A Quantitative Framework for Evaluating the Impact of Urban Transport Improvements

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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
Challenges

• Substantial uncertainty surrounding existing estimates of the impact of transport infrastructure improvements

KPMG to face MPs again over HS2 report

Consultants to defend forecast of £15bn economic boost following claims that calculation was ‘essentially made up’

– “The KMPG partners behind the report said their work was robust and stood by the £15bn forecast, despite admitting it did not have a firm statistical foundation.”

– “Henry Overman, professor of economic geography and a former adviser to HS2 Ltd, said the figure was arrived at using a procedure that was ‘essentially made up’.”
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

• Agglomeration economies

• Transport infrastructure and development

• Economics of transportation
Road Map

• Theoretical Model

• Data and Calibration

• Results
Consumption

- Utility for worker \( o \) residing in block \( i \) and working in block \( j \):

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

- Consumption of the final good \( (c_{ij}) \), chosen as numeraire \( (p_i = 1) \)
- Residential floor space \( (\ell_{ij}) \)
- Residential amenity \( B_i \)
- Commuting costs \( d_{ij} = e^{\kappa_{ij}} \)
- 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:

\[
F(z_{ijo}) = e^{-T_i E_j z_{ijo}^{-\epsilon}}, \quad T_i, E_j > 0, \quad \epsilon > 1,
\]
Commuting Decisions

• Probability worker chooses to live in block \( i \) and work in block \( j \) is:

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

• Residential and workplace choice probabilities

\[
\pi_{Ri} = \sum_{j=1}^S \pi_{ij} = \frac{\sum_{j=1}^S \Phi_{ij}}{\Phi}, \quad \pi_{Mj} = \sum_{i=1}^S \pi_{ij} = \frac{\sum_{i=1}^S \Phi_{ij}}{\Phi}.
\]

• Commuting market clearing

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

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

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

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

\[
\ln \left( \frac{\tilde{B}_i}{\bar{B}} \right) = \frac{1}{\epsilon} \ln \left( \frac{H_{Ri}}{H_R} \right) + (1 - \beta) \ln \left( \frac{Q_i}{Q} \right) - \ln \left( \frac{W_i}{W} \right),
\]
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:

\[ X_j = A_j H_{Mj}^\alpha L_{Mj}^{1-\alpha}, \quad 0 < \alpha < 1, \]

- 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 (\( \tilde{A}_i \)):

\[ \ln \left( \frac{\tilde{A}_{it}}{\tilde{A}_t} \right) = (1 - \alpha) \ln \left( \frac{Q_{it}}{Q_t} \right) + \alpha \ln \left( \frac{\tilde{w}_{it}}{\tilde{w}_t} \right), \]
General Equilibrium

• Model parameters: \{\alpha, \beta, \mu, \epsilon, \kappa\}
• Exogenous location characteristics: \{T, E, A, B, \varphi, K, \xi, \tau\}
• Equilibrium vector: \{\pi_M, \pi_R, Q, q, w, \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 \{\pi_M, \pi_R, H, Q, q, w, \theta\}. 
Introducing Agglomeration Forces

• Allow productivity to depend on
  – Exogenous production fundamentals
  – Endogenous production externalities

\[ A_j = a_j Y_j^\lambda, \quad Y_j = \sum_{s=1}^{S} e^{-\delta \tau_j} \left( \frac{H_{Ms}}{K_s} \right). \]

• Allow amenities to depend on
  – Exogenous residential fundamentals
  – Endogenous residential externalities

\[ B_i = b_i \Omega_i^\eta, \quad \Omega_i = \sum_{s=1}^{S} e^{-\rho \tau_i} \left( \frac{H_{Rs}}{K_s} \right). \]
Recovering Location Characteristics

• Adjusted location characteristics

\[ \tilde{A}_i = A_i E_i^{\alpha/\epsilon}, \quad \tilde{a}_i = a_i E_i^{\alpha/\epsilon}, \]
\[ \tilde{B}_i = B_i T_i^{1/\epsilon} \zeta_{Ri}^{1-\beta}, \quad \tilde{b}_i = b_i T_i^{1/\epsilon} \zeta_{Ri}^{1-\beta}, \]
\[ \tilde{w}_i = w_i E_i^{1/\epsilon}, \quad \tilde{w}_i = w_i E_i^{1/\epsilon}, \]
\[ \tilde{\phi}_i = \tilde{\phi}_i \left( \varphi_i, E_i^{1/\epsilon}, \zeta_i \right), \]

Proposition

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

- Theoretical Model
- Data and Calibration
- Results
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)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1 - \beta)$</td>
<td>Consumer expenditure residential floor space</td>
<td>0.25</td>
</tr>
<tr>
<td>$(1 - \alpha)$</td>
<td>Firm expenditure commercial floor space</td>
<td>0.20</td>
</tr>
<tr>
<td>$(1 - \mu)$</td>
<td>Share of Land in Construction Costs</td>
<td>0.25</td>
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<tr>
<td>$\nu$</td>
<td>Semi-elasticity Commuting Flows and Travel Times</td>
<td>0.07</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Fréchet Shape Parameter Commuting Decisions</td>
<td>6.83</td>
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<thead>
<tr>
<th>Parameter</th>
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<tr>
<td>$\lambda$</td>
<td>Production Externalities Elasticity</td>
<td>0.05</td>
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<tr>
<td>$\delta$</td>
<td>Production Externalities Decay</td>
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</tr>
<tr>
<td>$\eta$</td>
<td>Residential Externalities Elasticity</td>
<td>0.05</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Residential Externalities Decay</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Road Map

• Theoretical Model
• Data and Calibration
• Results
Mean Relative Travel Time Reduction

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

Mean Travel Time Reduction (Cftual/Actual)
- 0.726 - 0.851
- 0.852 - 0.927
- 0.928 - 0.977
- 0.978 - 0.996
- 0.997 - 1.000
# Aggregate Effects (Immobile Population)

<table>
<thead>
<tr>
<th>Percentage Increase</th>
<th>Counterfactual / Actual</th>
<th>Exogenous</th>
<th>Endogenous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility</td>
<td></td>
<td>0.22%</td>
<td>0.33%</td>
</tr>
<tr>
<td>Net City Employment</td>
<td></td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Value Total City Income</td>
<td></td>
<td>0.02%</td>
<td>0.11%</td>
</tr>
<tr>
<td>Value Total City Land Rents</td>
<td></td>
<td>0.02%</td>
<td>0.11%</td>
</tr>
<tr>
<td>Total Factor Productivity</td>
<td></td>
<td>0.03%</td>
<td>0.13%</td>
</tr>
<tr>
<td>Sum of Absolute Changes as Percent of Aggregate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workplace Employment</td>
<td></td>
<td>0.70%</td>
<td>0.92%</td>
</tr>
<tr>
<td>Residence Employment</td>
<td></td>
<td>0.36%</td>
<td>0.44%</td>
</tr>
<tr>
<td>Output</td>
<td></td>
<td>0.58%</td>
<td>0.78%</td>
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## Aggregate Effects (Mobile Population)

<table>
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<tr>
<th>Percentage Increase</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exogenous</td>
</tr>
<tr>
<td>Utility</td>
<td>0%</td>
</tr>
<tr>
<td>Net City Employment</td>
<td>0.55%</td>
</tr>
<tr>
<td>Value Total City Income</td>
<td>0.46%</td>
</tr>
<tr>
<td>Value Total City Land Rents</td>
<td>0.46%</td>
</tr>
<tr>
<td>Total Factor Productivity</td>
<td>0.03%</td>
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</tbody>
</table>

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<tr>
<th>Sum of Absolute Changes as Percent of Aggregate</th>
<th>Exogenous</th>
<th>Endogenous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workplace Employment</td>
<td>0.58%</td>
<td>1.06%</td>
</tr>
<tr>
<td>Residence Employment</td>
<td>0.55%</td>
<td>1.06%</td>
</tr>
<tr>
<td>Output</td>
<td>0.49%</td>
<td>1.01%</td>
</tr>
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</table>
## Aggregate Effects (Mobile Population)

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