The Aggregate and Distributional Effects of Urban Transit Infrastructure: Evidence from Bogota's TransMilenio[1]

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Motivation

- This paper analyzes the construction of the world's largest Bus Rapid Transit (BRT) system–TransMilenio–in Bogotá, Colombia.
- BRT provide an attractive alternative to subways in rapidly growing developing country cities since they are able to deliver similar reductions in commuting times at a fraction of the cost, and are much faster to build.
- **Why is this important?** To understand the implications of improving public transit on worker welfare, the GDP and the rents of the cities.

Research Question

How large are the benefits to improving transit in cities, and how are the gains shared between low and high skilled workers?

Target

How to attack this question?

1. First, Tsivanidis builds a quantitative general equilibrium model of a city where low- and high-skill workers sort over where to live, where to work, and whether or not to own a car.
2. Second, Tsivanidis develops a new reduced form methodology derived from general equilibrium theory to evaluate the effects of transit infrastructure and use it to empirically assess TransMilenio's impact on city structure.
3. Third, Tsivanidis structurally estimates the model and quantify the effects of the system.

Overview

1. Background
   a) Structure of Bogotá
   b) Commuting Prior and Posterior to TransMilenio
2. A Quantitative Model of a City with Heterogeneous Skills
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   b) Quantifying the Effect of TransMilenio
5. Advantages and limitations

Background

Structure of Bogotá: Bogotá is the political and economic center of Colombia, accounting for 16 % and 25 % of the country's population and GDP respectively.

Residence and Employment

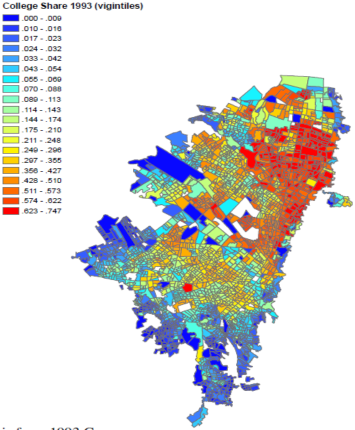
- Bogotá is characterized by a high degree of residential segregation between the rich and poor.
- The high-skilled or the college-educated are much more likely to live in the North, with low-skilled workers located primarily in the city's South and periphery.
- While overall employment is concentrated along two bands to the west and north of the city center, high-skill intensive industries are located more towards the North.

Background

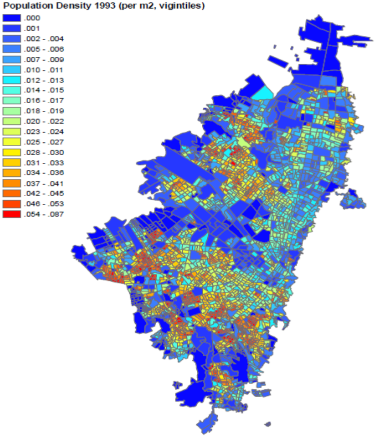
Structure of Bogotá

Figure 2: Population Density and Demographic Composition in 1993

(a) College Share



(b) Population Density



Note: Data is from 1993 Census.

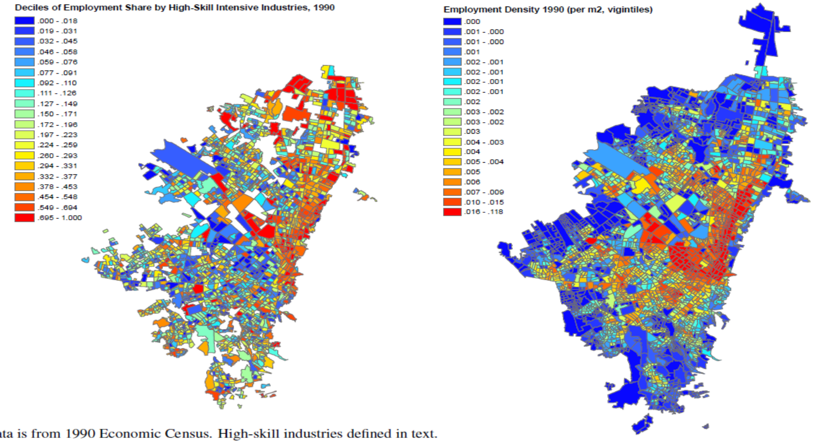
Background

Structure of Bogotá

Figure 3: Employment Density and Industry Composition in 1990

(a) High-Skill Industry Share

(b) Employment Density



Note: Data is from 1990 Economic Census. High-skill industries defined in text.

Commuting Prior to TransMilenio

- In 1995 the average trip to work in Bogotá took 55 minutes.
- The vast majority of these commutes was taken by bus (73 %), followed by car (17 %) and walking (9 %).
- Public transportation in the city was highly inefficient.

Commuting Posterior to TransMilenio

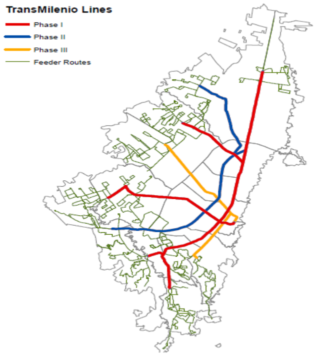
- Opened in 2000, TransMilenio is the world's most used BRT system with a daily volume of over 2.2mn trips.
- TransMilenio is more likely to be used for commutes to work rather than leisure trips, motivating the focus on access to jobs in this paper.

Background

Commuting Prior and Posterior to TransMilenio

- TransMilenio was approved in March 1998. First phase added 42 km.
- Phases 2 and 3 added an additional 70km in 2006 and 2011.

Figure 4: TransMilenio Routes



A Quantitative Model of a City with Heterogeneous Skills

This section presents a general equilibrium model of a city.

- The city is comprised of a discrete set of locations $i \in I$.
- The city is populated by different worker skill groups indexed by $g \in G = \{L, H\}$, each of which has a fixed population L_g. High- and low-skill workers decide where to live, where to work, and how to commute between a large number of discrete locations.
  - Tsivanidis assumes timing is such that workers first choose where to live and whether or not to own a car, and then choose where to work.
- Public transit is available to everyone to commute between home and work, but only those willing to pay to own a car have the option to drive.

A Quantitative Model of a City with Heterogeneous Skills

- Firms in different industries $s \in S$ produce using labor and commercial floorspace under perfect competition. Some locations are more productive than others.
- Each industry differs in its demand for skills: for example, hotels and restaurants demand more low-skilled workers while financial services require more highskilled individuals. Since industries may be located in different places, wages for low- and high-skill workers will differ across the city.

A Quantitative Model of a City with Heterogeneous Skills

Workers

A worker ω in group g chooses a location i in which to live, a location j in which to work, and whether or not to own a car denoted by $a \in \{0, 1\}$.

Assuming that individuals need a minimum amount of floorspace $\bar{h}$ in which to live, utility of a worker who has made choice (i, j, a) is:

$$\max_{\{C_i(\omega), H_{Ri}(\omega)\}} u_{iag} C_i(\omega)^{\beta} (H_{Ri}(\omega) - \bar{h})^{1-\beta} \nu_{ia}(\omega)$$

s.t.

$$C_i(\omega) + r_{Ri} H_{Ri}(\omega) + p_a a = \frac{w_{jg} \varepsilon_j(\omega)}{d_{ija}}$$

A Quantitative Model of a City with Heterogeneous Skills

Solving for the optimal demand for housing and consumption good yields the following expression for indirect utility:

$$U_{ijag}(\omega) = u_{iag}(\frac{w_{jg}\varepsilon_j(\omega)}{d_{ija}} - p_a a - r_{Ri}\bar{h})r_{Ri}^{\beta-1}\nu_{ia}(\omega)$$

where $d_{ija} = e^{\kappa t_{ija}}$, and $\kappa > 0$ controls the size of these commute costs.

Having chosen where to live i and whether or not to own a car a, individuals draw a vector of match-productivities with firms in locations across the city. Tsivanidis assume this is drawn from a multivariate Frechet distribution:

$$F_g(\varepsilon_1, ..., \varepsilon_J) = exp(-[\sum_j T_g \varepsilon_j^{-\frac{\theta_g}{1-\rho_g}}]^{1-\rho_g})$$

The parameter θ_g measures the dispersion of productivities for type-g workers.

A Quantitative Model of a City with Heterogeneous Skills

Properties of the Frechet distribution imply that the probability a worker of type g who has made choice (i, a) decides to work in j is given by:

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

Residential Location and Car Ownership Decisions. The supply of type-g individuals to location i and car ownership a is:

$$L_{Riag} = \lambda_U (u_{iag}(\bar{y}_{iag} - p_a a - r_{Ri}\bar{h}) r_{Ri}^{\beta-1})^{\eta_g}$$

Intuitively, workers are more attracted to locations with high amenities, expected incomes and low house prices.

A Quantitative Model of a City with Heterogeneous Skills

Firm Commuter Market Access and Labor Supply. Using the commuting probabilities, the supply of workers to any location is found by summing over the number of residents who commute there:

$$L_{Fg} = \sum_{i,a} \pi_{|iag} L_{Riag}$$

Firms

There are $s \in \{1, ..., S\}$ industries which produce varieties differentiated by location in the city under perfect competition. Firms produce using a Cobb-Douglas technology over labor and commercial floorspace

A Quantitative Model of a City with Heterogeneous Skills

$$Y_{js} = A_{js} N_{js}^{\alpha_s} H_{Fjs}^{1-\alpha_s}$$

where

$$N_{js} = (\sum_g \alpha_s L_{Fjgs}^{\frac{\sigma}{1-\sigma}})^{\frac{\sigma}{1-\sigma}}$$

Factor Demand Solving the firm's cost minimization problem, the demand for labor and commercial floorspace is

$$L_{Fjgs} = (\frac{w_{jg}}{\alpha_{sg} W_{ja}})^{-\sigma} N_{js}$$

$$H_{Fjs} = (1 - \alpha_s)\frac{X_{js}}{r_{Fj}}$$

where, r_{Fj} is the price of commercial floorspace in j and X_{js} is firm sales.

A Quantitative Model of a City with Heterogeneous Skills

Market Clearing

There is a fixed amount of floorspace H_i in any location, a fraction ϑ_i of which is allocated to residential use and $1 - \vartheta_i$ to commercial use. For any allocation, market clearing for residential floorspace requires that the supply of residential floorspace $H_{Ri} = \vartheta_i H_i$ equals demand:

$$r_{Ri} = (1 - \beta) \frac{E_i}{H_{Ri} - \beta \bar{h} L_{Ri}}$$

Likewise, the supply of commercial floorspace $H_{Fj} = (1 - \vartheta_i) Hj$ must equal that demanded by firms:

$$r_{Fj} = \frac{\sum_s (1 - \alpha_s)(W_{js}^{\alpha_s} r_{Fj}^{1-\alpha_s} / A_{js})^{1-\zeta} X}{H_{Fj}}$$

A Quantitative Model of a City with Heterogeneous Skills

Worker Welfare

Tsivanidis equate the overall welfare of group-g residents with the expected utility prior to drawing their idiosyncratic preferences in the first stage given by:

$$\bar{U}_g = \gamma_{\eta,g}[\sum_{i,a}(u_{iag}(\bar{y}_{iag} - p_a a - r_{Ri}\bar{h})r_{Ri}^{\beta-1})^{\eta_g}]^{1/\eta_g}$$

To build intuition for the channels through which changes in the transit network affect welfare, Tsivanidis totally differentiates the expression for average utility (the change in utility in response to a small change in commute costs).

Empirical Analysis

Using The Model To Guide Empirical Work

Consider a simplification of the model with one group of workers, firms and transit modes and a fixed allocation of residential and commercial floorspace.

Regression Framework In this simplified model, the equilibrium reduces to the following system

$$L_{Ri} = \lambda_U \left(u_i \Phi_{Ri}^{1/\theta} r_{Ri}^{\beta-1} \right)^{\eta}$$

$$r_{Ri} = \frac{1-\beta}{H_{Ri}} \Phi_{Ri}^{1/\theta} L_{Ri}$$

$$\tilde{L}_{Fi} = w_j^{\theta-1} \tilde{\Phi}_{Fj}$$

$$\tilde{L}_{Fi} = \frac{1}{\alpha} w_i^{\alpha(1-\sigma)-1} A_i^{\sigma-1} r_{Fi}^{(1-\sigma)(1-\alpha)} P^{\sigma-1} E$$

$$r_{Fi} = \left(\frac{A_i^{\sigma-1} w_i^{-\alpha(\sigma-1)} P^{\sigma-1} E}{(1-\alpha) H_{Fi}} \right)^{\frac{1}{1+(\sigma-1)(1-\alpha)}}$$

Taking logs, stacking the equations, and considering long-differences between two time periods, we obtain the following reduced form:

$$\Delta ln(Y_i) = A^{-1} B_R \Delta ln(\Phi_{Ri}) + A^{-1} B_F \Delta ln(\Phi_{Fi}) + A^{-1} e_i$$

where $\Delta ln(Y) = [\Delta Ln(L_{Ri}), \Delta Ln(r_{Ri}), \Delta Ln(r_{Fi}), \Delta Ln(L_{Fi})]'$

The regression specification reflects both the direct effect (in the B_R and B_F coefficient vectors) and the indirect effect (in A^{-1}) as the response to improved CMA filters through labor and land markets.

Empirical Analysis

Data

1. Primary source of population data is the Department of Statistics' (DANE) General Census of 1993 and 2005.
2. Housing market data between 2000 and 2012 comes from Bogotá's Cadastre. It reports the use, floorspace and land area, value per square meter of land and floorspace.
3. Microdata on commuting behavior come from the city's Mobility Survey administered by the Department of Mobility and overseen by DANE in 2005, 2011 and 2015.
4. Employment data at the worker level come from DANE's Continuing Household Survey (ECH) between 2000 and 2005, and its extension into the Integrated Household Survey (GEIH) for the 2008-2015.

Empirical Analysis

Target: Empirically assess the effect of TransMilenio on land and labor markets outcomes through improved CMA. Taking the first two entries of the reduced form system delivers the baseline specification:

$$\Delta ln Y_{Rit} = \beta \Delta ln \Phi_{Rit} + \alpha_I + \gamma' X_{it} + \varepsilon_{Rit}$$

Resident Commuter Market Access Φ_{Rit}.

Typically this regression will be estimated in long-differences over a pre- and post-period.

Empirical Analysis

Challenges to Identification There are two key challenges to estimating the specification:

- Changes in market access contain population and employment in both periods. Local productivity and amenity shocks that drive movements in residence and employment will therefore be mechanically correlated with the error.

  $\Longrightarrow$ *Address this by instrumenting for changes in CMA (Commuter Market Access) holding population and employment fixed at their initial values*

- Growth in CMA may be correlated with the error if routes targeted neighborhoods with differential trends in productivities or amenities.

  $\Longrightarrow$ *The instrument for the change in CMA is then defined as the difference between this predicted CMA under TransMilenio and its value in the initial period without the system.*

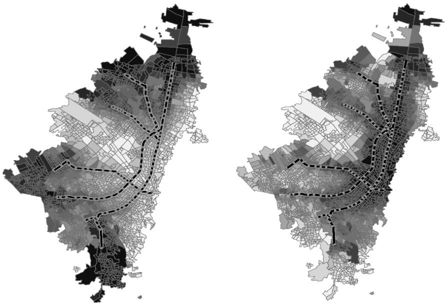
Empirical Analysis

Distribution of changes in commuter access across the city induced by the construction of the first two phases of the system.

Plot shows the baseline instrument for the change in CMA induced by holding population and employment fixed at their initial level and changing only commute costs. Darker shades indicating a larger increase in CMA.

Figure 1: Change in Commuter Market Access from TransMilenio

(a) Resident CMA (b) Firm CMA



Structural Estimation

Parameter Estimation

The procedure to estimate the parameters of the model can be summarized as follows:

- **Step 1.** Calibrate and estimate a subset of parameters without solving full model.
- **Step 2.** Solve for wages using parameters from step 1.
- **Step 3.** Estimate remaining elasticities via GMM using moments similar to reduced form analysis.
- **Step 4.** With all parameters in hand, invert the model to recover unobservables.

Structural Estimation

Quantifying the Effect of TransMilenio

Removing the System: Tsivanidis use the estimated model to quantify the impact of TransMilenio on GDP, total rents and welfare by simulating the effect of its removal from the 2012 equilibrium.

Table 11: Effect of Removing Phases 1 and 2 of TransMilenio

	No Spillovers	Spillovers
Panel A: Closed City		
GDP	3.119	3.918
Rents	3.285	3.721
Welfare Low	3.444	3.814
Welfare High	3.651	4.169
Inequality	0.215	0.369
Panel B: Open City		
GDP	10.347	15.596
Rents	13.145	16.275
Population Low	8.562	10.744
Population High	9.543	12.303
Relative Population	1.072	1.747

Structural Estimation

Quantifying the Effect of TransMilenio

Cost vs Benefits: How did the output gains from TransMilenio compare with the costs of the system?

	Closed City		Open City	
	No Spillovers	Spillovers	No Spillovers	Spillovers
Panel A: Costs & Benefits				
NPV Increase GDP (mm)	57,359	72,052	190,282	286,812
Capital Costs (mm)	1,137	1,137	1,137	1,137
NPV Operating Costs (mm)	5,963	5,963	5,963	5,963
NPV Total Costs (mm)	7,101	7,101	7,101	7,101
NPV Net Increase GDP (mm)	50,258	64,952	183,181	279,711
% Net Increase GDP	2.73	3.53	9.96	15.21

Note: All numbers in millions of 2016 USD. NPV calculate over a 50 year time horizon with a 5% discount rate. Each column describes to a different model. Row (1) reports the increase in NPV GDP from phases 1 and 2 of the TransMilenio network from the baseline equilibrium in 2012 (calculated as the fall in GDP from its removal). Row (2) reports the capital costs of constructing the system, averaging 12.23mm per km over 93km of lines. Row (3) reports the NPV of operating costs, defined conservatively as farebox revenue in 2012. Row (4) reports the NPV of total costs, while row (5) reports the difference between row (1) and row (4). Row (6) reports this difference as a percent of the NPV of GDP in 2012. Row (7) reports the government revenue from the distance band-based land value capture scheme as described in the text, while row (8) reports this as a percentage of capital costs. Rows (9) and (10) report the same figures for the commuter market access-based LVC scheme.

Comparison with VTTS Approach: The typical approach to evaluate the gains from commuting infrastructure is based on the Value of Travel Time Savings (VTTS) approach. In this framework, the benefits from new infrastructure are given by the marginal value of time times the amount of time saved. Welfare gains under VTTS are driven solely by mode choice: the low-skilled gain more than the high-skilled in row (1).

Table 15: Comparison with Value of Time Savings Calculation

	Welfare Low	Welfare High	Output	Rents
VTTS	4.203	3.396	0.000	0.000

Note: The first row reports the percentage change in each variable due to TransMilenio from a Value of Time Savings approach as described in the appendix. The second row reports the values from my model with the same θ, η and perfect substitutes in production, in partial equilibrium where commute times change but all prices and location decisions are fixed. The third row does the same in the baseline model. The fourth row reports the values from my model with full general equilibrium adjustment. Partial equilibrium results computed in the same way as in Table 13, but with spillovers set to their estimated values.

Advantages and limitations

Advantages

- The methodology developed in this paper can be applied to the specific geography and transit systems of any city where data on residence and employment are available to predict the effects of new infrastructure.
- Ready to data.
- This model allows a welfare analysis.

Limitations

- The structural model explains everything ... this is a problem in itself.
- The empirical model does not allow an analysis in welfare.
- The structural model does not explain the dynamics of GDP, employment and welfare as a result of the implementation of the BRT system over time.

Referencias

- Tsivanidis, N. (2018). The Aggregate and Distributional Effects of Urban Transit Infrastructure: Evidence from Bogotá's TransMilenio. Unpublished manuscript. https://economics.stanford.edu/sites/g/files/sbiybj9386/f/tsivanidis$_j$*mp.pdf*
- Redding, S. J., Rossi-Hansberg, E. (2017). Quantitative spatial economics. Annual Review of Economics, 9, 21-58.