Ms}}{K_s}\right)\right]^{-\lambda}.$$

Land Market Clearing

- Utility max and pop mobility imply demand residential floor space:

$$(1-\theta_i)L_i = \frac{H_{Ri}\bar{U}^{\frac{1}{1-\beta}}}{\beta^{\frac{\beta}{1-\beta}} B_i^{\frac{1}{1-\beta}} \bar{v}_i^{\frac{\beta}{1-\beta}}}.$$

- Profit max and zero profits imply demand commercial floor space:

$$\theta_i L_i = H_{Mi}\left(\frac{w_i}{\alpha A_i}\right)^{\frac{1}{1-\alpha}}.$$

- Floor space L supplied by a competitive construction sector using geographic land K and capital M as inputs

$$L_i = \varphi_i K_i^{1-\mu}, \qquad \varphi_i = M_i^{\mu},$$

- Density of development (φ_i) from land market clearing:

$$\varphi_i = \frac{L_i}{K_i^{1-\mu}} = \frac{(1-\theta_i)L_i + \theta_i L_i}{K_i^{1-\mu}}$$

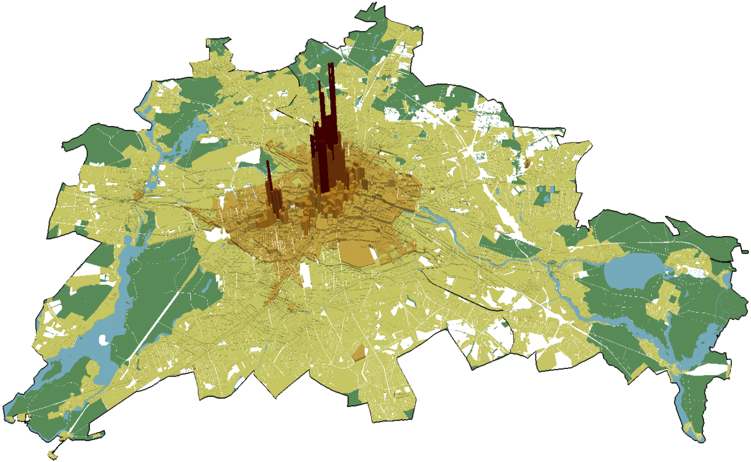
Qualitative Predictions for Division

- Firms in West Berlin cease to benefit from production externalities from employment centers in East Berlin
  - Reduces productivity, land prices and employment
- Firms in West Berlin lose access to flows of commuters from residential concentrations in East Berlin
  - Increases the wage required to achieve a given effective employment, reducing land prices and employment
- Residents in West Berlin lose access to employment opportunities and consumption externalities from East Berlin
  - Reduces expected worker income, land prices and residents
- The impact is greater for parts of West Berlin closer to employment and residential concentrations in East Berlin
- Employment and residents reallocate within West Berlin and the larger economy until wages and land prices adjust such that:
  - Firms make zero profits in each location with positive production
  - Workers are indifferent across all locations with positive residents
  - No-arbitrage between commercial and residential land use

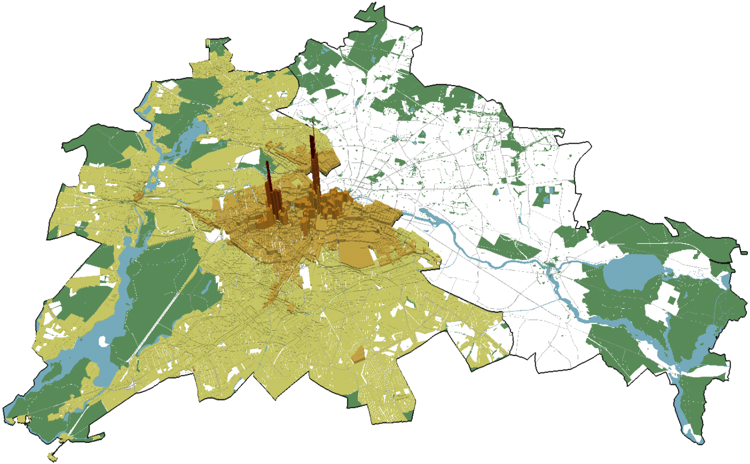
Data

- Data on land prices, workplace employment, residence employment and bilateral travel times
- Data for Greater Berlin in 1936 and 2006
- Data for West Berlin in 1986
- Data at the following levels of spatial aggregation:
  - Pre-war districts ("Bezirke"), 20 in Greater Berlin, 12 in West Berlin
  - Statistical areas ("Gebiete"), around 90 in West Berlin
  - Statistical blocks, around 9,000 in West Berlin
- Land prices: official assessed land value of a representative undeveloped property or the fair market value of a developed property if it were not developed
- Geographical Information Systems (GIS) data on:
  - land area, land use, building density, proximity to U-Bahn (underground) and S-Bahn (suburban) stations, schools, parks, lakes, canals and rivers, Second World War destruction, location of government buildings and urban regeneration programs

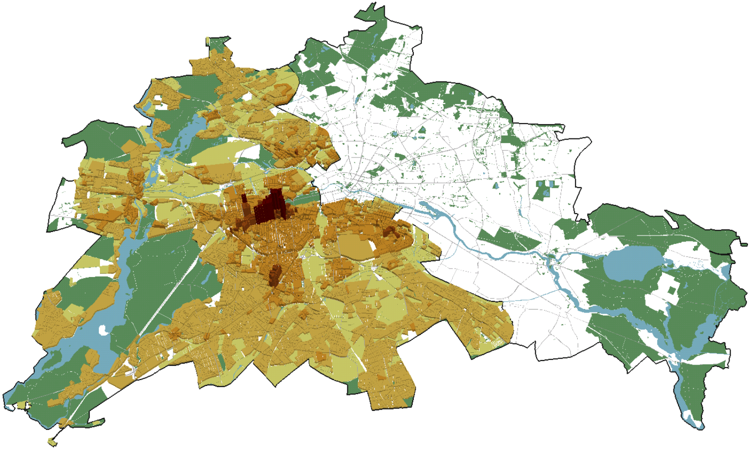
Berlin 1936



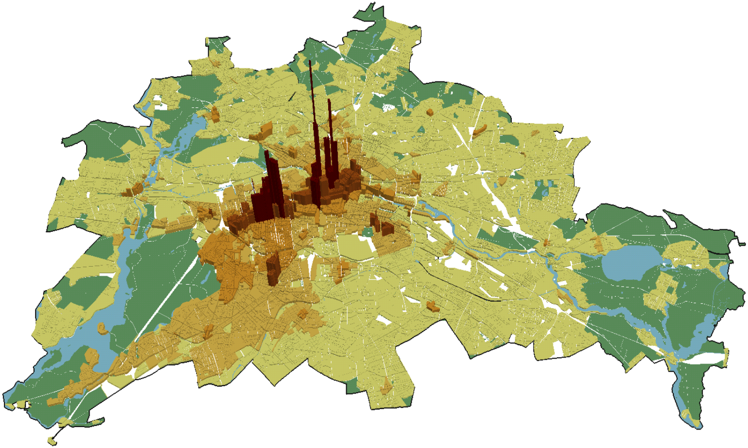
West Berlin 1936



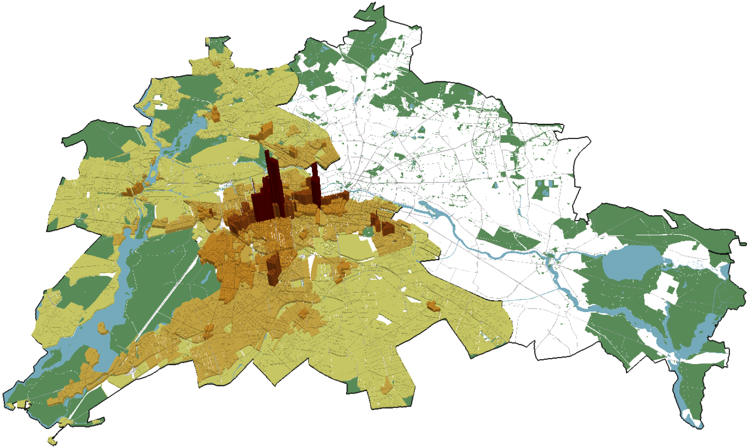
West Berlin 1986



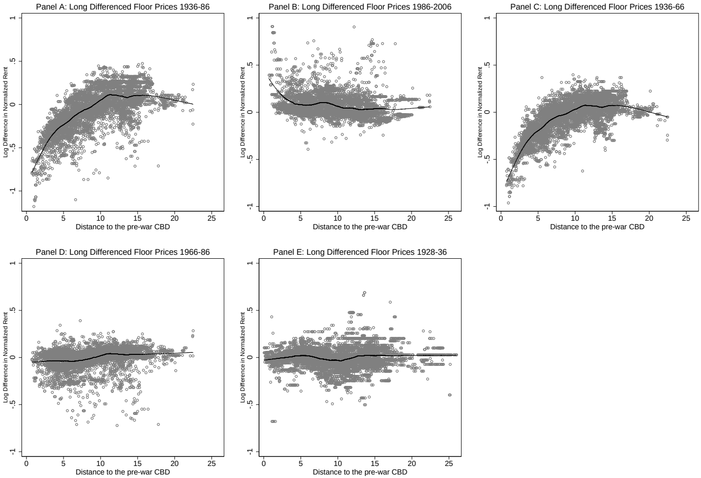
Berlin 2006



West Berlin 2006



Treatments and Placebos



Note: Log floor prices are normalized to have a mean of zero in each year before taking the long difference. Solid lines are fitted values from locally-weighted linear least squares regressions.

Gravity

- Gravity equation for commuting from residence i to workplace j:

$$\ln \pi_{ij} = -\nu \tau_{ij} + \vartheta_i + \varsigma_j + e_{ij}, \tag{1}$$

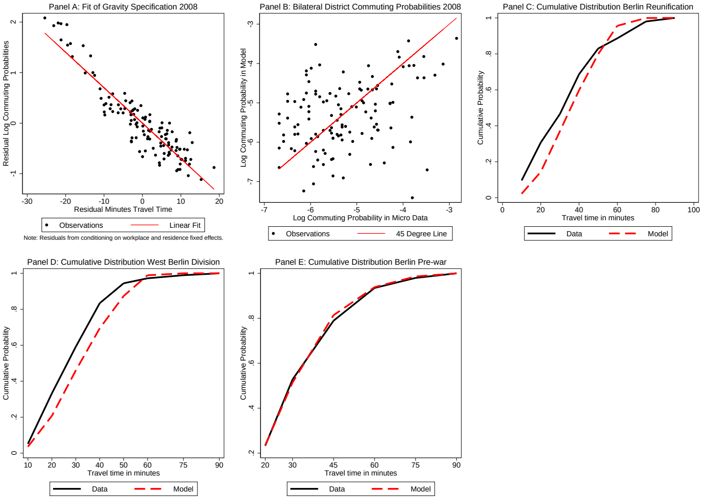
- where τ_{ij} is travel time in minutes and $\nu = \epsilon\kappa$ is semi-elasticity
- ϑ_i are residence fixed effects
- ς_j are workplace fixed effects
- Using estimated ν, can solve for transformed wages $\omega_j = w_j^{\epsilon}$ and recover overall productivity A_j and amenities B_i
- (Without making assumptions about the relative importance of production and residential externalities versus fundamentals)

Gravity Equation Estimation

	(1) ln Bilateral Commuting Probability 2008	(2) ln Bilateral Commuting Probability 2008	(3) ln Bilateral Commuting Probability 2008	(4) ln Bilateral Commuting Probability 2008
Travel Time ($-\kappa\varepsilon$)	-0.0697***	-0.0702***	-0.0771***	-0.0706***
	(0.0056)	(0.0034)	(0.0025)	(0.0026)
Estimation	OLS	OLS	Poisson PML	Gamma PML
More than 10 Commuters		Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes
Observations	144	122	122	122
R-squared	0.8261	0.9059	-	-

Note: Gravity equation estimates based on representative micro survey data on commuting for Greater Berlin for 2008. Observations are bilateral pairs of 12 workplace and residence districts (post 2001 Bezirke boundaries). Travel time is measured in minutes. Fixed effects are workplace district fixed effects and residence district fixed effects. The specifications labelled more than 10 commuters restrict attention to bilateral pairs with 10 or more commuters. Poisson PML is Poisson Pseudo Maximum Likelihood estimator. Gamma PML is Gamma Pseudo Maximum Likelihood Estimator. Standard errors in parentheses are heteroscedasticity robust. * significant at 10%; ** significant at 5%; *** significant at 1%.

Commuting Data and Model Predictions



Changes in Amenities and Productivity

	(1) Δ ln A 1936-86	(2) Δ ln B 1936-86	(3) Δ ln A 1986-2006	(4) Δ ln B 1986-2006	(5) Δ ln QC 1936-1986	(6) Δ ln QC 1986-2006
CBD 1	-0.207***	-0.347***	0.261***	0.203***	-0.229***	0.065***
	(0.049)	(0.070)	(0.073)	(0.054)	(0.020)	(0.014)
CBD 2	-0.260***	-0.242***	0.144**	0.109**	-0.184***	0.065***
	(0.032)	(0.053)	(0.056)	(0.058)	(0.008)	(0.009)
CBD 3	-0.138***	-0.262***	0.077***	0.059**	-0.177***	0.043***
	(0.021)	(0.037)	(0.024)	(0.026)	(0.012)	(0.009)
CBD 4	-0.131***	-0.154***	0.057***	0.010	-0.189***	0.048***
	(0.016)	(0.023)	(0.015)	(0.008)	(0.010)	(0.009)
CBD 5	-0.095***	-0.126***	0.028**	-0.014*	-0.188***	0.055***
	(0.014)	(0.013)	(0.013)	(0.007)	(0.012)	(0.012)
CBD 6	-0.061***	-0.117***	0.023**	0.001	-0.170***	0.035***
	(0.015)	(0.015)	(0.010)	(0.005)	(0.009)	(0.009)
Counterfactuals					Yes	Yes
Agglomeration Effects					No	No
Observations	2844	5978	5602	6718	6260	7050
R-squared	0.09	0.06	0.02	0.03	0.10	0.07

Note: Columns (1)-(4) based on calibrating the model for $\nu=\epsilon\kappa=0.07$ and $\epsilon=6.83$ from the gravity equation estimation. Columns (5)-(6) report counterfactuals for these parameter values. A denotes adjusted overall productivity. B denotes adjusted overall amenities. QC denotes counterfactual floor prices (simulating the effect of division on West Berlin). Column (5) simulates division holding A and B constant at their 1936 values. Column (6) simulates reunification holding A and B for West Berlin constant at their 1986 values and using 1936 values of A and B for East Berlin. CBD1-CBD6 are six 500m distance grid cells for distance from the pre-war CBD. Heteroscedasticity and Autocorrelation Consistent (HAC) standard errors in parentheses (Conley 1999). * significant at 10%; ** significant at 5%; *** significant at 1%.

Structural Residuals

- One-to-one mapping from known model parameters $\{\alpha, \beta, \mu, \nu, \epsilon, \lambda, \delta, \eta, \rho\}$ and observed data $\{\mathbb{Q}_{it}, H_{Mit}, H_{Rit}, K_i, \tau_{ijt}\}$ to adjusted production and residential fundamentals $\{\tilde{a}_i, \tilde{b}_i\}$
- Adjusted production and residential fundamentals $\{\tilde{a}_i, \tilde{b}_i\}$ capture other variables that enter the model isomorphically
- Adjusted production fundamentals relative to the geometric mean:

$$\triangle \ln\left(\frac{\tilde{a}_{it}}{\bar{\tilde{a}}_t}\right) = (1-\alpha)\triangle \ln\left(\frac{\mathbb{Q}_{it}}{\bar{\mathbb{Q}}_t}\right) + \frac{\alpha}{\epsilon}\triangle \ln\left(\frac{\omega_{it}}{\bar{\omega}_t}\right) - \lambda\triangle \ln\left(\frac{Y_{it}}{\bar{Y}_t}\right),$$

- Adjusted residential fundamentals relative to the geometric mean:

$$\triangle \ln\left(\frac{\tilde{b}_{it}}{\bar{\tilde{b}}_t}\right) = \frac{1}{\epsilon}\triangle \ln\left(\frac{H_{Rit}}{\bar{H}_{Rt}}\right) + (1-\beta)\triangle \ln\left(\frac{\mathbb{Q}_{it}}{\bar{\mathbb{Q}}_t}\right) - \frac{1}{\epsilon}\triangle \ln\left(\frac{W_{it}}{\bar{W}_t}\right) - \eta\triangle \ln\left(\frac{\Omega_{it}}{\bar{\Omega}_t}\right),$$

- Adjusted fundamentals are structural residuals

Parameters

Assumed Parameter		Source	Value
Residential land	$1-\beta$	Morris-Davis (2008)	0.25
Commercial land	$1-\alpha$	Valentinyi-Herrendorf (2008)	0.20
Fréchet Scale	T	(normalization)	1
Expected Utility	$\bar{u}$	(normalization)	1000

Estimated Parameter	
Production externalities elasticity	λ
Production externalities decay	δ
Residential externalities elasticity	η
Residential externalities decay	ρ
Commuting semi-elasticity	$\nu = \epsilon\kappa$
Commuting heterogeneity	ϵ

Moment Conditions

- Changes in adjusted fundamentals uncorrelated with exogenous change in surrounding economic activity from division/reunification

$$\mathbb{E}\left[\mathbb{I}_k \times \triangle \ln\left(\tilde{a}_{it}/\bar{\tilde{a}}_t\right)\right] = 0, \qquad k \in \{1, \ldots, K_{\mathbb{I}}\},$$

$$\mathbb{E}\left[\mathbb{I}_k \times \triangle \ln\left(\tilde{b}_{it}/\bar{\tilde{b}}_t\right)\right] = 0, \qquad k \in \{1, \ldots, K_{\mathbb{I}}\}.$$

- where $\mathbb{I}_k$ are indicators for distance grid cells
- Other moments are fraction of workers that commute less than 30 minutes and wage dispersion

$$\mathbb{E}\left[\vartheta H_{Mj} - \sum_{i \in \aleph_j}^{S} \frac{\omega_j / e^{\nu \tau_{ij}}}{\sum_{s=1}^{S} \omega_s / e^{\nu \tau_{is}}} H_{Ri}\right] = 0,$$

$$\mathbb{E}\left[(1/\epsilon)^2 \ln(\omega_j)^2 - \sigma_{\ln w_i}^2\right] = 0,$$

Estimated Parameters

	(1) Division Efficient GMM	(2) Reunification Efficient GMM	(3) Division and Reunification Efficient GMM
Commuting Travel Time Elasticity (κε)	0.0951***	0.1011***	0.0987***
	(0.0016)	(0.0016)	(0.0016)
Commuting Heterogeneity (ε)	7.6278***	7.7926***	7.7143***
	(0.1085)	(0.1152)	(0.1049)
Productivity Elasticity (λ)	0.0738***	0.0449***	0.0657***
	(0.0056)	(0.0071)	(0.0048)
Productivity Decay (δ)	0.3576***	0.8896***	0.3594***
	(0.0945)	(0.3339)	(0.0724)
Residential Elasticity (η)	0.1441***	0.0740***	0.1444***
	(0.0080)	(0.0287)	(0.0073)
Residential Decay (ρ)	0.8872***	0.5532	0.7376***
	(0.2774)	(0.3699)	(0.1622)

Note: Generalized Method of Moments (GMM) estimates. Heteroscedasticity and Autocorrelation Consistent (HAC) standard errors in parentheses (Conley 1999). * significant at 10%; ** significant at 5%; *** significant at 1%.

Localized Externalities

	(1) Production Externalities ($1 \times e^{-\delta\tau}$)	(2) Residential Externalities ($1 \times e^{-\rho\tau}$)	(3) Utility after Commuting ($1 \times e^{-\kappa\tau}$)
0 minutes	1.000	1.000	1.000
1 minute	0.698	0.478	0.987
2 minutes	0.487	0.229	0.975
3 minutes	0.340	0.109	0.962
5 minutes	0.166	0.025	0.938
7 minutes	0.081	0.006	0.914
10 minutes	0.027	0.001	0.880
15 minutes	0.005	0.000	0.825
20 minutes	0.001	0.000	0.774
30 minutes	0.000	0.000	0.681

Note: Proportional reduction in production and residential externalities with travel time and proportional reduction in utility from commuting with travel time. Travel time is measured in minutes. Results are based on the pooled efficient GMM parameter estimates: δ=0.3594, ρ=0.7376, κ=0.0128.

Counterfactuals

	(1) Δ ln QC 1936-86	(2) Δ ln QC 1936-86	(3) Δ ln QC 1936-86	(4) Δ ln QC 1936-1986	(5) Δ ln QC 1986-2006	(6) Δ ln QC 1936-1986
CBD 1	-0.839***	-0.667***	-0.666***	-0.752***	0.472***	0.923***
	(0.074)	(0.034)	(0.050)	(0.032)	(0.045)	(0.045)
CBD 2	-0.627***	-0.456***	-0.635***	-0.585***	0.251***	0.689***
	(0.048)	(0.025)	(0.045)	(0.030)	(0.055)	(0.071)
CBD 3	-0.518***	-0.348***	-0.592***	-0.476***	0.086*	0.416***
	(0.058)	(0.026)	(0.066)	(0.038)	(0.052)	(0.048)
CBD 4	-0.521***	-0.329***	-0.642***	-0.470***	-0.060	0.311***
	(0.060)	(0.019)	(0.071)	(0.035)	(0.040)	(0.044)
CBD 5	-0.544***	-0.306***	-0.733***	-0.482***	-0.076**	0.253***
	(0.042)	(0.022)	(0.044)	(0.036)	(0.034)	(0.042)
CBD 6	-0.489***	-0.265***	-0.709***	-0.417***	-0.133***	0.163***
	(0.043)	(0.015)	(0.059)	(0.027)	(0.038)	(0.042)
Counterfactuals	Yes	Yes	Yes	Yes	Yes	Yes
Agglomeration Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6260	6260	6260	6260	7050	6260
R-squared	0.12	0.15	0.09	0.11	0.01	0.06

Note: This table is based on the parameter estimates pooling division and reunification from Table 5. QC denotes counterfactual floor prices. Column (1) simulates division using our estimates of production and residential externalities and 1936 fundamentals. Column (2) simulates division using our estimates of production externalities and 1936 fundamentals but setting residential externalities to zero. Column (3) simulates division using our estimates of residential externalities and 1936 fundamentals but setting production externalities to zero. Column (4) simulates division using our estimates of production and residential externalities and 1936 fundamentals but halving their rates of spatial decay with travel time. Column (5) simulates reunification using our estimates of production and residential externalities, 1986 fundamentals for West Berlin, and 2006 fundamentals for East Berlin. Column (6) simulates reunification using our estimates of production and residential externalities, 1986 fundamentals for West Berlin and 1936 fundamentals for East Berlin. CBD1-CBD6 are six 500m distance grid cells for distance from the pre-war CBD. Heteroscedasticity and Autocorrelation Consistent (HAC) standard errors in parentheses (Conley 1999). * significant at 10%; ** significant at 5%; *** significant at 1%.

Conclusion

- This paper develops a quantitative theoretical model to provide evidence on agglomeration and dispersion forces
- Our framework allows for variation in production fundamentals, residential fundamentals and transport infrastructure
- We combine the quantitative model with exogenous variation provided by Berlin's division and reunification
- Division led to a re-orientation of West Berlin's land price gradient away from the pre-war city center
- Reunification led to a re-emergence of West Berlin's land price gradient towards the pre-war city center
- We provide evidence that this re-orientation of the land price gradient is in part shaped by the changing access to the surrounding concentration of economic activity emphasized in the model

The Making of the Modern Metropolis: Evidence from London

Motivation

- Modern metropolitan areas involve
  - 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)

Motivation

- Modern metropolitan areas involve
  - 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)

- What role does this separation of workplace and residence play in understanding these concentrations of economic activity?
  - Create predominantly commercial and residence neighborhoods with their distinctive characteristics for production and consumption

Motivation

- Modern metropolitan areas involve
  - 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)
- What role does this separation of workplace and residence play in understanding these concentrations of economic activity?
  - Create predominantly commercial and residence neighborhoods with their distinctive characteristics for production and consumption
- We provide new evidence on these questions using the mid-1800s innovation of the steam railway, newly-constructed historical data from London for 1801-1921, and a quantitative urban model

Motivation

- Modern metropolitan areas involve
  - 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)
- What role does this separation of workplace and residence play in understanding these concentrations of economic activity?
  - Create predominantly commercial and residence neighborhoods with their distinctive characteristics for production and consumption
- We provide new evidence on these questions using the mid-1800s innovation of the steam railway, newly-constructed historical data from London for 1801-1921, and a quantitative urban model
- 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

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
- Major change in transport technology during the 19th century
  - First steam railways haul freight at mines (Stockton-Darlington 1825)
  - First dedicated passenger steam railway (London and Greenwich 1836)

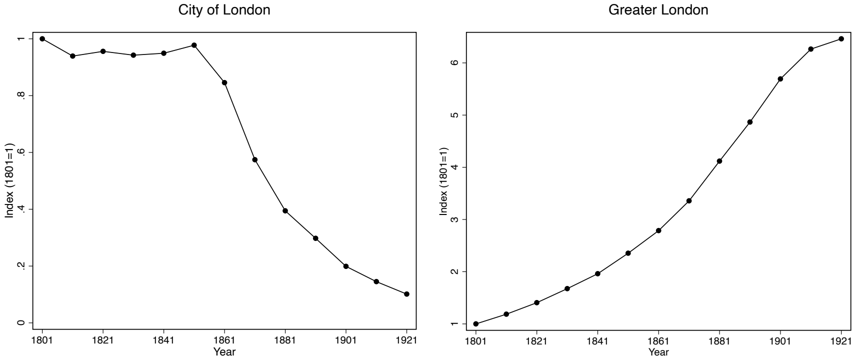
Empirical Setting

- 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
- Major change in transport technology during the 19th century
  - First steam railways haul freight at mines (Stockton-Darlington 1825)
  - First dedicated passenger steam railway (London and Greenwich 1836)
- Estimation methodology uses bilateral commuting data at the end of our sample and undertakes comparative statics back in time
  - Observe historical data on employment by residence and land values
  - Recover missing data on employment by workplace using the model

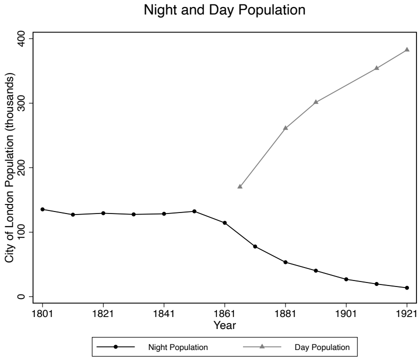
Empirical Setting

- 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
- Major change in transport technology during the 19th century
  - First steam railways haul freight at mines (Stockton-Darlington 1825)
  - First dedicated passenger steam railway (London and Greenwich 1836)
- Estimation methodology uses bilateral commuting data at the end of our sample and undertakes comparative statics back in time
  - Observe historical data on employment by residence and land values
  - Recover missing data on employment by workplace using the model
- 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

Residential (Night) Population



Day and Night Population



Estimating Historical Workplace Employment

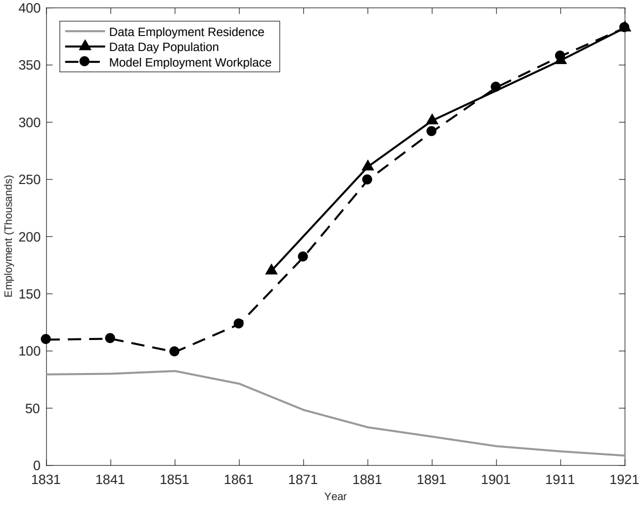
- Use DEK (2007) "exact-hat algebra" ($\hat{x}_t = x_\tau / x_t$) to generate model predictions for years $\tau < t$ starting from $t = 1921$
- Valid in an entire class of quantitative urban models
- Solve for changes in wages ($\hat{w}_{it}$) for $\tau < t$ from commuter and land market clearing

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

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

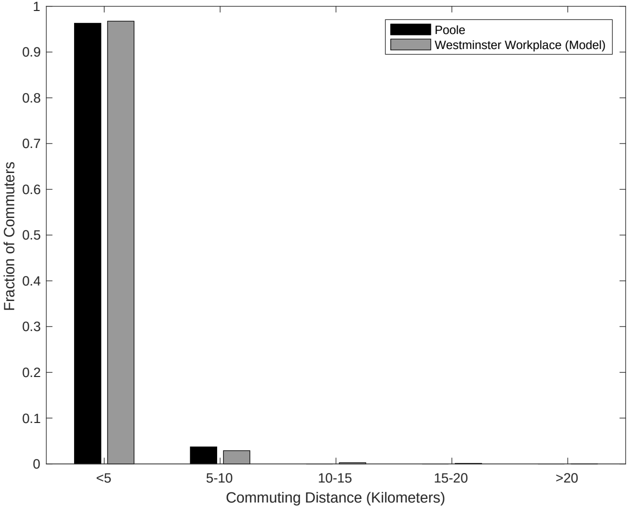
$$\hat{L}_{it}L_{it} = \sum_{n\in\mathbb{N}} \frac{\lambda^{C}_{nit|n}\hat{w}^{\epsilon}_{it}\hat{\kappa}^{-\epsilon}_{nit,\tau}}{\sum_{\ell\in\mathbb{N}}\lambda^{C}_{n\ell t|n}\hat{w}^{\epsilon}_{\ell t}\hat{\kappa}^{-\epsilon}_{n\ell t,\tau}}\hat{R}_{nt}R_{nt}.$$

Workplace Employment



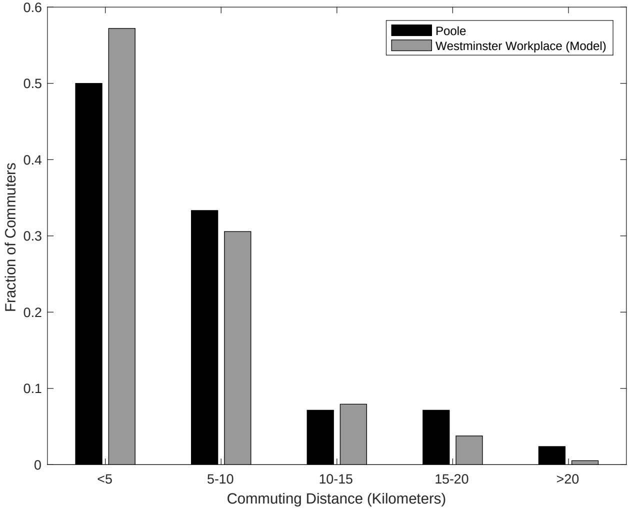
- Model captures sharp concentration of workplace employment in the City of London from 1860s onwards

Poole 1861

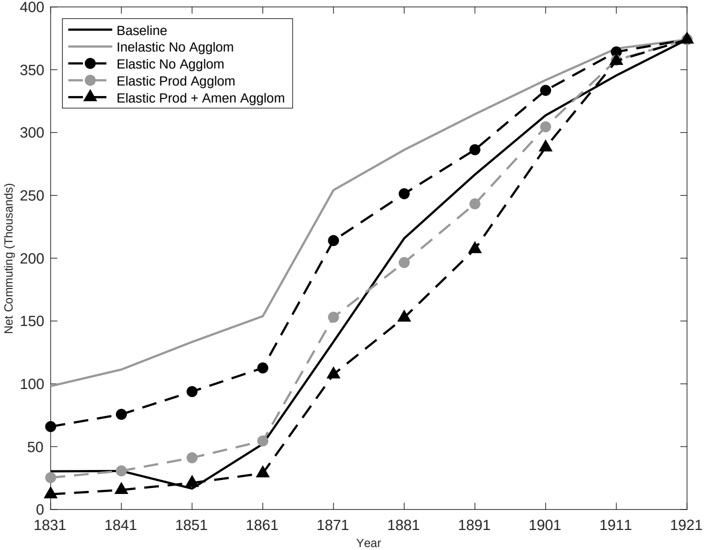


Poole
Westminster Workplace (Model)
Fraction of Commuters
Commuting Distance (Kilometers)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
<5
5-10
10-15
15-20
>20

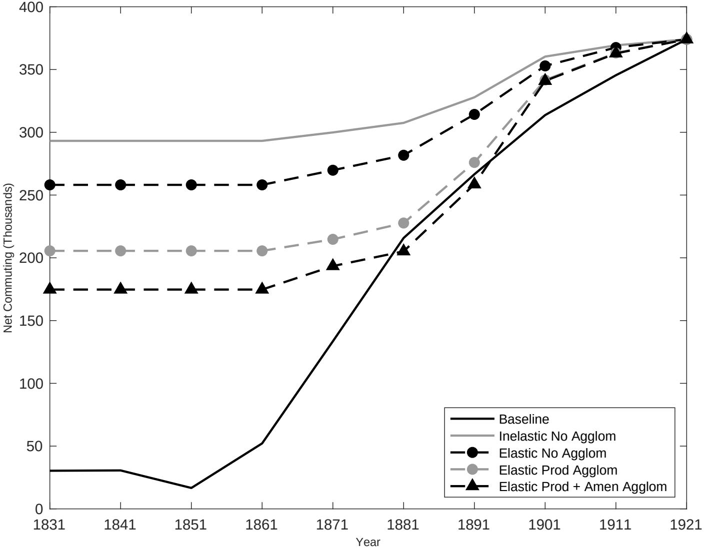
Poole 1901


0.6
0.5
0.4
0.3
0.2
0.1
0
Fraction of Commuters
Poole
Westminster Workplace (Model)
<5
5-10
10-15
15-20
>20
Commuting Distance (Kilometers)

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

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

- Undertaking counterfactuals for removing the entire railway network and only the underground network, we find
  - Substantial effects of the change in commuting costs
  - Commuting into City of London falls from $> 370,000$ to $< 60,000$
  - With endogenous supply of floor space and agglomeration forces, can account for much of Greater London's aggregate population growth
  - Changes in rateable values exceed construction costs

Thank You

Related Research

Related Research

- Theoretical models of non-monocentric cities
  - Fujita, M. and H. Ogawa (1982) "Multiple Equilibria and Structural Transformation of Non-Monocentric Urban Configurations," *Regional Science and Urban Economics*, 12(2), 161-196.
  - Lucas, R. E. and E. Rossi-Hansberg (2002) "On the Internal Structure of Cities," *Econometrica*, 70(4), 1445-1476.

- Surveys of quantitative urban and spatial economics
  - Holmes, Thomas J. and Holger Sieg (2015) "Structural Estimation in Urban Economics," *Handbook of Regional and Urban Economics*, Vol. 5, Gilles Duranton, J. Vernon Henderson, William C. Strange eds, Elsevier.
  - Redding, Stephen J. and Esteban Rossi-Hansberg (2017) "Quantitative Spatial Economics," *Annual Review of Economics*, 9, 21-58.

- Model of goods trade and commuting within and across cities
  - Monte, Ferdinando, Stephen Redding and Esteban Rossi-Hansberg (2018) "Commuting, Migration and Local Employment Elasticities," *American Economic Review*, 108(12), 3855-3890.

Related Research

- Transport infrastructure
  - Allen, Treb and Costas Arkolakis (2018) "The Welfare Effects of Transportation Infrastructure Improvements," Dartmouth College and Yale University, mimeograph.
  - Fajgelbaum, Pablo and Edouard Schaal (2020) "Optimal Transport Networks in Spatial Equilibrium," *Econometrica*, forthcoming

- Quantitative model where neighborhood development requires the coordination of developers and residents
  - Owens III, Raymond, Esteban Rossi-Hansberg and Pierre-Daniel Sarte (2020) "Rethinking Detroit," *American Economic Journal*, 12(2), 258-305.

- Granularity using data at a fine spatial scale
  - Dingel, Jonathan and Felix Tintelnot (2020) "Spatial Economics for Granular Settings," *NBER Working Paper*, No. 27287

Related Research

- Spatial sorting and heterogeneous groups of workers
  - Fajgelbaum, Pablo and Cecile Gaubert (2020) "Optimal Spatial Policies, Geography, and Sorting," *Quarterly Journal of Economics*, forthcoming.
  - Davis, Don and Jonathan Dingel (2020) "The Comparative Advantage of Cities," *Journal of International Economics*, forthcoming.
  - Redding, Stephen and Daniel Sturm (2016) "Estimating Neighborhood Effects: Evidence from War-time Destruction in London," Princeton University, mimeograph.
  - Tsivanidis, Nick (2019) "Evaluating the Impact of Urban Transit Infrastructure: Evidence from Bogotá's TransMilenio," UC Berkeley, mimeograph.
  - Almagro, Milena and Tomás Domínguez-Iino (2019) "Location Sorting and Endogenous Amenities: Evidence from Amsterdam," NYU mimeograph.

Related Research

- Endogenous consumption amenities
  - Couture, Victor, Cecile Gaubert, Jessie Handbury, Erik Hurst (2019) "Income Growth and the Distributional Effects of Urban Spatial Sorting," *NBER Working Paper*, 26142
  - Miyauchi, Yuhei, Kentaro Nakajima and Stephen Redding (2020) "Consumption Access and Agglomeration: Evidence from Smartphone Data," Princeton University, mimeograph