# A Quantitative Framework for Evaluating the Impact of Urban Transport Improvements

Gabriel M. Ahlfeldt
*London School of Economics and CEPR*

Stephen J. Redding
*Princeton University, NBER and CEPR*

Daniel M. Sturm
*London School of Economics and CEPR*

# Motivation

- Organization of economic activity within cities is crucially dependent on the transportation of people

- The London Underground
  - Handles 3.5 million passenger journeys a day
  - Trains travel 76 million kilometers each year (200 times distance between earth and moon)

- Public policy typically involved in transport infrastructure

- Transport for London
  - Annual operating expenditure of around £6bn in 2014-15
  - £1.7bn direct government grants
  - Remainder largely funded by charges to users
  - Annual capital investment program of around £1.7bn

- Determining the economic impact of transport infrastructure investments is of public policy relevance

# Challenges

- Economic evaluation of transport infrastructure improvements is subject to theoretical and empirical challenges

- A growing reduced-form literature provides quasi-experimental evidence on the impact of transport improvements
  - Cannot identify spatial equilibrium effects
  - Cannot distinguish reallocation from creation of economic activity
  - Typically abstracts from heterogeneous treatment effects
  - Substitution between alternative modes of transport

- Most existing theoretical models of internal city structure make simplifying assumptions such as monocentricity or symmetry
  - Locations within cities differ substantially in productivity, amenities and access to transport infrastructure

- Evaluations of transport infrastructure often
  - Adopt partial equilibrium cost-benefit approaches
  - Assume mechanical input-output relationships

# This Paper

- Quantitative framework for evaluating urban transport improvements building on Ahlfeldt, Redding, Sturm & Wolf (2015)

- Capture first-order features of the data such as locations differ in
  - Production and residential fundamentals
  - Production and residential externalities
  - Inelastic supply of land and commuting costs
  - Transportation infrastructure

- Parsimonious and tractable and requires only data on
  - Land prices and area
  - Employment by workplace and employment by residence
  - Travel times

- We use our framework for a quantitative evaluation of the U5 underground line in Berlin (under construction)
  - Relative land values
  - Reallocation of workplace and residence employment
  - Aggregate effects (e.g. city size and productivity)

# Related Literature

- Size and internal structure of cities
  - Alonso-Mills-Muth, Fujita & Ogawa (1982), Fujita & Krugman (1995), Lucas & Rossi-Hansberg (2002), Ahlfeldt et al. (2015), Arkolakis et al. (2015)

- Agglomeration economies
  - Fujita et al. (1999), Duration and Puga (2004), Rosenthal and Strange (2004), Moretti (2004), Combes et al. (2010), Greenstone et al. (2010), Kline and Moretti (2014), Arkolakis and Allen (2014)

- Transport infrastructure and development
  - McDonald & Osuji (1995), Baum-Snow & Kahn (2005), Gibbons & Machin (2005), Baum-Snow(2007), Michaels (2008), Donaldson (2014), Duranton & Turner (2012), Donaldson & Hornbeck (2013), Faber (2014), Fajgelbaum & Redding (2014), Baum-Snow et al (2014)

- Economics of transportation
  - Beckman et al. (1956), Fogel (1964), McFadden (1974), Parry and Small (2005, 2009), Small, Winston and Yan (2005), Small and Verhoef (2007), Anderson (2014), Couture et al. (2014)

# Road Map

- Theoretical Model

- Data and Calibration

- Results

# Consumption

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

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

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

- Indirect utility

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

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

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

# 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

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

- Commuting market clearing

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

## Residential Amenities

- Expected utility of moving to the city

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

- Residential choice probabilities:

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

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

- Solve for adjusted residential amenities ($\tilde{B}_i$):

$$\ln \left( \frac{\tilde{B}_i}{\bar{\tilde{B}}} \right) = \frac{1}{\epsilon} \ln \left( \frac{H_{Ri}}{\bar{H}_R} \right) + (1-\beta) \ln \left( \frac{Q_i}{\bar{Q}} \right) - \ln \left( \frac{W_i}{\bar{W}} \right),$$

# Productivity

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

$$X_j = A_j H_{Mj}^\alpha L_{Mj}^{1-\alpha}, \qquad 0 < \alpha < 1,$$

- Profit maximization and zero profits:

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

- Solve for adjusted productivity ($\tilde{A}_i$):

$$\ln\left(\frac{\tilde{A}_{it}}{\overline{\tilde{A}}_t}\right) = (1-\alpha)\ln\left(\frac{Q_{it}}{\overline{Q}_t}\right) + \alpha\ln\left(\frac{\tilde{w}_{it}}{\overline{\tilde{w}}_t}\right),$$

# General Equilibrium

- Model parameters: $\{\alpha, \beta, \mu, \epsilon, \kappa\}$
- Exogenous location characteristics: $\{\boldsymbol{T}, \boldsymbol{E}, \boldsymbol{A}, \boldsymbol{B}, \boldsymbol{\varphi}, \boldsymbol{K}, \boldsymbol{\xi}, \boldsymbol{\tau}\}$
- Equilibrium vector: $\{\boldsymbol{\pi_M}, \boldsymbol{\pi_R}, \boldsymbol{Q}, \boldsymbol{q}, \boldsymbol{w}, \boldsymbol{\theta}\}$ and total population $H$

## Proposition

*Assuming exogenous, finite and strictly positive location characteristics ($T_i \in (0, \infty)$, $E_i \in (0, \infty)$, $\varphi_i \in (0, \infty)$, $K_i \in (0, \infty)$, $\xi_i \in (0, \infty)$, $\tau_{ij} \in (0, \infty) \times (0, \infty)$), and exogenous, finite and non-negative final goods productivity $A_i \in [0, \infty)$ and residential amenities $B_i \in [0, \infty)$, there exists a unique equilibrium vector $\{\boldsymbol{\pi_M}, \boldsymbol{\pi_R}, H, \boldsymbol{Q}, \boldsymbol{q}, \boldsymbol{w}, \boldsymbol{\theta}\}$.*

▶ More

# Introducing Agglomeration Forces

- Allow productivity to depend on
  - Exogenous production fundamentals
  - Endogenous production externalities

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

- Allow amenities to depend on
  - Exogenous residential fundamentals
  - Endogenous residential externalities

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

# Recovering Location Characteristics

- Adjusted location characteristics

$$\begin{aligned}
\tilde{A}_i &= A_i E_i^{\alpha/\epsilon}, & \tilde{a}_i &= a_i E_i^{\alpha/\epsilon}, \\
\tilde{B}_i &= B_i T_i^{1/\epsilon} \zeta_{Ri}^{1-\beta}, & \tilde{b}_i &= b_i T_i^{1/\epsilon} \zeta_{Ri}^{1-\beta}, \\
\tilde{w}_i &= w_i E_i^{1/\epsilon}, \\
\tilde{\varphi}_i &= \tilde{\varphi}_i \left( \varphi_i, E_i^{1/\epsilon}, \xi_i \right),
\end{aligned}$$

## Proposition

*(i) Given known values for the parameters $\{\alpha, \beta, \mu, \epsilon, \kappa\}$ and the observed data $\{\mathbb{Q}, H_M, H_R, K, \tau\}$, there exist unique vectors of the unobserved location characteristics $\{\tilde{A}^*, \tilde{B}^*, \tilde{\varphi}^*\}$ that are consistent with the data being an equilibrium of the model.*
*(ii) Given known values for the parameters $\{\alpha, \beta, \mu, \epsilon, \kappa, \lambda, \delta, \eta, \rho\}$ and the observed data $\{\mathbb{Q}, H_M, H_R, K, \tau\}$, there exist unique vectors of the unobserved location characteristics $\{\tilde{a}^*, \tilde{b}^*, \tilde{\varphi}^*\}$ that are consistent with the data being an equilibrium of the model.*

# Road Map

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# Data

- Data on land prices, workplace employment, residence employment and bilateral travel times
- Data for Greater Berlin in 2006
- Data at the following levels of spatial aggregation:
  - Districts ("Bezirke"), 12 post-2001 reform
  - Statistical blocks, 15,937
  - Around 254 million bilateral connections
- 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
- Data on employment by residence and workplace
- Geographical Information Systems (GIS) data on:
  - Land area and geographical boundaries
  - U-Bahn (underground) and S-Bahn (suburban) lines and stations, bus and tram network

# Parameters

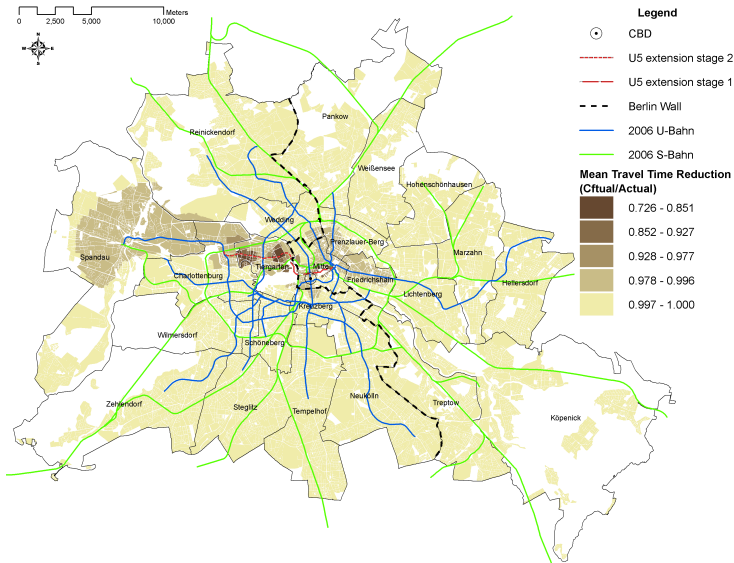- Assumed parameters from Ahlfedlt, Redding, Sturm & Wolf (2015)

| Parameter | Definition | Value |
|-----------|------------|-------|
| $(1-\beta)$ | Consumer expenditure residential floor space | 0.25 |
| $(1-\alpha)$ | Firm expenditure commercial floor space | 0.20 |
| $(1-\mu)$ | Share of Land in Construction Costs | 0.25 |
| $\nu$ | Semi-elasticity Commuting Flows and Travel Times | 0.07 |
| $\epsilon$ | Fréchet Shape Parameter Commuting Decisions | 6.83 |

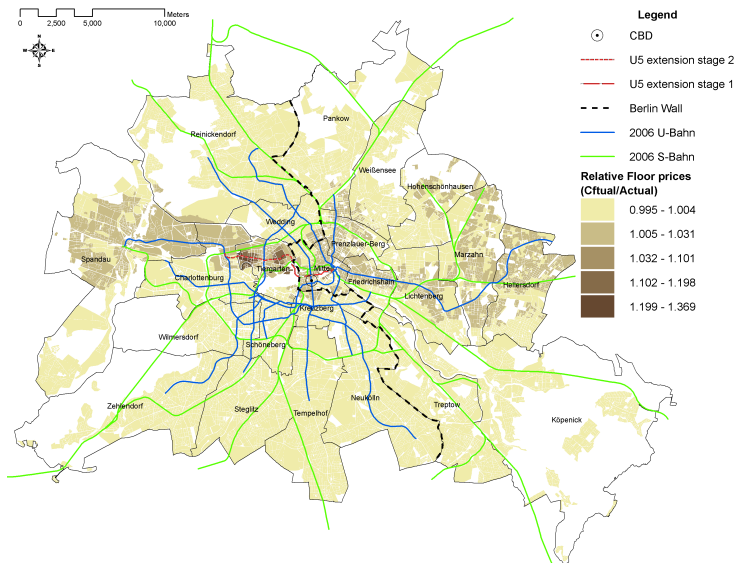| Parameter | Definition | Value |
|-----------|------------|-------|
| $\lambda$ | Production Externalities Elasticity | 0.05 |
| $\delta$ | Production Externalities Decay | 0.05 |
| $\eta$ | Residential Externalities Elasticity | 0.05 |
| $\rho$ | Residential Externalities Decay | 0.05 |

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# Mean Relative Travel Time Reduction

# Relative Increase Floor Prices



**Legend**

- ⊙ CBD
- ----- U5 extension stage 2
- ----- U5 extension stage 1
- ----- Berlin Wall
- ——— 2006 U-Bahn
- ——— 2006 S-Bahn

**Relative Floor prices (Cftual/Actual)**

- 0.995 - 1.004
- 1.005 - 1.031
- 1.032 - 1.101
- 1.102 - 1.198
- 1.199 - 1.369

# Aggregate Effects (Immobile Population)

|  | Counterfactual / Actual | |
|---|---|---|
| Percentage Increase | Exogenous | Endogenous |
| Utility | 0.22% | 0.33% |
| Net City Employment | 0% | 0% |
| Value Total City Income | 0.02% | 0.11% |
| Value Total City Land Rents | 0.02% | 0.11% |
| Total Factor Productivity | 0.03% | 0.13% |
| Sum of Absolute Changes as Percent of Aggregate | Exogenous | Endogenous |
| Workplace Employment | 0.70% | 0.92% |
| Residence Employment | 0.36% | 0.44% |
| Output | 0.58% | 0.78% |

# Aggregate Effects (Mobile Population)

|  | Counterfactual / Actual | |
|---|---|---|
| Percentage Increase | Exogenous | Endogenous |
| Utility | 0% | 0% |
| Net City Employment | 0.55% | 1.06% |
| Value Total City Income | 0.46% | 1.01% |
| Value Total City Land Rents | 0.46% | 1.01% |
| Total Factor Productivity | 0.03% | 0.18% |
| Sum of Absolute Changes as Percent of Aggregate | Exogenous | Endogenous |
| Workplace Employment | 0.58% | 1.06% |
| Residence Employment | 0.55% | 1.06% |
| Output | 0.49% | 1.01% |

# Aggregate Effects (Mobile Population)

| Variable | Exogenous | Endogenous |
|---|---|---|
| Berlin GDP (2012 1,000s Euro) | 105,148,850 | |
| Increase GDP (2012 1,000s Euro) | 479,421 | 1,056,767 |
| Increase Land Rents (2012 1,000s Euro) | 39,952 | 88,064 |
| NPV Increase GDP (60 year, 3%) | 13,747,679 | 30,303,380 |
| NPV Increase GDP (60 year, 5%) | 9,554,528 | 21,060,609 |
| NPV Increase GDP (60 year, 10%) | 5,257,890 | 11,589,726 |
| NPV Increase Land Rents (60 year, 3%) | 1,145,640 | 2,525,282 |
| NPV Increase Land Rents (60 year, 5%) | 796,211 | 1,755,051 |
| NPV Increase Land Rents (60 year, 10%) | 438,157 | 965,811 |
| Construction U5 (2012 1,000s Euro) | 650,000 | |
| Operating U5 (2%, 2012 1000s Euro) | 13,000 | |
| NPV Total Cost (3% discount rate) | 1,022,782 | |
| NPV Total Cost (5% discount rate) | 909,081 | |
| NPV Total Cost (10% discount rate) | 792,573 | |

# Conclusion

- Determining the economic impact of transport infrastructure improvements is an important public policy issue

- Evaluations of the economic impact of such transport improvements face a number of theoretical and empirical challenges

- We develop a theoretical framework for undertaking counterfactuals for the spatial equilibrium impact of transport improvements

- Rich spatial structure with locations differing in productivity, amenities and access to transport infrastructure

- Framework remains tractable and amenable to quantitative analysis

- Find substantial effects of empirically plausible transport infrastructure improvements on land rents, internal city structure and aggregate city economic activity

# Thank You