# Bread Lecture Series

*Evaluating the Effects of Transit Infrastructure*

Nick Tsivanidis
U.C. Berkeley

# Transport in Cities

- Urban models like Ahlfeldt et. al. (2015) are very well set-up to study impacts of urban policies (transport, housing, zoning)
- Today we focus on papers on impact of transit:
  - Tsivanidis (2022) - Bus Rapid Transit in Bogota
  - Extra: Allen and Arkolakis (2022) develop tractable, discrete choice framework of routing to think about locally optimal transport investments

# Urban Transit Infrastructure

**Empirical Questions**:

1. What are the **aggregate** effects of improving urban transit?
   - 2.5 billion people will move into cities by 2050, most in developing countries

2. How are the gains **distributed** across the low- and high-skilled?
   - Bogota in 1995: low-skilled 25% more likely to commute using informal bus...
   - Which were 32% slower than cars

# TransMilenio: World's Most Used Bus Rapid Transit System

Opened across 3 phases in 2000s

Similar speed to subways, but
**Faster** and **Cheaper** to build

Currently being built in many developing countries

Combine with detailed **tract-level data** to examine impact

# Approach of This Paper

1. **Quantitative general equilibrium model of a city**
   - New Features: Low/High-skill workers + Multiple transit modes
2. **New Commuter Market Access** approach from **general equilibrium theory** to measure effects of transit infrastructure within cities
   - Individuals: Access to Jobs. Firms: Access to Workers
   - Advantages vs Standard Distance-to-Station Approach
   - Sufficient Statistics: Change in CMA + Elasticities of Activity to CMA (in single-group special case of model)
3. **Structural Estimation + Quantification**:
   - Some of the first estimates of productivity/amenity spillovers w/in less dev. ctry cities
   - Connect with Value of Travel Time Savings (VTTS) approach, unpack differences

# Model Ingredients

**Extend workhorse quantitative urban model (Ahlfeldt, Redding, Sturm & Wolf 2015):**

- Multiple skill groups of workers
- Multiple transit modes (cars vs public)
- Multiple industries

# Model Environment

**Geography**: Many discrete locations $i \in I$ that differ in:

- Amenities and productivities
- Time to commute to other locations
- Total supply of housing floorspace

**Workers**:

- Fixed population type $g \in \{Low, High\}$
- Choose where to live, work, own car

**Firms**:

- Rep. firm in each location from each industry produces freely traded variety
- CES labor input over low- and high-skill

**Landowners**: Allocate floorspace between res and comm use to max profits

**General Equilibrium**: Wages and floorspace prices adjust to clear mkts

# Workers

**Utility**: Worker $\omega$ type-$g$ living in $i$ with car ownership $a \in \{0,1\}$

$$U_{iag}(\omega) = u_{iag} C^{\beta}(H - \bar{h})^{1-\beta}\nu_{ia}(\omega)$$

- Amenity $u_{iag}$
- Final numeraire good $C$
- Residential housing floorspace $H_R$, w/subsistence requirement $\bar{h}$
- Idiosyncratic pref. for choice $i, a$, $\nu_{ia}(\omega)$ (iid Frechet with shape $\eta_g$)

**Budget Constraint**: If works in $j$

$$C + r_{Ri}H + p_a a = \frac{w_{jg}\epsilon_j(\omega)}{d_{ija}}$$

- Price of housing $r_{Ri}$
- Price of car $p_a$
- Wage per eff unit of labor $w_{jg}$
- Commute cost $d_{ija} = \exp(\kappa t_{ija})$
- Idiosyncratic match-prod. with firms in $j$, $\epsilon_j(\omega)$ (iid Frechet with shape $\theta_g$)

**Timing**: First choose where to live, then choose where to work

# Workers

**Employment**: From $\max_j \{w_{jg}\epsilon_j(\omega)/d_{ija}\}$, probability commute to $j$ from $(i,a)$:

$$\pi_{j|iag} = \frac{(w_{jg}/d_{ija})^{\theta_g}}{\Phi_{Riag}} \quad \text{where} \quad \Phi_{Riag} \equiv \sum_s (w_{sg}/d_{isa})^{\theta_g}$$

where $\Phi_{Riag}$ (Resident Commuter Market Access) reflects access to well-paid jobs

**Residence**: Probability live in $i$ with car ownership $a$:

$$L_{Riag} \propto \left( u_{iag} \underbrace{\left( \bar{y}_{iag} - p_a a - r_{Ri}\bar{h} \right)}_{\text{Expected Net Income}} r_{Ri}^{\beta-1} \right)^{\eta_g}$$

where $\bar{y}_{iag} \propto \Phi_{Riag}^{1/\theta_g}$ is expected income

**Key Elasticities**:

- Higher $\theta \Rightarrow$ employment decisions respond more to commute costs
- Higher $\eta \Rightarrow$ residents more mobile

# Closing the Model

**Firms**: In industry $s$, produce using labor $N_{js}$ and commercial buildings $H_{Fjs}$

$$Y_{js} = A_{js} N_{js}^{\alpha_s} H_{Fjs}^{1-\alpha_s} \quad \text{where} \quad N_{js} = \left( \sum_g \alpha_{sg} \tilde{L}_{Fjgs}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$

where $A_{js}$ is TFP. Hire inputs taking wages $w_{jg}$ and floorspace price $r_{Fj}$ as given

**Landowners**: Choose share of floorspace allocated to each use ($r_{Ri}$ vs. $r_{Fi}$)

**General Equilibrium**:

1. Land Market Clearing:
   - Demand for floorspace equals supply $\Rightarrow$ floorspace prices
   - Floorspace allocated to most profitable use $\Rightarrow$ floorspace supply
2. Labor Market Clearing: Demand for workers equals supply $\Rightarrow$ wages
3. Closed City: Population adds up to city total $\Rightarrow$ welfare

- See paper for specification and estimation of productivity and amenity externalities

# Empirical Approach

- Consider special case of the model with (i) one group of workers, (ii) no fixed elements of expenditure or income, (iii) exogenous share of floorspace allocated to residential + commercial use.
  - Isomorphic to broader class of models which have log-linear equilibrium equations
- Model admits log-linear reduced form. Change in CMA and reduced form elasticities are sufficient statistics for impacts of transit
- Use this to guide empirics (validate class of models) and assess aggregate impacts using suff stats

# Commuter Market Access: Summarizes Effect of Transit

**Resident CMA** ($\Phi_{Ri}$): Reflects access to well-paid jobs $\Rightarrow \uparrow$ supply of residents

- Resident Supply: $L_{Ri} \propto \left(u_i \Phi_{Ri}^{1/\theta} r_{Ri}^{\beta-1}\right)^{\eta}$

**Firm CMA** ($\Phi_{Fi}$): Reflects access to workers $\Rightarrow \uparrow$ supply of labor

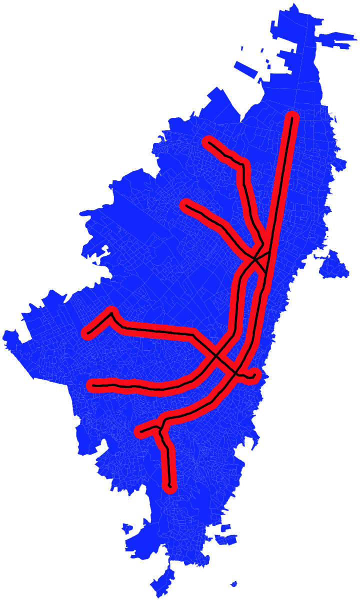
- Labor Supply: $L_{Fj} = \sum_i \pi_{j|i} L_{Ri} = w_j^{\theta} \Phi_{Fj}$

Given data $(L_{Fj}, L_{Ri})$ and commute costs $d_{ij}^{-\theta}$, CMA terms are unique solution to

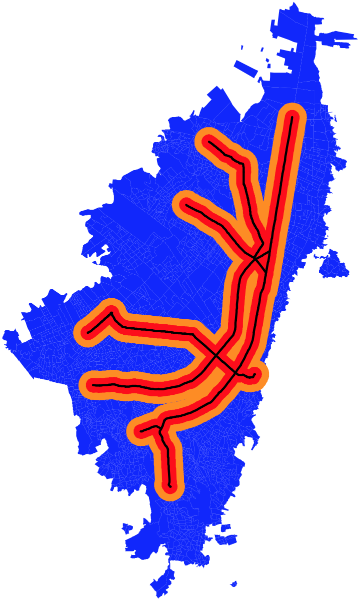
$$\Phi_{Ri} = \sum_j d_{ij}^{-\theta} \frac{L_{Fj}}{\Phi_{Fj}}$$

$$\Phi_{Fi} = \sum_j d_{ji}^{-\theta} \frac{L_{Rj}}{\Phi_{Rj}}$$

# Distance-Based Treatment Effect: Close vs Far

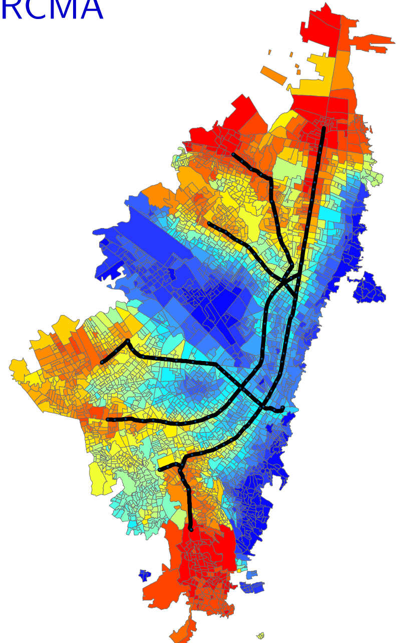


# Distance-Based Treatment Effect: Close vs Interm. vs Far



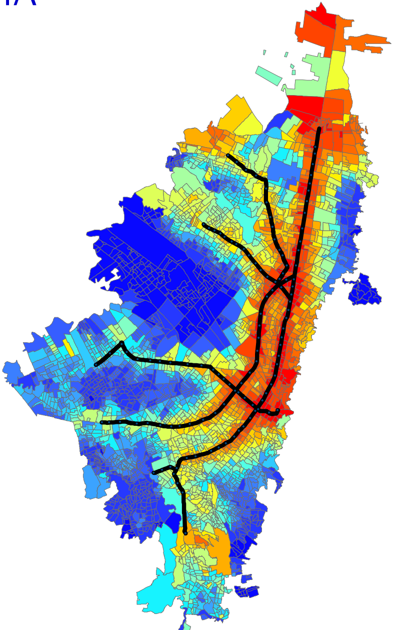
# Residents: Change in lnRCMA

Hot: Larger increase
Cool: Smaller increase



# Firms: Change in lnFCMA

Hot: Larger increase
Cool: Smaller increase



# Reduced Form Representation

In this special case, equilibrium can be written in the form:

$$\Delta \ln \mathbf{Y}_i = \mathbf{A}^{-1}\mathbf{B}_R \Delta \ln \Phi_{Ri} + \mathbf{A}^{-1}\mathbf{B}_F \Delta \ln \tilde{\Phi}_{Fi} + \mathbf{e}_i$$

where

- $\Delta \ln \mathbf{Y}_i = \begin{bmatrix} \Delta \ln L_{Ri} & \Delta \ln r_{Ri} & \Delta \ln r_{Fi} & \Delta \ln \tilde{L}_{Fi} \end{bmatrix}'$
- $\mathbf{B}_R, \mathbf{B}_F$ : Direct effects
- $\mathbf{A}^{-1}$ : Indirect effects
- $\mathbf{e}_i$ : Structural error containing changes in productivities/amenities

- Block structure of coefficients means R outcomes only depend on $\Phi_{Ri}$ (same for F)

# Sufficient Statistics for Impact of Transit

Due the block structure

$$\ln \hat{y}_{Ri} = \beta_R \ln \hat{\Phi}_{Ri} + e_{Ri},$$
$$\ln \hat{y}_{Fi} = \beta_F \ln \hat{\Phi}_{Fi} + e_{Fi}.$$

where $\hat{y}_{Ri} = \left[\hat{L}_{Ri}, \hat{r}_{Ri}\right]$ and $\hat{y}_{Fi} = \left[\hat{L}_{Fi}, \hat{r}_{Fi}\right]$. Proposition 1 says:

- Relative changes in in economic activity $\hat{\hat{y}}_i = \hat{y}_i / (\sum_r \hat{y}_r)^{1/I}$ can be computed using (i) estimates of $\beta_{L_R}, \beta_{r_R}, \beta_{r_F}, \beta_{L_F}, \theta$, (ii) data on the initial distribution of economic activity $\{L_{R_i}, L_{F_i}, d_{ij}\}$ and (iii) data on the change in commute costs $\{\hat{d}_{ij}\}$.
- Level changes in $\hat{y}_i$ and $\hat{L}, \hat{U}$ can be computed from relative changes in part 2 with (i) an assumption on population mobility between the city and the rest of the country, and (ii) values for $\sigma, \beta$.
- These, and the equations for $\Phi_i$, hold in a broader class of models with i) gravity in commuting and ii) log-linear supply and demand equations.

# Data

| Dataset | Source | Year | Variables |
|---|---|---|---|
| Population | General Census/DANE | 1993, 2005,2015 | Residential Population by Education Group |
| Commuting | DANE Mobility Survey | 1995, 2005, 2011, 2015 | Trip-diaries (trip and person characteristics) |
| Housing | Cadastral Department | 2000-2013 | Property value and characteristics, land use, land and floorspace area |
| Employment (Firms) | General Census | 1990, 2005 | Employment and industry (universe of estab.) |
| | Business Registry (Chamber of Commerce) | 2000, 2014 | Employment and industry (formal estab.) |
| Employment (Workers) | DANE Household Surveys (ECH/GEIH) | 2000-2014 | Worker demographics and employment characteristics |
| Commute Times | City Maps | - | Times by mode computed in ArcMap |

# Identification

$$\Delta \ln L_{Ri} = \beta \Delta \ln \Phi_{Ri} + \gamma_\ell + \gamma' X_i + \epsilon_{Ri}$$

**Challenges**: $\Delta$ Amenities in $\epsilon_{Ri}$ possibly correlated $\Delta \ln \Phi_{Ri}$

1. **Mechanical**: Contains population and employment in both periods
   - Instrument: $\widehat{\Delta \ln \Phi_{Ri}}$ holding $L_R + L_F$ fixed at initial levels
2. **Non-Random Route Placement**: Predict using
   i. **Location of Tram System in 1921**
   ii. **Least cost construction paths between portals and CBD**
   - Instrument: $\widehat{\Delta \ln \Phi_{Ri}}$ had TM been built along these predicted routes

Don't just rely on IV:

- Placebo/Burusyak and Hull: Use 4 planned networks to generate placebo/expected shock
- Falsification: No effects of CMA due to lines before opening
- Exploit residual variation in CMA conditional on distance to station
- Use variation in CMA due to new lines >1.5km away

# Connecting the Model to Existing Approaches

- Standard approach is to value welfare effects based on **value of travel time saved**.
- **Proposition**: In the model without spillovers and no preference heterogeneity across residential locations, the equilibrium is efficient. The first order impact on welfare of a change in commute costs $\{dt_{ij}\}$ is

$$d \ln \bar{U} = -\alpha\beta\kappa \sum_{ij} \frac{w_{ij} L_{ij}}{\sum_{rs} w_{rs} L_{rs}} dt_{ij},$$

  where $w_{ij}$ is average labor income on $ij$ .
- So in a special case of the model, the envelope theorem implies the first order impact is (a particular average of) these time savings.

# Aggregate Results from Sufficient Statistics Approach

Table 6: Aggregate Results Using Sufficient Statistics Approach

| **Panel A: VTTS Comparison** | **VTTS** | **GE** | **GE (No Ext.)** |
|---|---|---|---|
| Welfare Gain (%) | 1.260 | 2.335 | 1.527 |
| 90% CI | (0.740,3.106) | (0.740,5.861) | |
| 95% CI | [0.309,3.692] | [0.475,6.936] | |
| As Fraction of VTTS | | 53.95 | 82.49 |
| 90% CI | | (44.20,71.74) | |
| 95% CI | | [39.22,85.96] | |

# Welfare Decomposition

Table 9: Main Quantitative Results & Distributional Effects

| | Average Welfare | Inequality |
|---|---|---|
| **Panel A: Main Results** | | |
| Diff $\theta, \eta$, Imperf Sub | 1.007 | 0.546 |
| 90% CI | (0.254, 4.022) | (-0.159, 0.875) |
| 95% CI | [0.017, 4.407] | [-0.441, 1.138] |
| P-value $\widehat{\bar{U}}_H > \widehat{\bar{U}}_L$ | 0.15 | |
| **Panel B: Decomposing the Role of Elasticities** | | |
| Same $\eta, \theta$, Perf Sub | 2.191 | -0.371 |
| Diff $\theta$, same $\eta$, Perf Sub | 2.261 | -0.163 |
| Diff $\theta, \eta$, Perf Sub | 2.510 | -0.139 |
| **Panel C: Model Extensions** | | |
| Domestic Services | 0.832 | 0.585 |
| Local Home Ownership | 0.854 | 0.596 |
| All Renters | 0.867 | 0.619 |

- Low-skill hurt because $\theta_L > \theta_H$ (Panel B, row 1 $\rightarrow$ row 2)
- Low-skill hurt because by competition in the labour market (Panel B, row 3 $\rightarrow$ Panel A)

# Aggregate Impacts of TransMilenio

**Panel B: Aggregate Effects**

| | No Migration | Migration |
|---|---|---|
| Welfare | 2.282 | 0.597 |
| GDP | 3.121 | 15.131 |
| GDP Net of Costs | 2.504 | 14.514 |
| Population | 0.000 | 9.514 |
| Rents | -0.672 | 5.283 |
| % of Obs GDP Growth | 2.963 | 14.362 |
| % of Obs Population Growth | 0.000 | 34.886 |

# Incorporating Congestion

**Panel C: Incorporating Congestion**

| | % Change in Welfare | % of No Congestion Welfare Change |
|---|---|---|
| No Congestion | 3.921 | 100.00 |
| Congestion | 3.943 | 100.55 |
| Convert TM to Car Lanes | 0.028 | 0.641 |

# Land Value Capture

- In Bogota, change in transit w/o complementary change in zoning laws
  - $\Rightarrow$ No significant response in housing supply to TM
- **Land Value Capture**:
  - "Development Rights Sale" - Gvt sells permits to build at higher densities near stations
  - Successful in Asian cities to (i) finance construction and (ii) increase housing supply
- **2 Policies**: Allocate the same amount of new floorspace permits via
  1. Increase density by 30% within 500m of stations
  2. Increase density proportional to predicted change in CMA

# Land Value Capture

**Panel B: Land Value Capture Welfare Effects**

| | % Increase Relative to Baseline | |
|---|---|---|
| | **Welfare** | **Output** |
| Free Adjustment | 44.04 | 15.78 |
| LVC, Bands | 24.47 | 9.17 |
| LVC, CMA | 43.82 | 11.95 |

**Panel C: Land Value Capture Revenue Effects**

| | **Closed City** | **Open City** |
|---|---|---|
| LVC Band Revenue (mm) | 58.62 | 152.77 |
| As share of capital costs | 4.04 | 10.54 |
| LVC CMA Revenue (mm) | 88.31 | 297.57 |
| As share of capital costs | 6.09 | 20.53 |

1. Average welfare gain 24-43% larger under LVC
2. Gvt earns 4-20% of capital costs from air rights sales

# The Welfare Effects of Transportation Infrastructure Improvements

Allen and Arkolakis, 2021, *Review of Economic Studies* (forthcoming)

- Recent "quantitative" revolution in spatial economics
  - Spearheaded by flexible theory
    Eaton Kortum '02, Allen Arkolakis '14, Ahlfeldt Redding Sturm Wolf '15
  - Fueled with swaths of spatial data
- Key benefit: evaluation of major infrastructure projects
  - Trains (Donaldson '18), subways (Severen '19), BRT (Tsivanidis '19)
- The "elephant in the room": Roads

# Motivation