Transport Infrastructure and Spatial Sorting: Evidence from Buenos Aires

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Motivation

- Cities spend a lot of money on new public transport infrastructure.
- Existing quantitative spatial models used to measure welfare gains are **static** $\rightarrow$ "immediate" response + spatial eq. (in expectation)
- However: residential and work mobility is costly $\rightarrow$ takes time.
- Accounting for these dynamics matters when evaluating effects of new transport infrastructure.
- Research Questions:
  - **How do improvements in the urban transport infrastructure affect the dynamics of spatial sorting?**
  - **Welfare consequences for high- and low- skilled residents when considering these dynamics?**

In This Paper

- Study effects of new BRT lines on (residential) spatial sorting in Buenos Aires, Argentina.
- Use novel individual-level panel data $\rightarrow$ track residents as they move.
  1. Reduced form analysis: causal impact of new transport infrastructure on sorting by skill-type.
  2. **Dynamic** QSM of a city. Explicitly model within-city migration (sorting).
     - Measure welfare gains for high- and low-skilled by initial place of residence.
     - Study spatial heterogeneity of welfare gains within city.
     - Evaluate importance of dynamic adjustment costs: difference in welfare between *static* model and *dynamic* model.

Preview of Main Findings (today)

- Similar **average** gains for high-skilled (college educated) and low-skilled ($\sim$1%).
- But conditioning on *initial location* (before BRT) matters for welfare gains.
- Pro-poor (**spatially**): residents starting in initially poorer neighborhoods see highest welfare gains.
- Accounting for *dynamic transition* reduces welfare gains by 35% for HS and 31% for LS residents on avg. (compared to "static-model-style" estimation).
- Large spatial heterogeneity in dynamic adjustment costs.

Setting

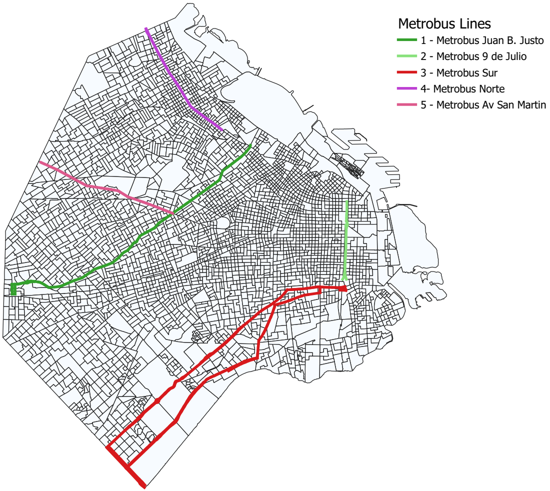
Buenos Aires 2011-2017 - New BRT System: Metrobus

Bus Rapid Transit System (BRT):

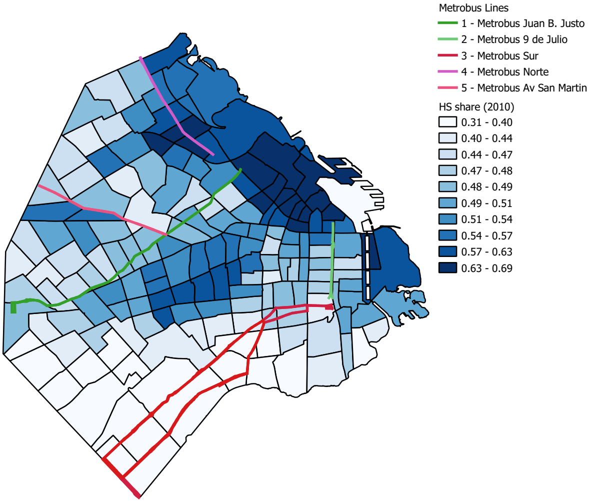
- Bus-based public transport system
- **Dedicated bus lanes.**
- **Platform level boarding.**
- Ideally similar speed gains to subways but cheaper to build.

Buenos Aires 2011-2017 - New BRT System: Metrobus

- 2011: Juan B Justo
- 2013: 9 de Julio and Sur
- 2015: Norte
- 2016: San Martin
- $\uparrow$ speed of buses $\approx$ 30% on average.
- For average commute time $\Rightarrow$ 110 hours saved in a year.



High-Skill Share in 2010 and Metrobus Lines



Subway Lines in 2010

Data

- Election registers for 2011, 2013, 2015, and 2017. Contains all citizens of voting age (>2.5m). Includes: *National ID number*, *address*, and *occupation*. $\rightarrow$ Track intra-city migration, update population every 2 years. Description
- Annual Household Survey (2010-2018) for the City of Buenos Aires $\rightarrow$ employment population by skill level.
- Commuting Survey for the city in 2010.
- Housing prices from online listings.
- Census data from 2010.

A Dynamic Quantitative Spatial Model of a City

Setup

- Combines:
  - *migration/dynamics* from Caliendo, et al. (2019) and Artuç et al. (2010) with
  - *commuting* from Ahlfeldt, et al. (2015)
- Closed city: I residence locations and J work locations.
- Two types of infinitely lived residents/workers: high-skilled and low-skilled.
- Two types of goods: housing and consumption good. Cobb-Douglas preferences.
- Assume rational expectations.

Model in a Nutshell

- Consumers/Workers are forward looking and choose where to work and live each period taking into account:
  - Commute costs
  - Wages
  - Moving/migration costs
  - Housing prices (rents)
  - Idiosyncratic shocks for residential location and workplace location.
- **Goods market:** Armington-style production using mix of high- and low-skilled labor.
- **Labor market:** labor demand depends on commuting costs and pop. distribution. Wages adjust to clear market.
- **Housing market:** Housing supply is fixed. Housing prices adjust every period to clear market.

Production Housing Mkt

Resident's Problem - Static Problem

- Cobb-Douglas on consumption (c_i^g) and floor space ($H_{R,ij}^g$).
- Income is effective wages ($w_j^g \varepsilon_j^g$) discounted by commute costs $d_{ij} = \exp(\kappa \tau_{ij})$.

$$\max_{\{c_i^g, H_{R,ij}^g\}} C_{ij}^g = \left(\frac{c_{ij}^g}{\alpha}\right)^{\alpha} \left(\frac{H_{R,ij}^g}{1-\alpha}\right)^{1-\alpha}$$

$$\text{subject to} \;\; c_{ij}^g + r_{Ri} H_{R,ij}^g = \frac{w_j^g \varepsilon_j^g}{d_{ij}}.$$

$$\Rightarrow C_{ij}^{g*} = \frac{w_j^g \varepsilon_j^g r_{Ri}^{\alpha-1}}{d_{ij}}.$$

Resident's Problem - Dynamic Problem

$$v^g_{n,t} = \max_{\{i,j\}} \left\{ \overbrace{C^{g*}_{nj,t}}^{\text{flow utility}} + \underbrace{\beta E_t[v^g_{i,t+1}]}_{\text{cont. value}} - \overbrace{\mu^g_{ni}}^{\text{mig. cost}} + \underbrace{\eta^g_{i,t}}_{\text{id. res. shock}} \right\}$$

Taking expectations w. r. t. the joint distribution of ε_j and η_i,

$$V^g_{n,t} = \tilde{T}_g \Phi^{\frac{1}{\theta_g}}_{Rgn,t} r^{\alpha-1}_{Rn} + \nu_g \ln \sum_{i=1}^{I} \exp\left(\beta V^g_{i,t+1} - \mu^g_{i,n}\right)^{\frac{1}{\nu_g}}. \tag{1}$$

Where

$$\overbrace{\Phi_{Rgn,t}}^{\text{CMA}} = \sum_j \left(\frac{w^g_{j,t}}{d_{nj,t}}\right)^{\theta_g},$$

Migration and Res. Population | Labor Supply

Transition Dynamics After New Transport Infrastructure

- Change in transport network $\rightarrow$ commute times ($d_{ij,t}$).
- Impacts spatial dist. of expected utility ($V^g_{i,t}$).
- But adjustment in residential pop. is gradual:
- **Residents wait for a large enough idiosyncratic shock ($\eta^g_{i,t}$) to pay moving cost μ^g_{ni} to move to i.**
- $\rightarrow$ Gradual changes in location characteristics and transition to SS.

Model Solution

- From Caliendo et al. (2019) $\rightarrow$ equilibrium in **first differences**. Extend dynamic exact-hat algebra to incorporate commuting.
- **Crucially**: use electoral register data to calculate residential migration matrices every two years (as well as migration elasticities).
- Calculate transport cost at time 0, ($d_{ij,0}$) (pre-BRT), add lines at times 1, 2 and 3, and calculate $d_{ij,t}$ for each period (2 years), then assume $d_{ij,t} = d_{ij,3}$ for all $t \geq 4$.

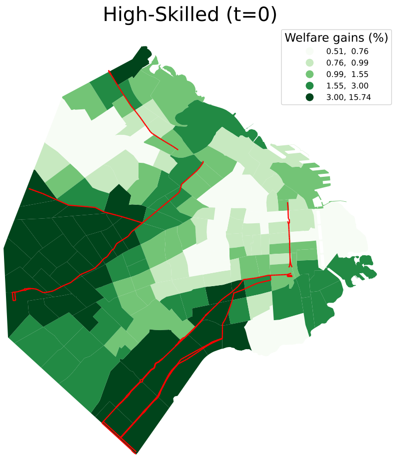
Estimation of model parameters

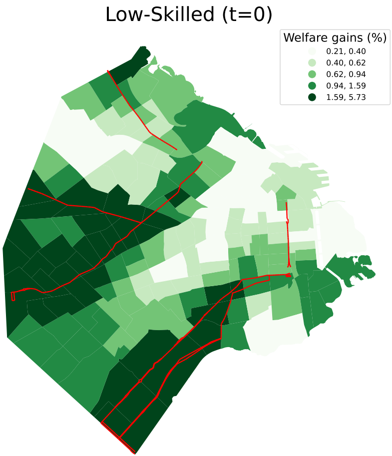
Welfare Gains for Residents at $t = 0$

- $V_{i,t}^{g}$ $\rightarrow$ expected utility at time t in location i for resident of skill type g.
- $\hat{V}_{i,t}^{g}$ $\rightarrow$ expected utility **without BRT**.
- Define $\delta_{n,t}^{g}$ as *consumption equivalent* compensating variation paid each period so that utility under counterfactual $\hat{V}_{i,t}^{g}$ (plus $\delta_{n,t}^{g}$) is equal to utility with new transport infrastructure ($V_{i,t}^{g}$).
- $\delta_{n,0}^{g}$ captures welfare gains for resident of skill level g living in n at time $t = 0$.

Welfare Gains: History Matters

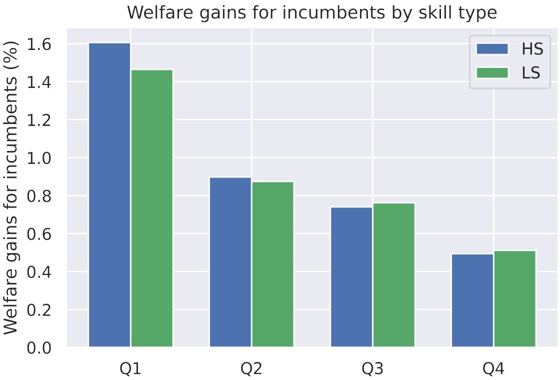
Initial location (before BRT) matters for gains from new infrastructure.





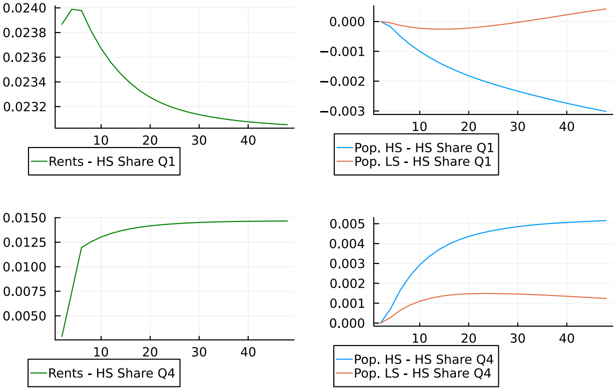
Welfare Gains for Incumbents By Quartile of HS share

- Avg. Welfare gains at $t = 0$ for locations < 1 km from line.
- On avg. welfare increased more in locations with lower initial HS share.
- BRT spatially "pro-poor" neighborhoods.



Short-run vs Long-Run: Dynamic Transitions Vary by Location

Evolution of housing prices (rents) and population relative to counterfactual (no BRT).



Location characteristics (rents, residential pop., etc.) adjust a different speeds and in different ways across locations.

Dynamics Transition Costs

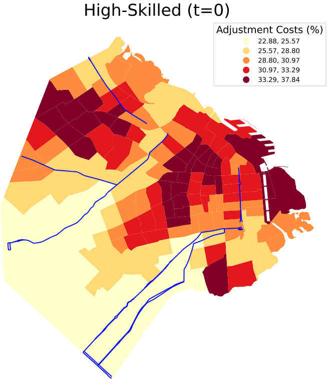
- Construct measure of adjustment cost that follows Davidson et al. (2010).

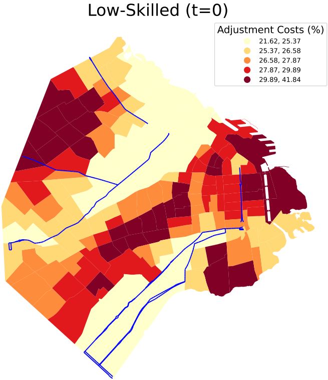
$$AC^g_{n,t} = \log\left(\frac{\delta^g_{n,SS}}{\delta^g_{n,t}}\right). \tag{2}$$

- Where $\delta^g_{n,t}$ is CD at time t, and $\delta^g_{n,SS}$ is the consumption equivalent compensating differential calculated starting from the steady state.
- **Intuition:** How much higher (or lower) would welfare be in location n if you could "jump" to new SS (as in static QSM models).

Dynamic Adjustment Costs at t=0

Larger AC further away from new BRT, where indirect gains require population changes.





Avg. $AC_h = 35\%$, Avg. $AC_l = 31\%$.

Conclusions

- Existing **static** models (Heblich et al. 2020; Tsivanidis, 2023; Severen 2023; etc.) assume: spatial eq. + "jump to SS".
- Accounting for dynamics matters because:
  - Initial exposure matters: large spatial heterogeneity in welfare gains conditional on initial location.
  - Dynamic transition matter: not accounting for transition overestimates gains by 35% for HS and 31% for LS residents.
  - Large spatial heterogeneity in dynamic adjustment costs.

Thank You Slide

Thank you!

Appendix

Neighborhood Migration Flows and Residential Population

$m_{in,t}$: fraction of agents that are residing in location n at the beginning of period t, and move to location i by the end of period t. From distribution of idiosyncratic preferences $\eta_{n,t}$ we obtain:

$$m^{g}_{in,t} = \frac{\left[\exp(\beta V^{g}_{i,t+1} - \mu^{g}_{in})\right]^{\frac{1}{\nu_g}}}{\sum_{m=1}^{N}\left[\exp(\beta V^{g}_{m,t+1} - \mu^{g}_{mn})\right]^{\frac{1}{\nu_g}}} \tag{3}$$

It follows that:

$$L^{g}_{Ri,t} = \sum_{n=1}^{I} \underbrace{m^{g}_{in,t} L^{g}_{Rn,t-1}}_{\text{Num. movers n to i}} \tag{4}$$

Back

Labor Supply

Given idiosyncratic productivity shocks ε_j^g, the probability that a worker that lives in i at time t decides to work in location j is:

$$\Pi_{j|tig} = \frac{(w_{j,t}^g / d_{ij,t})^{\theta_g}}{\sum_s \left(\frac{w_{s,t}^g}{d_{is,t}}\right)^{\theta_g}} = \frac{(w_{j,t}^g / d_{ij,t})^{\theta_g}}{\Phi_{Rgi,t}}. \tag{5}$$

Therefore, labor supply at time t for workplace location j will be

$$L_{Fj,t}^g = \sum_{i=1}^{I} \Pi_{j|tig} L_{Ri,t}^g, \tag{6}$$

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Equilibrium Definitions

- Given $\{L^g_{Ri,t}\}$ and $\{d_{ij,t}\}$ at time t, and $\{A_j\}$, a **temporary equilibrium**: as a vector of wages $\{w^g_j\}$ and floorspace prices $\{r_{Ri}\}$ that solve labor market clearing and floorspace market clearing at time t.
- Given L^g_{R0}, L^g_{F0},$\{m^g_{in,0}\}$ and $\{d_{ij,t}\}$, **sequential competitive equilibrium**: sequence of $\{L^g_{Rt}, L^g_{Ft}, m^g_t, w^g_t, r_{Rt}, V^g_t\}^\infty_{t=0}$ that solves residents' dynamic optimization problem, and temporary equilibrium at each time t.
- **Stationary equilibrium**: sequential competitive equilibrium such that all the elements of the vector $\{L^g_{Rt}, L^g_{Ft}, m^g_t, w^g_t, r_{Rt}, V^g_t\}^\infty_{t=0}$ are constant for all t.

Labor Market clearing | Housing Market clearing

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Labor Market clearing Housing Market clearing

Parameter Estimation

Parameters	Values	Source
Commute cost parameter	$\kappa = 0.01$	From Ahlfeldt et al. (2015)
Discount factor	$\beta = 0.92$	Based on Caliendo et al. (2019)
Non-housing consump. share	$\alpha = 0.7$	From hh. consumption survey 2010
Semi-elast. of commuting	$\theta_h = 3.7$, $\theta_l = 4.7$	Estimated as in Ahlfeldt et al. (2015) using commuting survey data
Inverse migration elast.	$\nu_h = 1.4$, $\nu_l = 1.8$	Estimated with intra-city migration data (following Artuç et al. 2010)

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Consumers/Workers

- Consumers/workers consume **consumption good** and **housing** (floorspace). They:
- Start period in residence location i.
- Observe idiosyncratic match productivities for each workplace location j (ε_j^g, Frechet).
- Choose a workplace location j to maximize wage income discounted by **commuting costs**. $\rightarrow$ **Labor supply.**
- Consume housing and consumption good. $\rightarrow$ **Housing demand and consumption demand.**
- Observe idiosyncratic preference shocks for each residence location next period (η_n^g, Gumbel).
- Choose residential location for next period. $\rightarrow$ **Migration probabilities.**

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Production

- J varieties of the consumption good, differentiated by location of production, and supplied in a competitive market.
- Consumers have CES preferences over each variety, with elasticity of substitution $\sigma > 1$.
- Firms solve static problem.
- Production function $\rightarrow$ Cobb-Douglas combines high- and low-skilled labor.
- Using all these assumptions, determine effective **labor demand** by skill as function of wage vector $\mathbf{w}_t = \{\{w_{jt}^h\}_{j=1}^J, \{w_{jt}^l\}_{j=1}^J\}$.

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Housing Market

- Fixed supply of housing (floorspace).
- Demand for floorspace by skill group comes from FOC of consumer problem.
- As population moves around, demand for housing changes $\Rightarrow$ change in housing prices.

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Floorspace Prices in 2010 and Metrobus Lines

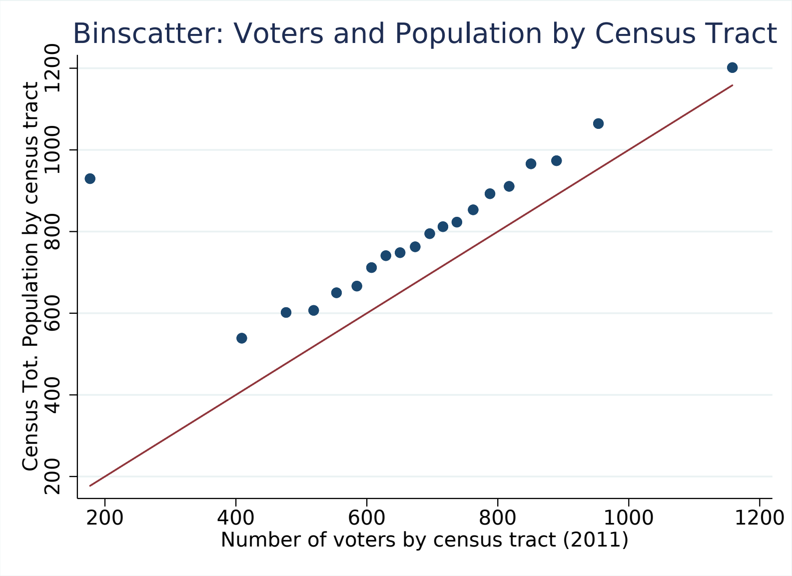
metrobus_lines_and_floorspace_prices_0_with_arrow.pdf

Electoral Register Data

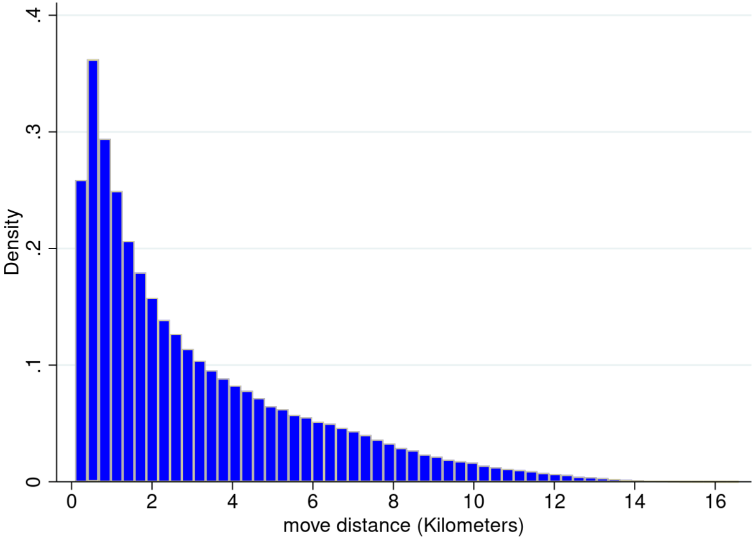
- Voting is compulsory for all Argentine citizens between 18 and 70.
- Your polling place is decided based on your residence.
- So the government keeps an "up to date" record of every person's address, which it updates for each election.
- I have electoral registry for the entire country for 2011, 2013, 2015, and 2017.
- Includes: National ID number, name, sex at birth, birth year, *address* as free text, and *occupation* as free text.
- Cleaned and geotagged (assigned GPS coordinates) for almost all addresses in the city of Buenos Aires (aprox. 2.5 million people).
- Residence changes are self-reported. This might imply under-reporting of changes in residence.

Back

Electoral Register Data - Population Comparison to 2010 Census Back



Electoral Registry Data - Distance Decay Back



ISCO 1 Digit Classification

1	Managers	
2	Professionals	
3	Technicians and associate professionals	High-Skilled
4	Clerical support workers	
6	Skilled agricultural, forestry and fishery workers	
5	Service and sales workers	
7	Craft and related trades workers	
8	Plant and machine operators, and assemblers	Low-Skilled
9	Elementary occupations	
0	Armed forces occupations	

Back

Occupations and Skill Level

hs_by_occupation.pdf

High-skill Share by Census Tract: Census vs Constructed Measure

census_tract_hs_plot.pdf

CMA for Low-Skilled in 2011

CMA_l_0.pdf

Δ CMA for Low-Skilled 2011-2017

change_CMA_l_8_census_tracts.pdf

Creating Skill Level Indicator

- Classify occupation descriptions using International Standard Classification of Occupations. Classification
- Divide Occupations by share of college educated workers into high-skilled and low-skilled: Graph
- Assign each person in electoral registry to high-skill/low-skill according to coded occupation.

Comparison with Census Data Back

Definition of Commuter Market Access (CMA)

$$CMA_{gn,t} = \sum_j \left(\frac{w_{j,t}^g}{d_{nj,t}} \right)^{\theta_g}$$

- g: High-Skilled (h) or Low-Skilled (l).
- n: residential location.
- j: workplace location.
- Commute costs: $d_{nj,t} = \exp(\kappa \tau_{ij})$, with τ_{ij} being commute time from i to j.
- $w_{j,t}^g$: model-consistent wages for type g at time t, calculated with residential and employment population.
- θ_g: semi-elasticity of commute shares with respect to commute times for skill type g.

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CMA for High-Skilled in 2011

Pre BRT: market access higher near subway lines and near Central Business District (CBD).

CMA_h_0.pdf

Δ CMA for High-Skilled 2011-2017

Δ CMA larger near new BRT lines and further from Central Business District (CBD).

change_CMA_h_0_census_tracts.pdf

Identification: Historical IV

- Large tramway system dismantled in 1963.
- Buses competed directly with trams, and kept same routes.
- Metrobus lines follow existing bus routes along large two-way avenues.
- Use subset of tramway system built by 1938 that ran through two-way avenues to instrument for placement of Metrobus lines.
- IV: predicted Δ CMA if BRT placement followed tramway lines. Details
- Identifying assumption: placement decided before 1938 of tramway not correlated with contemporary changes in unobservables.

Photo Map Back

Tramway in 1938 and Metrobus System

tramway_lines_and_metrobus.pdf

Tramway and Buses Competing in 1936

Horacio_Coppola_-_Buenos_Aires_1936_-_Sarmiento_y_Diag

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Historical IV - Details

$$CMA_{gn,t} = \sum_j \left(\frac{w^g_{j,t}}{d_{nj,t}} \right)^{\theta_g}$$

- $d_{nj,t} = \exp \kappa \tau_{nj}$.
- Where τ_{nj} are calculated using a model of the city's transportation network.
- ΔCMA comes from calculating τ_{nj} before and after the BRT.
- For IV, replace τ_{nj} after BRT with $\hat{\tau}_{nj}$, assuming BRT runs through tramway lines.

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Production - Details on Labor Demand

Output of the final good in location j at time t:

$$q_{jt} = A_j(\tilde{L}^l_{jt})^{\rho_j}(\tilde{L}^h_{jt})^{(1-\rho_j)}.$$

Solving producer's problem we obtain

$$w^h_{j,t}\tilde{L}^h_{Fj,t} = (1-\rho_j)X_{jt}, \tag{7}$$

$$w^l_{j,t}\tilde{L}^l_{Fj,t} = \rho_j X_{jt}. \tag{8}$$

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Production - Details on Labor Demand

- From CES demand we know that $X_{jt} = p_{jt}^{1-\sigma} X$, where
  - $X = \sum_{i=1}^{I} \alpha \sum_{g \in \{h,l\}} \bar{y}_{igt}$ is total city exp. on consumption.
  - $\bar{y}_{igt}$ is mean income for worker of type g in location i at time t.
- Perfect competition implies price equals marginal cost:

$$p_{jt} = A_j^{-1} (w_{jt}^{l})^{\rho_j} (w_{jt}^{h})^{(1-\rho_j)}.$$

- Combining previous results we obtain labor demand at each location j at time t for each skill type g as a function of the wage vector $\mathbf{w}_t = \{\{w_{jt}^{h}\}_{j=1}^{J}, \{w_{jt}^{l}\}_{j=1}^{J}\}$:

$$\tilde{L}_{Fj,t}^{g} = f_{jgt}(\mathbf{w}_t) \tag{9}$$

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$$\underbrace{L^g_{Fjt} = \frac{f_{jgt}(\mathbf{w}_t)}{\bar{\varepsilon}^g_{jt}}}_{\text{labor demand}} = \overbrace{\sum_{i=1}^{I} \frac{(w^g_{j,t}/d_{ij,t})^\theta}{\sum_j \left(\frac{w^g_{j,t}}{d_{ij,t}}\right)^\theta} L^g_{Ri,t}}^{\text{labor supply}}. \tag{10}$$

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Floorspace Market Clearing

- Assume fixed supply of floorspace $\bar{H}_{Ri}$.
- Demand for floorspace by skill group comes from FOC of consumer problem.
- Implies floorspace market clearing condition:

$$r_{Ri,t} = \frac{\sum_{g\in\{h,l\}} L^{g}_{Ri,t} \overbrace{\tilde{T}_g \Phi^{\frac{1}{\theta_g}}_{Rgi,t}}^{\text{total income by g}} (1-\alpha)}{\bar{H}_{Ri}}. \tag{11}$$

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Share of employment by commune for each skill level

workers_by_commune.pdf

Reduced Form vs. Model (Districts)

	Reduced Form (IV)		Model
	Δ log(hs share)		$\Delta \log(hs\ share_{BRT}) - \Delta \log(hs\ share_{CF})$
$\Delta \log(CMA)$	-2.31 (0.52)***	$\Delta \log(CMA_{BRT}) - \Delta \log(CMA_{CF})$	-2.20 (0.62)***
hs share$_0$	0.11 (0.05)**	hs share$_0$	-0.03 (0.04)
$\Delta \log(CMA) \times$ hs sh. avg.$_0$	4.14 (0.85)***	$\Delta \log(CMA_{BRT}) - \Delta \log(CMA_{CF}) \times hs\ share_0$	6.17 (1.65)***
cons	-0.42 (0.04)***	cons	-0.01 (0.02)
N	2,282	N	167

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Welfare Gains With Only Medium HS Share Lines Built

Gains are largest close to BRT line.

welfare_t_0_cf_med.png

Gains are almost the same than with full BRT system.

welfare_t_0_cf_med_comp.png

Welfare Gains With Only High HS Share Line Built

Gains are largest close to BRT line.

welfare_t_0_cf_high.png

Compared to full BRT system, gains are slightly smaller close to BRT line.

welfare_t_0_cf_high_comp.png

Reduced Form Results: Increase in Segregation by Skill Type

- Using IV specification:
  - $\frac{\Delta log(\text{HS share})}{\Delta \log(\text{CMA})}$ for census tract at **20th** percent. of HS share: **0.1**
  - $\frac{\Delta log(\text{HS share})}{\Delta \log(\text{CMA})}$ for census tract at **80th** percent. of HS share: **0.6**

	Δ log(hs share)				
	OLS	IV	OLS	IV	IV
Δ log(CMA)	-0.122	0.202	-2.797	-2.308	-2.609
	(0.087)	(0.096)**	(0.564)***	(0.522)***	(1.197)**
hs share$_0$	0.192	0.296	0.153	0.113	0.191
	(0.038)***	(0.044)***	(0.078)**	(0.052)**	(0.097)**
Δ log(CMA) $\times$ hs sh. avg.$_0$			4.629	4.143	3.489
			(0.895)***	(0.847)***	(1.925)*
cons	-0.457	-0.538	-0.445	-0.419	-0.404
	(0.026)***	(0.031)***	(0.053)***	(0.036)***	(0.063)***
Neigh. FE	NO	NO	NO	NO	YES
F first	-	410	-	403	135
N	2,282	2,282	2,282	2,282	2,282

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

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Reduced Form Results: Housing Prices Increase more in Richer Neighborhoods

- Using IV specification:
  - $\frac{\Delta \mathit{log}(\text{floorspace price})}{\Delta \log(\text{CMA})}$ at $\mathbf{20^{th}}$ percent. of HS share: $\mathbf{0.3}$
  - $\frac{\Delta \mathit{log}(\text{floorspace price})}{\Delta \log(\text{CMA})}$ at $\mathbf{80^{th}}$ percent. of HS share: $\mathbf{1}$

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Why a Dynamic Model?

- Previous literature (Tsivanidis 2019, Ahlfeldt, et al. 2015, etc.) rely on comparative statics after the policy for welfare analysis.
- This tells us welfare gains in location for residents living there **after** changes (new equilibrium).
- But people can move around.
- Policy maker interested in welfare gains for residents living there **before** changes (**incumbents**).
- Must model explicitly migration $\Rightarrow$ forward-looking agents.

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Transport Use by Mode of Transport

81% of low-skilled and 73% of high-skilled commute by public transport or walking within the city.

Mode of Transport	Low-Skilled	High-Skilled	Total
Car / motorcycle	16.5%	22.9%	19.3%
Taxi	2.1%	3.7%	2.8%
Bus	37.1%	39.3%	38.1%
Subway	4.4%	14.5%	8.8%
Train	1.6%	3.2%	2.3%
Walking / bicycle	38.1%	16.3%	28.5%
Other	0.2%	0.0%	0.1%

Table: Percentage of trips made by mode of transport by skill type. Source: 2010 mobility survey.

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Resident's Problem - Static Problem

- Cobb-Douglas on CES bundle of consumption varieties (c) and floor space (H^R).
- Income is effective wages ($w_j^g \varepsilon_j^g$) discounted by commute costs $d_{ij} = \exp(\kappa \tau_{ij})$.
- Implies indirect utility:

$$\Rightarrow C_{ij}^{g*} = \frac{w_j^g \varepsilon_j^g r_{Ri}^{\alpha-1}}{d_{ij}}.$$

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$$v^g_{n,t} = \max_{\{i,j\}} \left\{ \overbrace{C^{g*}_{nj,t}}^{\text{flow utility}} + \underbrace{\beta E_t[v^g_{i,t+1}]}_{\text{cont. value}} - \overbrace{\mu^g_{ni}}^{\text{mig. cost}} + \underbrace{\eta^g_{i,t}}_{\text{id. res. shock}} \right\}$$

Taking expectations w. r. t. the joint distribution of ε_j and η_i,

$$V^g_{n,t} = \tilde{T}_g \Phi^{\frac{1}{\theta_g}}_{Rgn,t} r^{\alpha-1}_{Rn} + \nu_g \ln \sum_{i=1}^{I} \exp\left(\beta V^g_{i,t+1} - \mu^g_{i,n}\right)^{\frac{1}{\nu_g}}. \qquad (12)$$

Where

$$\overbrace{\Phi_{Rgn,t}}^{\text{CMA}} = \sum_j \left(\frac{w^g_{j,t}}{d_{nj,t}}\right)^{\theta_g},$$

and $\tilde{T}_g = T_g \times \Gamma(1 - 1/\theta_g)$, with T_g the scale parameter of the e.v. type II distribution for type g.

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$m_{in,t}$: fraction of agents that are residing in location n at the beginning of period t, and move to location i by the end of period t. From distribution of idiosyncratic preferences $\eta_{n,t}$ we obtain:

$$m^g_{in,t} = \frac{\left[\exp(\beta V^g_{i,t+1} - \mu^g_{in})\right]^{\frac{1}{\nu_g}}}{\sum_{m=1}^{N}\left[\exp(\beta V^g_{m,t+1} - \mu^g_{mn})\right]^{\frac{1}{\nu_g}}} \tag{13}$$

It follows that:

$$L^g_{Ri,t} = \sum_{n=1}^{I} \underbrace{m^g_{in,t} L^g_{Rn,t-1}}_{\text{Num. movers n to i}} \tag{14}$$

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The probability that a worker that lives in i at time t decides to work in location j is:

$$\Pi_{j|tig} = \frac{(w^g_{j,t}/d_{ij,t})^{\theta_g}}{\sum_s \left(\frac{w^g_{s,t}}{d_{is,t}}\right)^{\theta_g}} = \frac{(w^g_{j,t}/d_{ij,t})^{\theta_g}}{\Phi_{Rgi,t}}. \tag{15}$$

Therefore, labor supply at time t for workplace location j will be

$$L^g_{Fj,t} = \sum_{i=1}^{I} \Pi_{j|tig} L^g_{Ri,t}, \tag{16}$$

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Subway Lines in 2010

subway_2010_map.pdf