Commuting Infrastructure in Fragmented Cities*

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Abstract

Cities are divided into local governments responsible for local roads, which are oftentimes used by external commuters. In this paper, I study how metropolitan fragmentation affects the provision of commuting infrastructure and the distribution of economic activity. I develop a quantitative spatial model in which municipalities compete for residents and workers by investing in commuting infrastructure to maximize net land value in their jurisdictions. In equilibrium, relative to a central metropolitan planner, municipalities underinvest in areas near their boundaries and overinvest in core areas away from the boundary. Infrastructure investment in fragmented cities results in higher cross-jurisdiction commuting costs, more dispersed employment, and more polycentric patterns of economic activity. Estimating the model using data from Santiago, Chile, I find substantial gains from centralizing investment decisions. Centralization increases aggregate infrastructure investment and population. More importantly, for a given amount of investment, centralization yields large welfare gains due solely to more efficient infrastructure allocation.

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1 Introduction

Metropolitan areas are politically fragmented: in the OECD, the average city with more than 500,000 people is divided into 74 local municipalities (Brueckner & Selod, 2006). Although some cities coordinate city-wide public transportation services, this cooperation does not extend to all types of infrastructure investment for transportation purposes. Many decisions on local infrastructure, like roads, avenues, and bridges, are made by decentralized municipalities.

Municipal infrastructure investment decisions affect residents and businesses in both the municipality where the decision is made and in neighboring municipalities. Many commuters live and work in different municipalities and, hence, rely on local infrastructure built by other municipalities. For example, in Santiago, Chile, 73% of commuters' trips span across municipalities, and 80% of the typical trip's travel time is spent in municipal infrastructure.[1] Since economic interactions in cities span across municipalities, how does failure to coordinate distort the optimal allocation of commuting infrastructure and aggregate welfare?

In this paper, I study how political decentralization affects the provision of local commuting infrastructure and, consequently, the distribution of population and employment within cities and welfare. To illustrate why decentralized investment decisions by municipalities can be inefficient, let's consider the following example: There are two municipalities, Downtown and Suburb, that make investments to maximize their land value.[2] Downtown evaluates whether to build a new road to Suburb, expanding the commuting capacity between the two municipalities. The construction of such a road would lead to households adjusting their choices of where to live and work. On the one hand, Downtown could expect a decrease in its residential population as households choose to relocate to Suburb for more affordable housing, resulting in a decline in residential property values in Downtown. On the other hand, the improved connectivity with Suburb would attract more workers to Downtown due to easier commuting, thereby increasing its commercial property values. Downtown's decision to proceed with the road hinges on whether the overall change in land value in its jurisdiction outweighs the road's costs. However, if a hypothetical metropolitan government were to decide whether to build the road, it would consider not only the change in land value in Downtown but also the impact on residential and commercial land values in Suburb.

To evaluate the potential losses from decentralization, I develop a quantitative spatial model of the internal structure of a metropolitan area divided into local municipalities that invest in infrastructure within their jurisdiction to maximize local land value net of building costs. The metropolitan area is embedded in a greater economy, where households choose whether to move

[1] In the U.S., there is significant commuting across jurisdictions. Monte, Redding, and Rossi-Hansberg (2018) document that in the median county in the year 2000, 39% of commuters work outside the county where they live. Moreover, most roads are municipal, and municipalities are typically smaller geographical units than counties.

[2] If households are mobile, welfare benefits of local public goods will be capitalized into land values (Starrett, 1981).

into the city. Households also choose where to live and work within the city and commute between these locations through the network of infrastructure built by municipalities. Locations within the metropolitan area are heterogeneous in their productivity, residential amenities, and position within the network.[3] Municipal governments understand that improving infrastructure in a link in the network affects the distribution of residents and employment throughout the city. When deciding whether to invest in infrastructure, municipal governments evaluate whether the investment would result in more or fewer residents and workers in their jurisdiction and how these population shifts would affect its land value. However, municipal governments do not account for the benefits or costs accrued to other jurisdictions.

The theoretical framework has two core predictions about infrastructure misallocation in the decentralized equilibrium relative to centralized metropolitan planning. The first prediction is about the pattern of investment *within* municipalities, and the second prediction is about the overall level of investment *across* municipalities.

First, within their jurisdiction, municipalities underinvest in areas near their boundaries where additional infrastructure benefits the neighboring jurisdictions through households relocating outside their jurisdiction. This is a key prediction of the model: infrastructure declines with proximity to the boundary and changes discontinuously at the boundary. Conversely, municipalities might overinvest in core locations, that is, locations away from the boundary.

Second, whether a municipality's overall level of investment is higher or lower relative to the optimum is a function of its productivity, its residential amenities, and its location relative to their neighboring jurisdictions. Municipalities with the advantage of central or productive land underinvest because higher commuting costs encourage households to live closer to their workplaces, which, in turn, drives up residential land values in those areas. Municipalities located on the periphery or with high residential amenities, on the other hand, tend to overinvest. Lower commuting costs allow residents to move farther from work and enjoy lower housing prices and better residential amenities, benefiting residential municipalities.[4] Finally, municipalities located in between productive and residential municipalities underinvest the most. This is because, given their relative location to high-wage locations and high-amenity locations, investment in these areas results in the outflow of both workers and residents.

Given this pattern of infrastructure misallocation, decentralization leads to higher commuting

[3] Productivity, residential amenities, and position within the network are exogenous in the model. The position of a location within the network refers to its placement in the broader metropolitan area; some locations are more central or well-connected than others.

[4] Which municipalities tend to overinvest or underinvest depends on how municipalities value residents relative to workers. Given the structure of my model and using standard parameter values, municipalities value residents more than workers. If municipalities value workers more, some of the patterns described above would switch. For example, municipalities with productive locations would overinvest relative to a metropolitan planner. Importantly, my framework allows for alternative objective functions for the governments and can be applied flexibly to different political settings.

costs across municipalities, dispersed employment, and shorter commutes. Employment is less concentrated in productive locations, and households tend to live closer to where they work, resulting in a more polycentric urban pattern. In the aggregate, the metropolitan area has a smaller total population and lower welfare.

To quantify the implications of decentralized infrastructure investment, I focus on Santiago in Chile. Santiago's metropolitan area is divided into 34 municipalities, and each has control over transportation planning within its own boundaries. Municipalities' two main sources of tax revenue, aside from transfers, are property taxes and commercial permits.[5] Chile is otherwise a relatively centralized country. For example, the national government provides most public school funding in Chile, and students are not restricted to attending the public school of their municipality of residence. Furthermore, tax rates are uniform across municipalities and established by the national government. These characteristics allow me to focus on differences in commuting infrastructure among local municipalities.

I use data from Santiago's metropolitan area to test the model's key predictions. I start by documenting a significant discontinuity in the density of roads at the border between municipalities. I also show that infrastructure increases with the distance to the border. Both these patterns are consistent with the forces in the model: municipalities' incentives to invest change discontinuously at the border, and the fraction of benefits captured by neighboring municipalities is larger close to the border.

I then estimate the model's key parameters. First, following the standard approach in the literature, I use data on commuting flows between residential and work locations and travel time data to estimate the households' commuting parameters and the exogenous location characteristics (productivity and amenities) that match the observed distribution of residents and employment. Second, I collect data on travel speed across different locations in the city and combine this data with administrative data on traffic flows to estimate the congestion elasticity of travel times. Third, I exploit the discontinuity in infrastructure at the border between municipalities to estimate the infrastructure elasticity of travel times. The infrastructure elasticity controls how travel times improve as a function of the density of roads in an area. Finally, I use publicly available data on the network of roads and information on travel times to construct the network of links between locations within the city and estimate the baseline infrastructure level in each link.

With the estimated model, I quantify political decentralization's aggregate and local effects. I examine a counterfactual scenario where a metropolitan planner chooses the infrastructure for Santiago's entire network. The main result from this counterfactual exercise is that centralizing investment decisions would substantially increase investment: expenditure in infrastructure would

[5] In 2012, on average, 41% of municipalities' income came from transfers between municipalities and from the national government. Out of their income raised from local taxes and permits, 37% comes from property taxes, and 39% comes from commercial permits (Bravo Rodríguez, 2014).

be 98% higher. In response to the new infrastructure, the city would be 7% larger in population, and welfare would be 2% higher. These results suggest there is aggregate underinvestment in the current fragmented equilibrium.

Importantly, the gains from centralizing are not only about building more but also about allocating the infrastructure more efficiently. I consider a counterfactual scenario where a metropolitan planner chooses the infrastructure but is constrained to spending the same aggregate amount as in the decentralized equilibrium. By shifting infrastructure towards the locations that underinvest the most, the constrained metropolitan planner achieves 63% of the aggregate gains in welfare and population from the unconstrained counterfactual without increasing the total amount of investment.

Some municipalities are worse off in the centralized counterfactuals. These municipalities have lower levels of productivity and residential amenities compared to their neighboring areas. Hence, when infrastructure improvements occur within their jurisdiction, there is an outflow of residents towards the suburbs and an outflow of workers towards the productive central municipalities. In the centralized equilibrium, these municipalities significantly boost their infrastructure investments but reap few benefits, as the advantages largely accrue to their neighboring jurisdictions.

The municipalities with the biggest gains from centralization are the ones where poor households live today. Lower-income households are concentrated in municipalities in the city's south and west peripheries. These locations are far from the productive areas where jobs are located and are next to the municipalities that most underinvest in the baseline scenario. As a result, lower-income households commute farther and through areas with fewer roads than their higher-income counterparts. Therefore, lower-income households would benefit the most from the increased investment in the municipalities they must commute through to get to work.[6]

Related literature. The benefits and costs of political decentralization have been widely studied, dating back to Tiebout (1956). Decentralization's key benefit is the efficient allocation of local public services in the presence of imperfect information or heterogeneous preferences for public goods (Wallis & Oates, 1988; Oates, 2005). Local governments can have better information about local conditions than central governments, enabling them to tailor services to residents' needs. Moreover, if households have heterogeneous preferences for public goods, they benefit from having a menu of options. Another important benefit of decentralization is enhancing competition across governments, as households can "vote with their feet."[7]

[6] Note that the theoretical framework in this paper does not account for household income heterogeneity; therefore, the counterfactual analysis is not suitable to study how the income composition of municipalities would change in response to the new infrastructure.

[7] Agrawal, Hoyt, and Wilson (2022) provide a great survey of the recent empirical and theoretical literature on local policy choice.

The literature also highlights potential costs associated with decentralization. These include underinvestment when there are spillovers across jurisdictions, uncoordinated public investment, and increasing economic disparities across local governments (OECD, 2019). My contribution to this literature is to study these costs in the context of one public good with important economic spillovers: roads. I provide a rich quantitative model that captures the conflicting incentives between the different levels of government and allows me to quantify these costs.

In developing this model, I borrow and contribute to the literature on quantitative spatial economic model (Redding & Rossi-Hansberg, 2017). The theoretical framework presented in this paper has two blocks: First, given the infrastructure network, households' and firms' decisions determine the city's spatial equilibrium: where people live and work, wages, and land prices. Second, there is the optimal infrastructure block, where local governments choose infrastructure to maximize their land value.

In the first block of the theory, the city equilibrium, I follow the model by Ahlfeldt et al. (2015) without production externalities closely. My primary contribution to the literature on quantitative spatial economics is in the second block: developing a framework with endogenous commuting infrastructure built by non-cooperative municipalities. Moreover, the provided framework also contributes to the study of optimal commuting infrastructure networks in spatial equilibrium, even in the case of a single planner.

I build upon recent papers studying optimal transport infrastructure for the trade of goods. Felbermayr and Tarasov (2022) study transportation infrastructure by non-cooperative planners focused on the international and intra-national trade of goods. Their analytical framework is a stylized linear geography with two countries, where they show that decentralizing transportation investments leads to underinvestment, particularly in border regions between countries. Further, Fajgelbaum and Schaal (2020) study optimal transport networks in spatial equilibrium. Their framework considers the complete network structure and is amenable to quantitative exercises.

The trade of commuters presents an additional technical challenge compared to the trade of goods, especially when studying a network structure. A key finding in Fajgelbaum and Schaal (2020) is that goods are transported through the network based on price differences. Producers will only opt to transport a particular good through a network link if the price gap between the link's endpoints justifies the transportation cost. In the context of urban commuting, individuals might travel to locations with lower wages or use links with lower wages to access areas with higher wages. My paper contributes to this body of research by offering a framework that studies optimal commuting networks. This framework accounts for the more idiosyncratic travel behavior of commuters compared to the transportation of goods. Furthermore, I contribute by studying how political forces, such as decentralization, lead to suboptimal infrastructure networks.

Allen and Arkolakis (2022) propose a spatial framework with traffic congestion that allows the study of the benefits of infrastructure both in the context of commuting and trade of goods. With their framework, they can characterize the welfare benefits of improving any network segment. I build upon their model and contribute by studying the globally optimal infrastructure network rather than the marginal benefits of each segment.

There is also theoretical literature studying cities and optimal urban structure in a circular city. On the one hand, Rossi-Hansberg (2004) studies the optimal allocation of land to business and residential use in cities with commuting and production externalities. On the other hand, Solow (1973), Wheaton (1998), and others study land allocation to roads in models with congestion in commuting times. I contribute to this literature by studying the role of metropolitan political structure, how these political forces result in sub-optimal road investment, and how these distortions affect the equilibrium urban structure.

This project also relates to the large literature studying the impact of transportation infrastructure on economic activity and its spatial distribution—for example, Tsivanidis (2019). Other related papers on this literature are Zárate (2020), Donaldson and Hornbeck (2016) and Hornbeck and Rotemberg (2019). While this literature focuses on the effects of transportation investment on economic activity, it does not study the optimality of the infrastructure itself.

There is a separate literature studying the political economy of transport investment. Brueckner and Selod (2006) examine how the socially optimal transport system compares to the one chosen under the voting process. They show that the voting equilibrium can result in a transportation system that is slower and cheaper than the social optimum. Another example is Glaeser and Ponzetto (2018), which studies how voters' perceptions of different costs of transportation projects can distort the type of project chosen by politicians. Finally, the recent paper by Fajgelbaum et al. (2023) studies how politicians' preferences for redistribution and approval shape transportation policy in the context of California's High-Speed Rail. I contribute to this literature by studying the role of political decentralization relative to centralized infrastructure planning.

2 Model

2.1 Environment

This section presents a general equilibrium model of a metropolitan area composed of multiple locations populated by households that choose where to live and work and commute between these locations. The metropolitan area is divided into local governments that optimally invest in commuting infrastructure to maximize their land value. The model provides a framework to study the equilibrium infrastructure and city structure as a function of the local governments' incentives and metropolitan political fragmentation.

The metropolitan area is composed of J distinct locations, indexed by $j \in \mathcal{J} = \{1, ..., J\}$. Locations are arranged on a directed graph $(\mathcal{J}, \mathcal{E})$, where $\mathcal{E}$ is a set of edges (links) connecting pairs of locations in $\mathcal{J}$. For each location j, there exists a set $\mathcal{N}(j)$ of connected locations. Workers can only commute through connected locations and travel through multiple edges until they reach their destination.

Each location j is endowed with a fixed supply of land for residential purposes, $\bar{H}_{Rj}$, and a fixed supply of land for production purposes, $\bar{H}_{\mathrm{F}j}$.[8] Furthermore, locations differ in their exogenous productivity and their residential amenities.

The metropolitan area is divided into a finite set of local governments $\mathcal{G}$. A local government g is defined as a set of locations, $\mathcal{J}^g$, and a set of edges, $\mathcal{E}^g$. Local governments only control the commuting infrastructure on the edges within their jurisdiction.

Intuitively, we can think of the underlying graph as a metropolitan area composed of J city blocks, where geographically contiguous blocks are connected by an edge. Workers commute from their residency to their workplace through the network, traveling through multiple edges. Different city blocks and streets (edges) belong to different local governments.

Notation. Residential locations are indexed with i and work locations with j. Indices k and ℓ are used to discuss edges that connect location k to location ℓ. Therefore, a commuter will travel from their home location i (origin) to their work location j (destination) through a sequence of edges $\{d_{k\ell}\}$.

Variables with a bar, e.g., $\bar{A}_j$, are exogenous in the model, as opposed to variables without a bar, which are endogenous. Greek letters are preference or technology parameters.

2.1.1 Production

Perfectly competitive firms produce a freely traded numeraire good using labor and land with a constant returns to scale technology. The output of a firm located in j is given by,

$$Y_j = \bar{A}_j \left(\frac{L_{Fj}}{\beta}\right)^{\beta} \left(\frac{H_{Fj}}{1-\beta}\right)^{1-\beta}, \tag{1}$$

where $\bar{A}_j$ is the exogenous productivity, L_{Fj} is labor, and H_{Fj} is land. Firms take local productivity and factor prices as given, where w_j is the wage paid in location j and $q_{\mathrm{F}j}$ is the rental price per unit of productive land in location j.

Productive land is in fixed supply, $\bar{H}_{\mathrm{F}j}$, so output in location j has diminishing marginal returns to local labor. Hence, in equilibrium, the wage is a decreasing function of labor supply; more people

[8] This assumption is relaxed in Appendix X. Allowing for endogenous shares of productive and residential land amplifies the forces of the model.

traveling to work at a location j puts downward pressure on wages in j. Local wages are given by,

$$w_j = \bar{A}_j \Big(\frac{\beta}{1-\beta} \frac{\bar{H}_{\mathrm{F}j}}{L_{Fj}} \Big)^{1-\beta}. \tag{2}$$

2.1.2 Households' preferences

Households are geographically mobile and make three discrete choices to maximize utility. First, they choose whether to live in the metropolitan area or the outside option: other cities in the country or the countryside. Then, conditional on choosing the metropolitan area, they choose where to live and work in the metropolitan area. Finally, they choose a commuting route between their home and work locations.[9]

The preferences of a household ν that lives in the metropolitan area c, resides in location i, works in location j, and commutes via route $r \in \mathcal{R}_{ij}$ are defined over the consumption of the numeraire good, C_{ij}, residential land, H_{ij}, commuting costs, $\tau_{ij,r}$, residential amenities, $\bar{B}_i$, and idiosyncratic preferences, $\epsilon_{cij,r}(\nu)$, according to the Cobb Douglas form,

$$U_{cij,r}(\nu) = \frac{\bar{B}_i}{\tau_{ij,r}} \Big(\frac{C_{ij}}{\alpha} \Big)^{\alpha} \Big(\frac{H_{ij}}{1-\alpha} \Big)^{1-\alpha} \epsilon_{cij,r}(\nu). \tag{3}$$

The commuting cost $\tau_{ij,r}$ is a utility cost of commuting via route $r \in \mathcal{R}_{ij}$, where $\mathcal{R}_{ij}$ is the set of all possible routes between i and j. Households' idiosyncratic preferences are defined over the metropolitan area c, the residence-work pair ij, and the commuting route r, denoted $\epsilon_{cij,r}(\nu)$. These are drawn independently across households according to a Generalized Extreme Value (GEV) distribution:

$$G(\{\epsilon_{cij,r}\}) = \exp\Bigg(- \Bigg[\sum_{c} \Bigg(\sum_{ij \in \mathcal{J}^2} \Big(\sum_{r \in \mathcal{R}_{ij}} \epsilon_{cij,r}^{-\rho} \Big)^{-\frac{\theta}{\rho}} \Bigg)^{-\frac{\mu}{\theta}} \Bigg] \Bigg), \tag{4}$$

with $\mu < \theta < \rho$. The parameter μ captures the substitutability between the metropolitan area and the outside option, while θ shapes the substitutability across residence-work location pairs within the metropolitan area. The parameter ρ governs the substitutability across commuting routes. The $\mu < \theta < \rho$ condition implies that households can more easily substitute across commuting routes than across neighborhoods or work locations, which is easier than substituting across metropolitan areas.

Workers choose among these options by trading off their idiosyncratic preferences, residential amenities, land prices, $q_{\mathrm{R}i}$, wages, w_j, and commuting costs. Given the preferences specified in equation (6), a household ν that lives in the city c, resides in location i, works in location j, and commutes via route $r \in \mathcal{R}_{ij}$ has the following indirect utility,

[9] Households make these three decisions simultaneously.

$$V_{cij,r}(\nu) = \frac{w_j}{\tau_{ij,r}} \frac{\bar{B}_i}{q_{\mathrm{R}i}^{1-\alpha}} \epsilon_{cij,r}(\nu), \tag{5}$$

The idiosyncratic preference structure in equation (4) results in a demand system similar to a nested logit, where the upper nest is across the metropolitan area and the countryside, the middle nest is across residence-work pairs within the metropolitan area, and the lower nest is across commuting routes.[10] Before describing each in more detail, it is helpful to define the following indexes:

$$U \equiv \Big[\sum_{ij} \tau_{ij}^{-\theta} \times \Big(\frac{\bar{B}_i}{q_{\mathrm{R}i}^{1-\alpha}} \Big)^{\theta} \times w_j^{\theta} \Big]^{\frac{1}{\theta}}, \tag{6}$$

$$\tau_{ij} \equiv \Big[\sum_{r \in \mathcal{R}_{ij}} \tau_{ij,r}^{-\rho} \Big]^{-\frac{1}{\rho}}, \tag{7}$$

where U represents the ex-ante expected utility of moving to the metropolitan area, and τ_{ij} represents the ex-ante expected commuting cost between i and j.

Upper nest: City choice

Households choose whether to live in the metropolitan area or an outside option. The outside option is not explicitly modeled and is represented by a fixed exogenous utility value, $\bar{U}_o$. The country has a fixed aggregate population, $\bar{L}$, and given households' preference structure, the endogenous total population of the city is given by:

$$L = \frac{U^{\mu}}{U^{\mu} + \bar{U}_o^{\mu}} \bar{L}, \tag{8}$$

where U is given by equation (6) and is the expected utility of choosing to live in the metropolitan area. The better the expected utility of living in the metropolitan area relative to the outside option, the more people choose to live there. This model of population supply to the metropolitan area nests a closed-city model ($\mu = 0$) and a fully elastic city model ($\mu = \infty$).

Middle nest: Choice of residence and work location

Conditional on choosing to live in the metropolitan area, households choose where to live and where to work by observing amenities, $\bar{B}_i$, land prices, $q_{\mathrm{R}i}$, wages, w_j, and the expected commuting cost, τ_{ij}. Given households' preference structure, the number of households that choose the residence-work pair ij is given by:

[10] See Train (2009), chapter 4, for a more detailed discussion of the properties of the resulting demand system.

$$L_{ij} = \frac{\tau_{ij}^{-\theta}\left(\frac{\bar{B}_i}{q_{\mathrm{R}i}^{1-\alpha}}\right)^{\theta} w_j^{\theta}}{\sum_{od}\tau_{od}^{-\theta}\left(\frac{\bar{B}_o}{q_{\mathrm{R}o}^{1-\alpha}}\right)^{\theta} w_d^{\theta}} L. \tag{9}$$

Local labor supply is increasing in the nominal wage w_j, with elasticity θ. Likewise, when there are better rent-adjusted amenities ($\frac{B_i}{q_{\mathrm{R}i}^{1-\alpha}}$), more households opt to reside in that location. On the other hand, a higher commuting cost results in fewer households selecting the ij option. Note that the denominator is the expected utility of choosing the metropolitan area, and the fraction represents the fraction of households that choose ij. Hence, we can write equation (9) as,

$$L_{ij} = \tau_{ij}^{-\theta}\left(\frac{\bar{B}_i}{q_{\mathrm{R}i}^{1-\alpha}}\right)^{\theta} w_j^{\theta}\frac{L}{U^{\theta}}. \tag{10}$$

The number of people choosing ij is a function of two endogenous aggregate variables: the expected utility of the city, U, and the total population of the city, L. We can also define the number of residents and number of workers in a location with

$$L_{Ri} = \sum_j L_{ij}, \quad L_{Fj} = \sum_i L_{ij}.$$

Lower nest: Routing

Households choose their commuting route $r \in \mathcal{R}_{ij}$. A route r is defined as a sequence of edges in the network. I will start by describing how I model the costs of traveling through an individual edge, $k\ell$, where $\ell \in \mathcal{N}(k)$. Let $d_{k\ell}$ be the utility cost of traveling through the edge $k\ell$,

$$d_{k\ell} = \exp\left(\kappa \underbrace{\bar{t}_{k\ell}\frac{Q_{k\ell}^{\sigma}}{\mathrm{I}_{k\ell}^{\xi}}}_{\text{Travel Time}}\right). \tag{11}$$

Commuting costs are an exponential function of travel time, as in Ahlfeldt et al. (2015), where κ controls the disutility from commuting; a larger κ means that households strongly dislike commuting. Travel time depends on some exogenous edge characteristics, denoted by $\bar{t}_{k\ell}$. For example, the slope of the terrain might make traveling through the edge slower. Travel time is increasing in the traffic flows, $Q_{k\ell}$, with a congestion elasticity σ. Finally, time is decreasing in the level of infrastructure on the edge, $\mathrm{I}_{k\ell}$, with elasticity ξ. Traffic flows, $Q_{k\ell}$, and infrastructure investment, $\mathrm{I}_{k\ell}$, are endogenous outcomes resulting from the decisions of commuters and the local governments, respectively. The total cost of traveling through a given route $r \in \mathcal{R}_{ij}$ is a function of the edge-level commuting costs and is given by

$$\tau_{ij,r} = \prod_{k\ell \in r} d_{k\ell}. \tag{12}$$

Given households' preference structure for routes, we can derive the equilibrium expected commuting cost between i and j as a function of the network of edge-level commuting costs, represented as a matrix. Following Allen and Arkolakis (2022), we can rewrite equation(7) as

$$\tau = \left((\mathbf{I} - \mathbf{A})^{-1} \right)^{-\frac{1}{\rho}} \tag{13}$$

where $\mathbf{A} \equiv \left[d_{k\ell}^{-\rho} \right]$ is a matrix where the (k, ℓ) element is $d_{k\ell}^{-\rho}$. The resulting τ from equation (13) is a matrix where the (i, j) element is the expected bilateral commuting costs, τ_{ij}.

From this routing framework, we can derive helpful results that simplify the computation and study of the equilibrium. First, the *link intensity*; the expected number of times in which the edge $k\ell$ is used by households that live in i and work in j, is given by

$$\pi_{ij}^{k\ell} \equiv \left(\frac{\tau_{ij}}{\tau_{ik} d_{k\ell} \tau_{\ell j}} \right)^{\rho}. \tag{14}$$

The intensity with which households of pair ij use the edge $k\ell$ is a function of the ratio between the expected cost between i and j, and the expected cost of traveling from i to the beginning of the edge, k, then through the edge, and then from ℓ to the destination j. Therefore, the more inconvenient the edge $k\ell$ is for households living in i and working in j, the fewer people use it.

Second, we can use this framework to describe the equilibrium traffic flows in the network. The total number of commuters flowing through edge $k\ell$ is a function of the number of households living in every pair ij in the metropolitan area and the link intensity given by equation (14) according to

$$Q_{k\ell} = \sum_{ij} L_{ij} \pi_{ij}^{k\ell}. \tag{15}$$

This expression illustrates the benefit of introducing idiosyncratic preferences over commuting routes, which greatly simplifies the numerical computation of the equilibrium. Suppose we did not have idiosyncratic preferences for routes and instead had households choose the least-cost route. Then, when improving one edge in the network, we would have to re-compute the set of origins and destinations that use that edge. By smoothing the problem with this routing framework developed in Allen and Arkolakis (2022), we make the problem more tractable.

2.1.3 Land Market Clearing

In each location, there is a fixed supply of land for residential purposes, $\bar{H}_{\mathrm{R}i}$, and for productive purposes, $\bar{H}_{\mathrm{F}i}$. This implies two distinct land prices per location since agents cannot arbitrage across uses.

First, in the residential land market, we can derive the equilibrium rental price by equating the supply and demand of land, namely,

$$q_{\mathrm{R}i} = \frac{1-\alpha}{\bar{H}_{\mathrm{R}i}} \sum_j L_{ij} w_j. \tag{16}$$

Similarly, for the commercial land market, we can equate the fixed land supply to firms' demand for land, namely,

$$q_{\mathrm{F}i} = \bar{A}_i \Big(\frac{1-\beta}{\beta} \frac{L_{Fi}}{\bar{H}_{\mathrm{F}i}} \Big)^{\beta}. \tag{17}$$

The price of residential land is increasing in the number of residents in a location, and the price of commercial land is increasing in the number of workers in a location. Hence, governments want to maximize their land value by investing in infrastructure to attract residents and workers.

2.1.4 Local Governments' Problem

There are G local governments. A local government $g \in \mathcal{G}$ is defined by a set of nodes $\mathcal{J}^g$ and a set of edges $\mathcal{E}^g$ under its jurisdiction. A government g chooses the infrastructure allocation I_{ij} for $ij \in \mathcal{E}^g$, taking as given all the infrastructure investments by other governments, according to

$$\max_{\mathrm{I}_{ij} \in \mathcal{E}^g} \sum_{i \in \mathcal{J}^g} \{ q_{\mathrm{R}i} \bar{H}_{\mathrm{R}i} + q_{\mathrm{F}i} \bar{H}_{\mathrm{F}i} \} - \sum_{k\ell \in \mathcal{E}^g} \delta^{\mathrm{I}}_{k\ell} \mathrm{I}_{k\ell}, \tag{18}$$

subject to:

(i) expected utility, given by equation (6),

(ii) aggregate population, given by equation (8),

(iii) travel demand, given by the equilibrium number of households living in ij in equation (9),

(iv) residential land market clearing, given by equation (16),

(v) commercial land market clearing, given by equation (17),

(vi) wages, as a function of equilibrium commercial land values,[11]

$$w_j = \left(\frac{\bar{A}_j}{q_{\mathrm{F}j}^{1-\beta}} \right)^{\frac{1}{\beta}} \quad \text{for all } j, \quad \left(\lambda_{Fj}^{g}\right) \tag{19}$$

(vii) equilibrium traffic flows, given by equation (15),

(viii) bilateral commuting cost index, given by equation (13),

(ix) edge-level commuting costs, given by equation (11),

where $\delta_{k\ell}^{\mathrm{I}}$ is the building cost in the edge $k\ell$.

Municipalities maximize their economic surplus, defined as their land value net of the building costs of providing the infrastructure, subject to the equilibrium of the city given by households and firms' decisions. The equilibrium of the city acts as an implementability constraint on the governments' problem; they understand how people and firms respond to infrastructure and commuting costs.

In this setting, maximizing land value relates closely to maximizing total consumer surplus, defined as

$$\mathrm{CS}^g = \sum_{j \in \mathcal{J}^g} \omega_{Ri}^{g} L_{ij} U + \sum_{i \in \mathcal{J}^g} \omega_{Fj}^{g} L_{ij} U,$$

where ω_{Ri}^{g} and ω_{Fj}^{g} are the government g's social weights for residents in i and workers in j respectively. Maximizing land value implies assuming that the social weights of residents and workers are given by the marginal land value of an additional resident and an additional worker, respectively.[12] Note that this problem of how we value residents relative to workers disappears when studying the metropolitan planner because the population of residents and workers is the same. Everyone works and lives within the city. However, when dividing the metropolitan area into multiple local governments, the populations of residents and workers at the municipality level are different; some people live and work in different municipalities.

We can also think of equation (18) as local governments maximizing land tax revenue, where the tax rate of productive land equals the tax rate of residential land. Moreover, the framework allows

[11]It is more standard to express the equilibrium wages as a function of labor supply. However, it simplifies the exposition in the next section to express the wage as a function of the commercial land price, $q_{\mathrm{F}j}$. We want to keep track of just one price in the origin locations (residential land value) and one price in the destination locations (commercial land value).

$$w_j = \bar{A}_i \left(\frac{\beta}{1-\beta} \frac{\bar{H}_{\mathrm{F}i}}{L_{Fi}} \right)^{1-\beta} = \left(\frac{\bar{A}_j}{q_{\mathrm{F}j}^{1-\beta}} \right)^{\frac{1}{\beta}}$$

[12]Note that maximizing aggregate land value has a long tradition in urban economics, for example, as used in Kanemoto (1977),Wheaton (1998), and Rossi-Hansberg (2004), to name a few. This tradition arises from the Henry George theorem, where, under certain conditions, the welfare benefits of local public goods are capitalized into land values (Starrett, 1981).

for more general objective functions for local governments, where we could allow for income tax based on workplace or other types of tax revenue.

The local government maximizes this objective subject to the implementability constraints, that is, internalizing how prices and quantities from the competitive equilibrium change as a function of the infrastructure. This means that the governments "understand" the equilibrium forces of the city, including how quantities and prices of nodes outside its jurisdiction might affect prices and quantities within its jurisdiction. Finally, governments take the infrastructure investments of other governments, $\mathrm{I}_{k\ell}$ for $(k\ell) \in \mathcal{E}^{g'}$, as given. I focus on the Nash equilibrium: every municipality chooses its optimal infrastructure conditional on the infrastructure chosen by the other governments in the metropolitan area.

Centralized Planner (Metropolitan)

In the following sections, I compare the decentralized equilibrium, where each municipality optimizes the objective described in equation (18), to the centralized equilibrium, where a metropolitan planner chooses the infrastructure that maximizes economic surplus for the entire city. This implies that the metropolitan planner internalizes the full benefits and costs of its investments.

It is worth noting that the solution to the metropolitan planner's problem is not the first-best because of the congestion externalities. I assume that the metropolitan planner can only control the infrastructure and can not implement other tools, such as congestion pricing.[13]

2.1.5 Equilibrium

Given the model's parameters, $\{\alpha, \beta, \theta, \rho, \mu, \kappa, \sigma, \xi\}$, the reservation utility of the economy, $\bar{U}_o$, the total population of the country, $\bar{L}$, and the exogenous location characteristics $\{\bar{A}_i, \bar{B}_i, \bar{H}_{\mathrm{R}i}, \bar{H}_{\mathrm{F}i}, \bar{t}_{k\ell}\}$, an equilibrium of the model satisfies the following 9 sets of equations: households maximize utility (9 and 8), labor markets clear (2), land markets clear (16 and 17), traffic equilibrium holds (15, 11, and 13), governments maximize land value net of building costs (18).[14]

2.2 Illustrative Example: Linear City

This section uses the particular, simple case of a linear geography with common land and amenities to illustrate the model's trade-offs.

Suppose the metropolitan area is a finite number of locations arranged in a line, where locations

[13] In the context of Santiago, municipalities can not charge tolls on their local roads. Hence, I compare the decentralized equilibrium, where municipalities can only control the infrastructure, with a metropolitan planner that has the same policy tools as the municipalities, infrastructure investment, such that I can focus on the effect of the level of decision-making.

[14] The optimal infrastructure equation is given by equation (28).

are indexed by the distance to the start of the line, x. Every location in the metropolitan area has equal amounts of land for production and housing and the same residential amenities. The only differences across locations are their exogenous productivity, $\bar{A}_x$, their location x, and their local government $g(x)$.

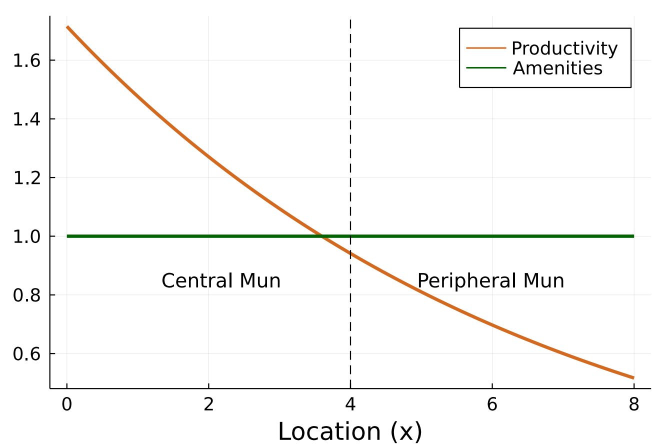
As an illustrative example, I study a metropolitan area where productivity is high at $x = 0$ and declines with distance. In particular, I model productivity as follows:

$$\bar{A}_x = e^{-\delta x},$$

where the parameter δ controls the productivity dispersion in space, larger values of δ imply that productivity falls more rapidly in space. Therefore, central locations are more productive relative to peripheral locations for larger δ.

The metropolitan area is divided into two local municipalities: central and peripheral. I illustrate this city in Figure 1. The brown line represents the productivity for each location, and the dashed line is the boundary between the two municipalities. Amenities are the same everywhere and are represented by the green line. We can think of this metropolitan area as N locations on a road. Half of the locations and the road are under the jurisdiction of one municipality, and the other half under the other. Municipalities can invest in infrastructure and increase the width or quality of the road within their jurisdiction.

Figure 1: Linear city



The only difference between this setting and the model outlined in the previous section is the routing problem. I simplify the households' routing decisions by assuming everyone takes the shortest path, that is, the straight line between the origin and the destination. This effectively removes the lower nest of the households' decisions. The equations that change given this simplification are the commuting costs and traffic flows,

$$\tau_{ij} = \prod_{k\ell} \mathbb{1}_{ij}^{k\ell} d_{k\ell}, \tag{20}$$

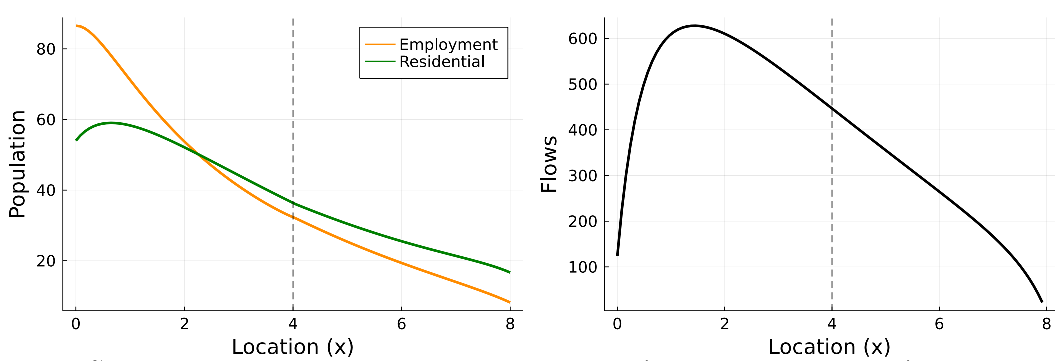
$$Q_{k\ell} = \sum_{ij} L_{ij} \mathbb{1}_{ij}^{k\ell}, \tag{21}$$

where $\mathbb{1}_{ij}^{k\ell}$ is an indicator function that equals one when the origin-destination ij uses the edge $k\ell$.[15]

Before shifting our attention to the optimal infrastructure in this linear city, describing the city's equilibrium for some fixed infrastructure level is helpful. Figure 2 shows the equilibrium population and traffic flows given some positive and uniform level of infrastructure everywhere in the line, $\mathrm{I}_{k\ell} = C$ for all $k\ell$.[16] In equilibrium, employment is high in locations close to $x = 0$, where productivity is high. Even though residential amenities are the same everywhere, the residential population is also higher closer to $x = 0$, because of better access to jobs.[17] Net commuting flows to work travel towards $x = 0$. However, there are commuting flows in both directions, given the idiosyncratic preference shocks.

Figure 2: Equilibrium given constant $\mathrm{I}_{k\ell}$

(a) Population (b) Traffic Flows



Note: Commuters travel in both directions because of the idiosyncratic preference shocks for origin-destination pairs. Panel (b) plots the total commuting flows, the sum over both directions. However, most of commuters travel towards $x = 0$, where wages are higher.

2.2.1 Optimal Infrastructure

In this stylized city example, I describe how decentralization distorts the distribution of commuting infrastructure. From the local governments' problem defined in Section 2.1.4, I derive the following

[15] The origin-destination ij will use the edge $k\ell$ if $i \leq k$ and $j \geq \ell$ or if $i \geq k$ and $j \leq k$.

[16] For this example and every figure in this section, I chose the parameter values in Table B.1.

[17] Residential population declines slightly at $x = 0$ because there is nothing on the other side, so market access to jobs is better for $x \approx 0.5$ than exactly at $x = 0$. You can think about this linear city as Chicago, and $x = 0$ is where Lake Michigan starts. Access to jobs is better inside the city than exactly at the lake shore.

expression, which equates the marginal value to the marginal cost of infrastructure,

$$\frac{\partial d_{k\ell}}{\partial \mathrm{I}_{k\ell}} \sum_{ij} \lambda_{ij}^{g} \frac{\partial L_{ij}}{\partial d_{k\ell}} = \delta_{k\ell}^{\mathrm{I}}. \tag{22}$$

Infrastructure provides several benefits. First, we have the direct effect, $-\frac{\partial d_{k\ell}}{\partial \mathrm{I}_{k\ell}}$: more infrastructure translates into faster commute times. Second, we have the benefits from reorganizing economic activity in the city, $\sum_{ij} -\lambda_{ij}^{g} \frac{\partial L_{ij}}{\partial d_{k\ell}}$, which governments capture in land value. Changing travel time in one edge, $d_{k\ell}$, will affect where people live and work. The Lagrange multiplier λ_{ij}^{g} is the multiplier on the travel demand constraint in equation (9), and it represents the marginal land value for government g of an increase in L_{ij}. Namely, how much does land value in g's locations increase?

The land value of reorganizing economic activity in the city and how the different governments capture it summarize the main equilibrium forces of the model. To provide some insight into how local governments capture only fractions of the benefits and costs from their investments, I group the equilibrium forces into three groups: residential effects, employment effects, and congestion effects, as the following,

$$\sum_{ij} \lambda_{ij}^{g} \frac{\partial L_{ij}}{\partial d_{k\ell}} = \underbrace{\sum_{ij} \eta_{\mathrm{R}i}^{g} \frac{\partial q_{\mathrm{R}i}}{\partial L_{ij}} \frac{\partial L_{ij}}{\partial d_{k\ell}}}_{\text{Residential Force: } \equiv Q_{\mathrm{R}k\ell}^{g}} + \underbrace{\sum_{ij} \eta_{\mathrm{F}j}^{g} \frac{\partial q_{\mathrm{F}j}}{\partial L_{ij}} \frac{\partial L_{ij}}{\partial d_{k\ell}}}_{\text{Employment Force: } \equiv Q_{\mathrm{F}k\ell}^{g}} + \underbrace{\sum_{ij} \sum_{rs} \phi_{rs}^{g} \frac{\partial Q_{rs}}{\partial L_{ij}} \frac{\partial L_{ij}}{\partial d_{k\ell}}}_{\text{Congestion Force: } \equiv Q_{\mathrm{Q}k\ell}^{g}}. \tag{23}$$

Residential and Employment Forces

First, the residential force, $Q_{\mathrm{R}k\ell}^{g}$, corresponds to all the changes to residential land value throughout the city from an improvement in the edge-level commuting cost $d_{k\ell}$, valued by the government g. Governments value these changes in residential land value according to the weight $\eta_{\mathrm{R}i}$; the Lagrange multiplier of constraint (16). We can think about these multipliers as government-specific weights for residential (origin) locations given by

$$\eta_{\mathrm{R}i}^{g} = \mathbb{1}[i \in \mathcal{J}^{g}] \bar{H}_{\mathrm{R}i} + \sum_{od} \lambda_{od}^{g} \frac{\partial L_{od}}{\partial q_{\mathrm{R}i}}. \tag{24}$$

These government-specific residential multipliers have two terms. First, governments care directly about increasing residential land value in locations within their jurisdiction. Second, they value residential price changes in every location (even outside their jurisdiction) through population responses. For example, they might benefit from an increase in housing prices in the neighboring municipality if that pushes residents to move to their locations or increases the market access to workers of their firms.

The second term in equation (23), the employment force, $Q^g_{\mathrm{F}k\ell}$, corresponds to all the changes to commercial land value throughout the city from an improvement in the edge-level commuting cost $d_{k\ell}$, valued by government g. In the same spirit as in the residential force, government g values change to commercial land value according to the Lagrange multipliers $\eta_{\mathrm{F}j}$; the multiplier of constraint (17). These multipliers are government-specific weights for productive (destination) locations and are given by

$$\eta^g_{\mathrm{F}j} = \mathbb{1}[i \in \mathcal{J}^g]\bar{H}_{\mathrm{F}j} + \sum_{od} \lambda^g_{od} \frac{\partial L_{od}}{\partial w_j} \frac{\partial w_j}{\partial q_{\mathrm{F}j}} + \sum_{o} \eta^g_{Ro} \frac{\partial q_{Ro}}{\partial w_j} \frac{\partial w_j}{\partial q_{\mathrm{F}j}}. \tag{25}$$

Governments value attracting workers to a location because of the effect of labor supply on two prices: the commercial land value and the wage. For tractability, I express the wage in equation (19) as a function of the equilibrium commercial land value instead of labor supply to reduce the number of Lagrange multipliers we have to keep track of. Hence, the multiplier in equation (25) represents the full valuation of changes in commercial land value, including the effects on wages.

Let us consider each term in equation (25) at a time. First, governments care directly about increasing commercial land value within their jurisdiction. Second, commuters throughout the city respond to movements in wages in j, captured by the second term. Third, wage changes will also affect the residential land value in the origin location of those workers.[18] These two forces imply governments value destination locations outside their jurisdiction: governments can capture benefits from wage increases in other jurisdictions if that translates into higher residential land value in their jurisdiction, or they can value a wage decrease if that pushes workers to work in their locations.

Equations (24) and (25) highlight how governments internalize both effects in locations within their jurisdiction and effects outside their jurisdiction through the spatial linkages given by population mobility and commuting. These weights ($\eta_{\mathrm{R}i}$ and $\eta_{\mathrm{F}j}$) can be positive or negative, depending on whether a price change in the location will increase or reduce total land value for government g.

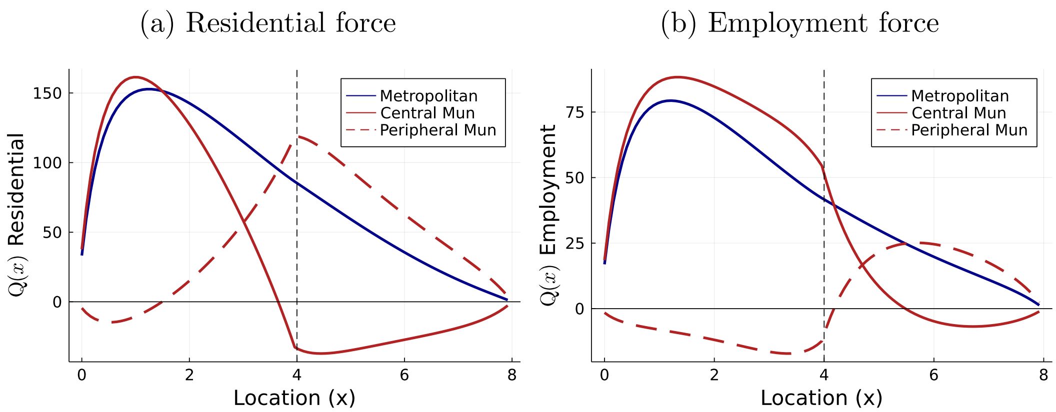
Figure 3 shows the residential and employment forces from the perspective of the three governments.[19] The blue lines represent the perspective of the metropolitan government, and the red lines represent the perspective of the central municipality (solid) and the peripheral municipality (dashed). For example, for the residential force, the blue line represents the full residential land value derived from a marginal investment in the roads in that location. Then, the red lines are the residential forces from the perspective of the central municipality (solid) and the peripheral

[18] Note the equation (25) is not symmetric to equation (24) because of the effect of wages on residential land value. The indirect effects captured in these destination weights, $\eta^g_{\mathrm{F}j}$, are twofold: movements in wages affect both residential land value in origin locations and population throughout the city. The residential weight, $\eta_{\mathrm{R}i}$, captures how movements in residential land value affect other locations only through population responses.

[19] Appendix B.1 shows how we can interpret $Q^g_{\mathrm{R}k\ell}$, $Q^g_{\mathrm{F}k\ell}$, and $Q^g_{\mathrm{Q}k\ell}$ as weighted traffic flows, where the weights are a function of government-specific Lagrange multipliers.

municipality (dashed). These lines sum up to the blue line: They represent how the full effect in residential land value is divided between municipalities.

Figure 3: Different effects by government



Note: These are constructed in the decentralized equilibrium, such that the sum of the red lines equals the blue line. We can interpret the red lines as how value is distributed between the central and peripheral municipalities.

First, let's focus on the residential force in Figure 3(a). Investment in edges closer to the boundary, on the central municipality side, mostly benefits commuters that reside in the peripheral municipality. Further, better infrastructure induces residents to move towards the periphery and enjoy lower residential land prices. This implies that, for most edges, the central municipality only captures a small fraction of the residential land value gains as the distribution of residents shifts towards the periphery. Even more, the central municipality's residential force is negative at the boundary, implying that the central municipality is losing residential value by investing in these locations.

On the other hand, in peripheral locations, the residential force is larger for the peripheral municipality than the metropolitan government. The periphery gains residents and, in turn, land value at the expense of central locations. The metropolitan planner, by contrast, internalizes that the increase in land value comes partly at the cost of reducing land value in other locations.

Consider the employment force in Figure 3(b). In this case, most employment is concentrated in central locations, and better infrastructure allows for a shift towards more productive locations in the city's center. This implies the opposite pattern for the employment force: the central municipality gains land value derived from employment at the expense of the periphery.

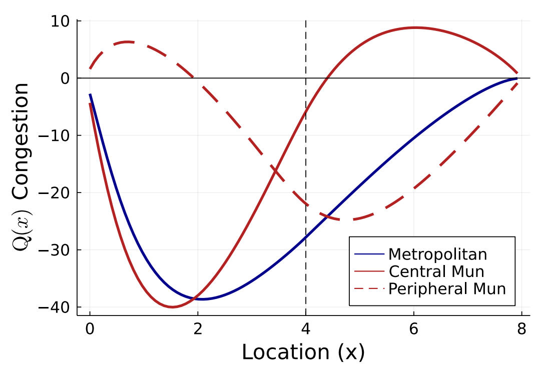
The size of the residential force relative to the employment force is important to determine the infrastructure pattern in equilibrium. If the residential force is larger, as in this case, the central municipality tends to underinvest, and the periphery overinvests. If, instead, the employment force was relatively larger, the central municipality would underinvest less or even overinvest. The relative size of these forces is a function of the land shares of utility and production and the dispersion in productivity relative to the dispersion in residential amenities.

Congestion Force

The third component in equation 23 is the congestion force, $Q^g_{\mathrm{Q}k\ell}$, which captures the congestion costs associated with reshuffling traffic flows in the network and population growth of the city, as valued by the government g. Municipalities internalize how changes in $d_{k\ell}$ might divert traffic flows to their edges or away from their edges. These changes are valued according to the Lagrange multiplier ϕ^g_{rs}, associated with the constraint (15).[20] The Lagrange multiplier captures how more traffic flows reduce land value for government g through travel time congestion for their residents and workers.

Figure 4 shows the congestion force from the perspective of the three governments. Investment in one edge might increase congestion for other municipalities, in which case the local government will internalize only a fraction of this cost. That is the case closer to the boundary, where the red lines are less negative than the blue line. On the other hand, investment might alleviate traffic in other municipalities, in which case the local government will internalize a higher cost than the metropolitan planner. That is the case for core locations around $x = 0$ and $x = 8$, where traffic flows are pushed inside the controlling municipality, alleviating traffic in the neighboring municipality.

Figure 4: Congestion effect



Note: Constructed in the decentralized equilibrium, such that the sum of the red lines equals the blue line.

The congestion force is generally negative from the metropolitan perspective because the aggregate population grows with more infrastructure, causing more congestion overall. From the perspective of each local government, this force can be positive if it diverts enough traffic away from their

[20] See Appendix B for this multiplier.

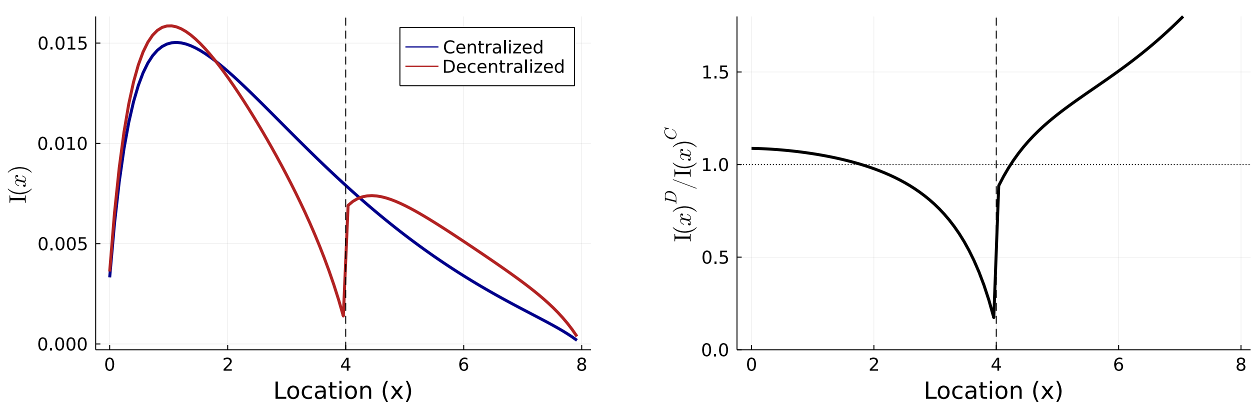
locations. This generally happens in locations farther away from their boundaries, outside their jurisdiction.

Equilibrium Infrastructure

Figure 5(a) shows the optimal infrastructure function for the centralized metropolitan planner (in blue) and for the decentralized equilibrium where each municipality chooses its investments (in red). Figure 5(b) shows the ratio of the decentralized infrastructure to the optimal metropolitan infrastructure. Values below one indicate underinvestment and values above one indicate overinvestment. For this set of parameters, in equilibrium, local governments underinvest close to the boundary and overinvest away from the boundary. Further, if we look at the aggregate investment by municipality, defined as the sum of infrastructure across locations, the central municipality underinvests overall, and the peripheral municipality overinvests.

Figure 5: Decentralized vs Centralized Infrastructure

(a) Optimal Infrastructure (b) Relative Infrastructure: $\mathrm{I}^g/\mathrm{I}^*$



This example illustrates the two main predictions of the model. First, the distortions within each municipality: Within a given municipality, relative to a metropolitan planner, local governments underinvest near the boundary and overinvest at their core locations.[21] Second, we have the "level" distortions across municipalities: Taking the total investment at the municipality level, the central municipality underinvests, and the peripheral municipality overinvests. This second prediction about total investment across municipalities depends crucially on two ingredients. First the land share of utility and production, as these affect how governments weigh residents versus workers. Second, the city's geography, that is, the distribution of exogenous productivity and residential amenities across space.

[21] Core locations are those farthest from the boundary.

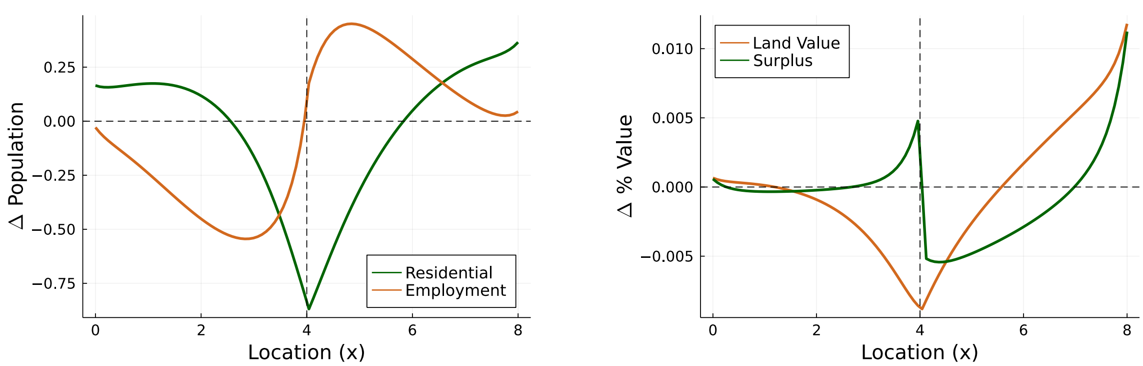
2.2.2 City Structure

Let us now shift our attention to the effects of decentralization on the city's equilibrium: where people live and work and the prices across these locations.

Figure 6(a) shows the change in the population distribution of both residents and workers. The residential population "hollows out," shifting away from the border between municipalities with less infrastructure. Employment shifts towards the periphery and is less concentrated in productive central locations relative to the centralized equilibrium. Hence, decentralization makes cities less specialized, with a more mixed distribution of residents and employment. This follows from the municipalities underinvesting near the boundaries, which results in higher cross-municipality commuting costs and dispersing employment across municipalities. Hence, the urban pattern is more polycentric in the decentralized equilibrium. Residents live closer to where they work, leading to shorter commutes. The shorter commutes and lower aggregate population make traffic flows smaller overall.

Figure 6: Changes to the city's equilibrium

(a) Δ in population (b) Δ in land value and surplus



Note: The changes above compare the decentralized equilibrium relative to the centralized (metropolitan) one.

Surplus losses are concentrated in the peripheral municipality. The periphery gains land value relative to the metropolitan equilibrium but loses overall surplus when accounting for the infrastructure costs. The central municipality gains a small amount of surplus. Figure 6(b) shows the percentage change of surplus and land value across space. In the decentralized equilibrium, the central municipality loses land value but gains surplus thanks to the reduction in building costs.

2.3 From the linear geography to the full network

Now that I have illustrated the main economic forces of the model, I describe how we can extend these results to the full network structure. Again, the main simplification of the linear geography was removing the routing problem.

Incorporating the routing problem, the benefits side of equation (22) changes to:

$$\frac{\partial d_{k\ell}}{\partial \mathrm{I}_{k\ell}} \sum_{ij} \left(\lambda_{ij}^{g} \frac{\partial L_{ij}}{\partial d_{k\ell}} + \sum_{rs} \phi_{rs} L_{ij} \frac{\partial \pi_{ij}^{rs}}{\partial d_{k\ell}} \right) = \delta_{k\ell}^{\mathrm{I}}. \tag{26}$$

To understand this new equation, recall that $Q_{k\ell} = \sum_{ij} L_{ij} \pi_{ij}^{k\ell}$. In the linear geography, given the trivial routing problem, instead of $\pi_{ij}^{k\ell}$, we had the indicator $\mathbb{1}_{ij}^{k\ell}$. Hence, in the linear geography, the only effect of $d_{k\ell}$ on traffic flows was through the effect on the population, L_{ij}. However, in the full network, changes to $d_{k\ell}$ also affect the routing decisions. Holding population L_{ij} fixed everywhere, commuters will adjust their routing decisions in response to a change in the travel time of one edge, $d_{k\ell}$.

This new term is grouped into the congestion force,

$$Q_{\mathrm{Q}k\ell}^{g} = \sum_{ij} \sum_{rs} \phi_{rs}^{g} \left(\frac{\partial L_{ij}}{\partial d_{k\ell}} \pi_{ij}^{rs} + L_{ij} \frac{\partial \pi_{ij}^{rs}}{\partial d_{k\ell}} \right) \tag{27}$$

Using equation (11), (9),(14), (13), and (26) we can express the optimal infrastructure as

$$\mathrm{I}_{k\ell}^{g} = \xi \frac{d_{k\ell}}{\delta_{k\ell}^{\mathrm{I}}} \frac{\log d_{k\ell}}{1 + \rho\sigma \log d_{k\ell}} \left(Q_{\mathrm{R}k\ell}^{g} + Q_{\mathrm{F}k\ell}^{g} + Q_{\mathrm{Q}k\ell}^{g} \right), \tag{28}$$

where $Q_{\mathrm{R}k\ell}^{g}$ and $Q_{\mathrm{F}k\ell}^{g}$ are given by the definitions in equation (23), and $Q_{\mathrm{Q}k\ell}^{g}$ is given by equation (27). Finally, in the full network, we have that the marginal change in the number of households living in ij from an improvement in the commuting costs in edge $k\ell$ is given by

$$-\frac{\partial L_{ij}}{\partial d_{k\ell}} = \theta L_{ij} \pi_{ij}^{k\ell} - L_{ij} \frac{Q_{k\ell}}{L} \Big(\theta - \varepsilon_L \Big). \tag{29}$$

where ε_L is the elasticity of the aggregate metropolitan populations with respect to the ex-ante expected utility level, U.[22]

The first term, $\theta L_{ij} \mathbb{1}_{ij}^{k\ell}$, is the direct effect. If the origin-destination ij uses the edge $k\ell$, then the commuting elasticity of travel demand is θ. The second term is the indirect effect. It arises from how changes to $d_{k\ell}$ affect the aggregate variables: the expected utility of the city, U, and the aggregate population of the city, L. Even for ij pairs that do not use the edge $k\ell$, travel demand changes because the denominator in equation (9) changes, and the aggregate population of the city, L, grows.

[22]This elasticity is given by

$$\varepsilon_L \equiv \frac{\partial L}{\partial U} \frac{U}{L} = \mu \left(1 - \frac{1}{U^{\mu} + \bar{U}_o^{\mu}} \right).$$

Since $\theta > \varepsilon_L$, that is, the population supply to a location pair within the city is higher than the aggregate population supply to the metropolitan area, this indirect effect is negative. Hence, for location pairs that do not use the edge $k\ell$ (and therefore, the direct effect is zero), the indirect effect reflects how the population declines. This decline translates into population growth in the locations pairs that do use the edge $k\ell$.

3 Decentralization and Infrastructure in Santiago, Chile

I now describe how the forces described in the theory lead to the misallocation of infrastructure in the metropolitan area of Santiago, Chile. Santiago's metropolitan area is divided into 34 municipalities with autonomy over transportation planning within their jurisdiction, making it a good laboratory to study decentralization.

In this section, I first describe the data sources used for the empirical evidence and structural estimation. Then, I describe the city's political structure, commuting activity, and the distribution of economic activity. Finally, I show empirical support for the forces in the model by documenting the infrastructure pattern at the border between municipalities.

3.1 Data Sources

Travel survey

This paper uses Santiago's 2012 travel survey, *Encuesta Origen Destino de Viajes*, as the main data source. This survey data provides information on the daily trips of 60,000 individuals from 18,000 distinct households. This information includes the origin and destination of each trip, the purpose of the trip, the mode of travel, and the duration of the trip. The survey data also provides information about the individuals, such as wage and education level.

The sample is representative at a granular geographic level, with 866 spatial units over 45 municipalities in the metropolitan region. I restrict the sample to 700 central locations in 34 municipalities. I define central locations as locations within the city's urban limit defined by Google Maps. Locations are, on average, 1 km squared. This sub-sample captures 80% of the work-related trips documented in the data and 83% of the city's residential population.

I restrict the sample for two reasons. First, the locations outside the city's urban limit are more rural, larger in area, and with more dispersed population. Location within the city's urban limit are polygons of approximately 1 km side, and the locations outside are, on average, polygons of 4 km side. Second, these locations have more complicated geography, such as mountainous terrain. These characteristics make it harder to map these rural locations into nodes in the network and accurately measure their infrastructure. Moreover, since these locations are rural and outside the city's urban limits, there is no available information on floor space.

Land use and land prices

I use a public database of real estate appraisals by the tax authority of Chile, *Servicio de Impuestos Internos* (SII), that has information on the assessed value of the property, floorspace, use, and address for each property in the country. I use data from 2018, the first year for which the data is public.[23]

With this information, I can compute the available floor space for residential and business purposes for each location: $\bar{H}_{Ri}$ and $\bar{H}_{Fi}$ in the model. I construct the category of "business" by including land uses that employ people in urban areas: commercial, hotels, industry, offices, public administration, and hospitals. I exclude categories like storage, churches, and parking since these categories usually do not employ many people.

Infrastructure

I use public data from Open Street Maps on the road network and road characteristics for the Santiago area. Open Street Maps records data on the type of road for each road segment and information on the number of lanes and width for some roads. The type of road includes categories such as motorway, residential, primary road, service road, etc.

I also combine this information with official government data on the road network documented in the 2017 census. Importantly, the government dataset includes information on who owns the road, the national or local government, but does not include information on the physical characteristics of roads, such as number of lanes.

Real-time traffic flows and speed data

Chile's Transportation and Communications Ministry collects real-time traffic data through automatic readers. These automatic readers count the number of cars traveling through a specific avenue or intersection in 15-minute intervals. They are located in 70 main traffic spots across nine municipalities in Santiago's metropolitan area.

I also collected real-time traffic speed data for those 70 locations using the Google Maps API. I recorded this information for six weeks, from August 1st to September 17th, 2022, a window of time for which the Ministry kindly agreed to share the data on traffic flows. I use the data on

[23]There is a five year gap between the data on land use and the travel survey. However, no major events or urban policies took place during that time window to think the land use would be significantly different in 2012. The one notable exception is the opening of a new subway line at the end of 2017 (line number 6). Still, since I use this data to calculate available floor space by purpose, it is unlikely that the supply of floorspace changed in one year from the opening of the subway.

flows and speed for this set of locations to estimate the relationship between travel time and traffic flows.

3.2 Context: Santiago, Chile

Santiago is Chile's capital, as well as its industrial and financial center. It has a population of six million people in its metropolitan area. In 2017, Santiago's GDP was comparable to that of Denver or San Diego in the United States.

Chile is a relatively centralized country. For example, public schools are managed by municipalities but are mainly financed by the central government. Some municipalities choose to complement the existing public school funding; however, households do not have to reside in the municipality to attend, and residents do not get priority in admissions. Further, tax rates are determined by the national government and are the same across municipalities. These characteristics allow me to focus on commuting infrastructure without worrying about residential sorting patterns driven by differential tax rates or access to other public goods, such as schools. Having said that, there are some municipality-specific public goods that only residents can enjoy; for example, some municipalities offer subsidized gyms or additional security.

Municipalities in Santiago are responsible for building and maintaining surface infrastructure, such as local roads and avenues, bike lanes, and parking facilities. Larger infrastructure projects, such as highways and subways, are designed and built by the national government. Subways are mostly underground infrastructure, and highways are often located at the boundary between municipalities. Figure A.1 in the Appendix shows the city's distribution of large roads, including avenues and highways. Avenues are owned and maintained by the municipalities and drawn in blue. Highways are owned and maintained by the national government and drawn in red.

Although national infrastructure, such as highways, is heavily used, most travel time is spent on municipal infrastructure. For the average commuting trip, 60% of the distance and 80% of the travel time takes place in municipal infrastructure. I calculate this number by computing the shortest route for the trips observed in the travel survey and mapping each step to either municipal infrastructure or highways.

Most commuting in Santiago uses surface infrastructure rather than subways or trains. For instance, 31% of people commute using only their private car, but roughly 62% of trips use a car, bus, bike, taxi, or combination of these surface modes of transport. Nevertheless, the subway system is important and used for 22% of the trips. More than two-thirds of these subway trips also involve buses, bikes, or cars to connect to the subway system. Hence, most subway trips also use local roads.

In the model estimation and counterfactual analysis, I focus on surface infrastructure, namely, roads. I don't model travel choices between using surface transportation or subway or trains. Hence, we can think about the model quantification and subsequent counterfactual analysis as capturing only the fraction of households and trips that use surface infrastructure. Note that both private cars and public buses use roads and surface infrastructure.

Santiago's economics, political, and natural geography

Geographically, the Metropolitan Region of Santiago is located in the central area of Chile. The region is nestled within a valley and is flanked by the Andes Mountains to the east. There is one important river that flows from its source in the Andes mountains onto the west and divides Santiago in two.

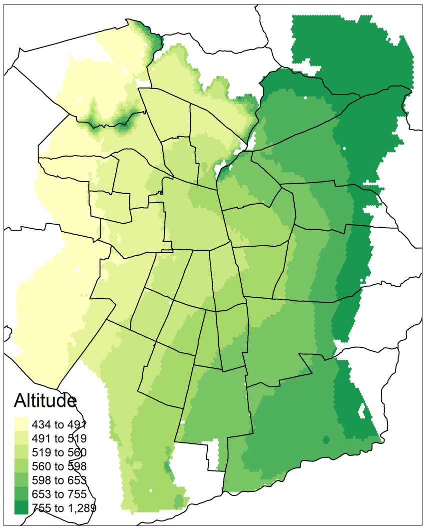
The political structure of the region consists of 52 individual municipalities and a regional metropolitan government. Municipalities are led by publicly elected mayors and the metropolitan government is led by a publicly elected governor.[24] The metropolitan government is responsible for the coordination, supervision, and inspection of regional public services. However, there are few coordination instruments for regional-municipal cooperation (Zegras & Gakenheimer, 2000). Even the current governor, Claudio Orrego, has been vocal about the important challenges related to the political fragmentation of the metropolitan area and the difficulties of enacting coordination (CitiesToBe, 2023).

Figure 7(a) shows the altitude of different locations within the city in meters. The black lines correspond to the municipalities' borders. Note that there are important differences in altitude across city locations, with the altitude more than doubling from the west to the east. For this reason, I control for altitude and slope in the empirical analysis and estimation of the paper. Figure 7(b) shows the distribution of socio-economic quintiles in the city, calculated using the 2017 population census. Richer households are concentrated in the city's northeast, towards the mountains. Lower-income households live primarily in the West.

[24]Only 34 municipalities fall within Santiago's urban limit.

Figure 7: Build density and altitude

(a) Altitude



(b) Socio-economic status

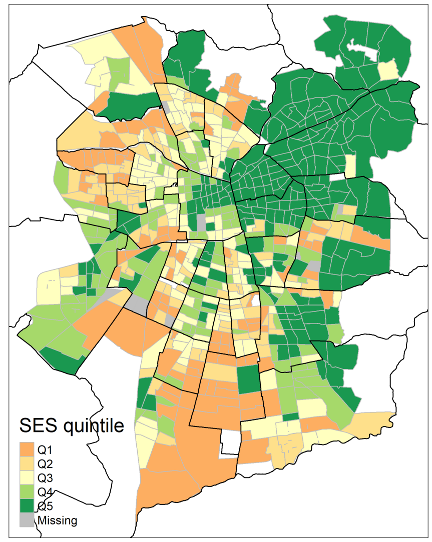
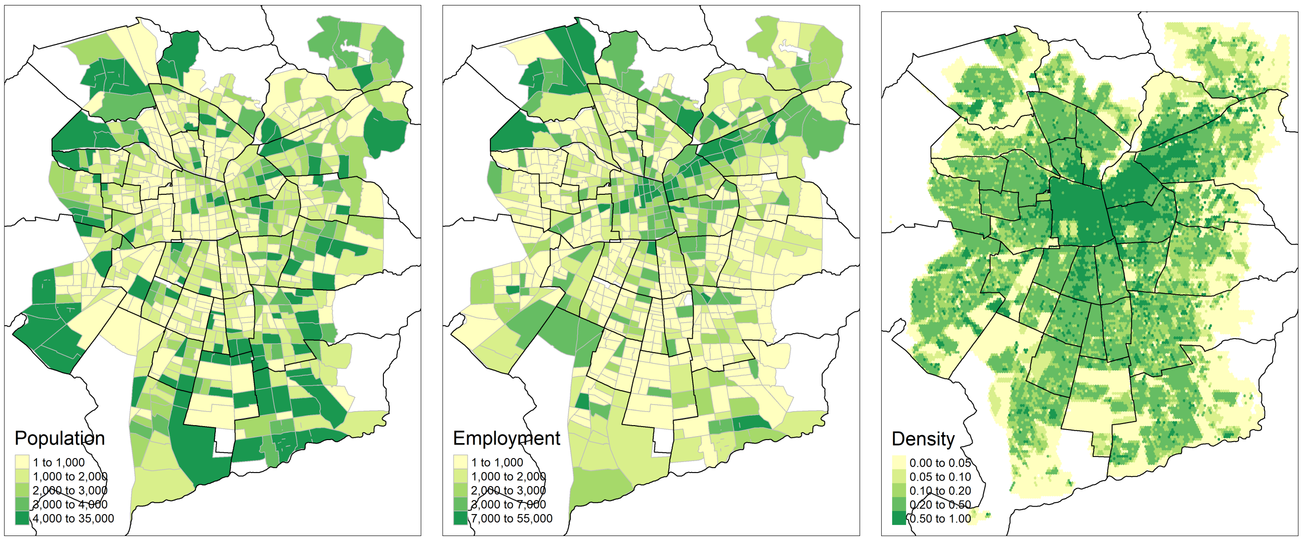


Figure 8 shows the distribution of residents, workers, and urban density throughout the city. I calculated the distribution of residents and workers by location using the travel survey. Residents live everywhere in the city and are more concentrated in the periphery of the city. Employment is more concentrated than the residential population, located in the city center and the north of the city. Figure 8(c) is the urban density, defined as total floor space over land area. Hence, this figure shows urban density both from commercial and residential floor space. As usual, the city is more dense at the center, where employment is high.

Figure 8: Santiago's metropolitan area economic geography

(a) Residential Population (b) Employment (c) Urban Density



Note: The darker black lines correspond to the municipalities' borders. The smaller geographical units inside are the Origin-Destination survey locations.

Santiago is a densely populated and compact urban center divided into municipalities. It is important to note that these municipalities do not function as separate, independent cities; rather, they collectively constitute a unified and cohesive metropolis. Figure 8 highlights that all municipalities have both residents and employment. However, employment is more concentrated in a subset of municipalities. Moreover, although density is the highest at the central "business" municipalities, urban density is still high throughout the city's core.

Commuting interactions across municipalities

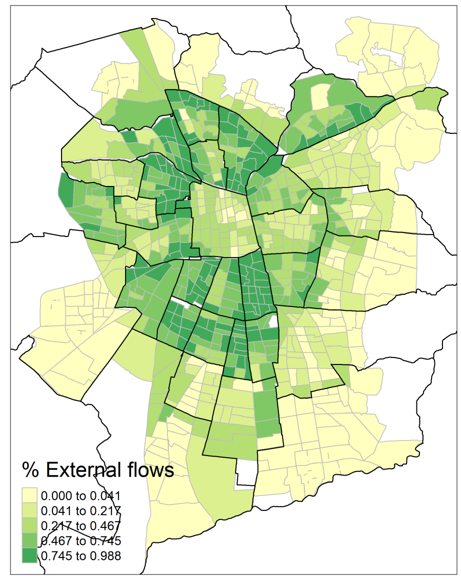
Roads are often used by residents or workers of other municipalities: more than 70% of commuters live and work in different municipalities. Moreover, I compute the fraction of external commuters, i.e., those who do not live or work in the municipality building and maintaining the road. These commuters travel through the municipality, but both their origin and destination are in another jurisdiction. We can estimate the fraction of external commuters using the travel survey and Google Maps to compute the shortest path route: on an average road, 40% of commuters are external. However, this city-wide average hides significant heterogeneity in space. The municipality with the highest fraction of external commuters, San Joaquin, has an average of 85% external commuting flows. Figure 9 shows the distribution of external flows in space; external flows are concentrated in the ring of municipalities that connect residential locations to employment locations.

Connecting this empirical pattern to the forces in the model, the municipalities with a high fraction of external commuters have both low residential and employment forces relative to a metropolitan planner. Hence, they capture a small fraction of the value of any investment.

3.3 Local infrastructure at the border

One key prediction of the theory is that infrastructure changes discontinuously at the border and increases with distance to the border. This prediction is driven by two factors: First, municipalities' incentives change discontinuously at the border. Second, closer to the border, a larger fraction of the benefits from infrastructure are captured by neighboring locations, leading to less investment. In this section, I document a statistically significant jump and slope in the density of roads around the border between municipalities in Santiago.

Figure 9: Fraction of external flows



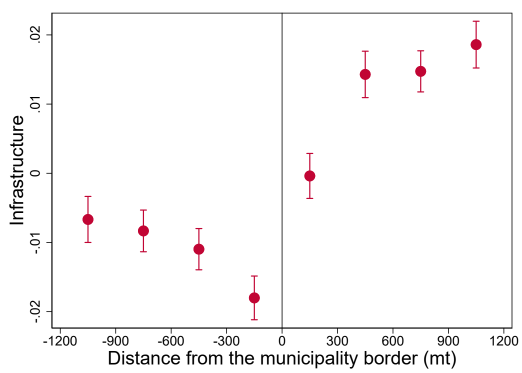
To document this fact, first, I construct a measure of infrastructure in space. I lay a grid of hexagonal cells over the area of the city; the grid cells have an area of 16 acres. Figure 10 shows one example of a border between municipalities. Black lines indicate the municipality boundaries and the gray lines show the grid cells. In the following analysis, I focus on grid cells within a 1.2-kilometer (0.75-mile) window of the border. Within the metropolitan limits, there are 81 municipality pairs that share a border. I exclude borders that coincide with geographical faults, such as rivers, resulting in a sample of 71 border pairs. Within the grid cells, I define infrastructure as the percentage of area covered by roads. I calculate this as the sum of the road segments within the polygon, weighted by the width of each road, divided by the total area of the cell.

Figure 10: Example of one border between municipalities

This exercise aims to test whether there is a systematic discontinuity in the density of roads around the border between municipalities. To visually show this, I order municipalities according to their relative *average* infrastructure. For two neighboring municipalities, A and B, I calculate the average road density of each municipality over the entire area around the border. In Figure 10, that would be the average road density in the area to the north of the border for one municipality and the average road density in the area to the south of the border for the other municipality. Suppose the average density of A is larger than the average of its neighbor, municipality B. In that case, Municipality A is ordered to the right of the border (positive distances), and Municipality B is ordered to the left of the border (negative distances).

Figure 11 shows the resulting pattern. The dots indicate the average road density over 300-meter intervals around the border, with their 95% confidence intervals. We can clearly see a significant jump at the border, and the infrastructure density is increasing with (absolute) distance to the border. This pattern is consistent with the model—both the jump and the slope. Closer to the border, a larger share of the benefits from infrastructures are captured by neighboring municipalities. We can compare the documented pattern with the pattern implied by the model in Figure 5(b).

Figure 11: Infrastructure at the border



Note: The y-axis shows the infrastructure residual after controlling for border fixed effects.

I estimate the above discontinuity using a standard spatial regression discontinuity design, described in more detail in Appendix A.2. The estimated average jump at the border is 0.019, which can be interpreted as 1.9% more land allocated to roads and commuting infrastructure. The sample's average infrastructure is 9%; hence, the jump corresponds to roughly a 20% change in the infrastructure level, a fairly large change.

We might worry that the ordering procedure of municipalities around the border, where I order them according to their relative average infrastructure, is driving the discontinuity. To address this concern, I compare the estimated discontinuity with one estimated from placebo municipalities.

To do so, I partition the area of Santiago into 30 random artificial municipalities. One example partition is shown in Figure A.3. Then, using the new placebo boundaries, I estimate both the discontinuity in infrastructure and the slope (as a function of absolute distance) using the same ordering and estimating procedure described above.

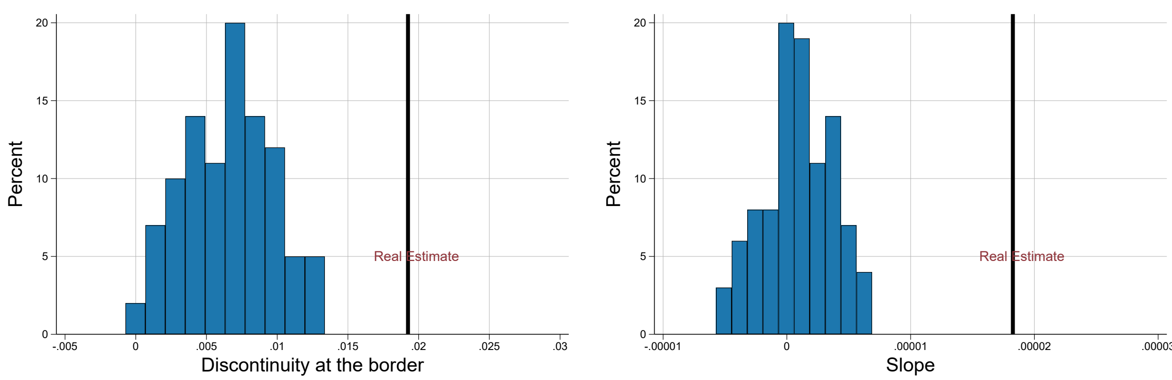
I repeat this exercise 100 times and plot the estimated border discontinuities and slope distribution. Figure 12 shows the histogram of the placebo estimates, compared to the "real" estimate using the true boundaries, highlighted with the bold black vertical line.

Note that the distribution of placebo discontinuities is not centered at zero. The ordering procedure, where I place the neighbor with relatively higher infrastructure on the positive side of the border, leads to positive jumps at the border. However, the estimated placebo discontinuities are always smaller than the real estimates, suggesting that it is unlikely that the pattern in Figure 11 is driven by the ordering procedure.

Figure 12: Placebo Analysis

(a) Histogram: Discontinuities at the border

(b) Histogram: Slope with absolute distance (mts)



Note: These plots show the histogram of placebo estimates across the 100 sets of artificial municipalities. The bold vertical lines indicate the real estimates derived from the true municipality borders.

4 Model Quantification

This section describes how I estimate the model's key parameters and exogenous location characteristics.

4.1 Structural Parameters and Location Characteristics

This section explains how I either estimate or obtain values for all the parameters of the model. I also describe how I transform the data of locations and infrastructure to build the network of nodes and edges.

Land shares

Two important parameters are the floor space share in production and the housing share in utility. The land shares affect how local governments value residents relative to workers in their jurisdiction, ultimately affecting how much infrastructure is built and the degree of underinvestment.

I take the value for the land share in production from Tsivanidis (2019). He estimates $(1-\beta) = 0.2$, by computing the share of floorspace in total costs across non-agricultural establishments in Bogotá, Colombia. This value is similar to the one estimated in Ahlfeldt et al. (2015). I calculate the housing share of utility, $(1-\alpha)$, from a household survey in Chile (CASEN), where people report spending on average 25% of their income in housing rent, $(1-\alpha) = 0.25$.

Other preference parameters

The other household preference parameters are the idiosyncratic preferences shape parameters of each nest, $\{\theta, \rho, \mu\}$, and the level of the disutility of commuting, κ.

I take the shape parameter of the idiosyncratic preference shocks for residence-work pairs from Pérez Pérez, Vial Lecaros, and Zárate (2022). They estimate $\theta = 8.2$ in the context of Santiago.[25] This parameter is important in my framework because it controls the elasticity with which households substitute residential or work locations; that is, how much residents and workers reorganize in space in reaction to new infrastructure.

Then, with a value of θ at hand, I estimate the disutility of commuting parameter, κ, by exploiting equation (9).[26] I estimate

$$\ln L_{ij} = \alpha_i + \beta_j - \theta\kappa \text{Time}_{ij} + \epsilon_{ij}, \tag{30}$$

where I measure travel time, Time_{ij}, using the least cost path route travel time between every pair origin-destination computed by Google Maps. The data on travel demands, L_{ij}, comes from the bilateral commuting data in the travel survey. A large pair of locations have zero commuting flows. Hence, I estimate the above relationship with Poisson Pseudo Maximum Likelihood (Silva & Tenreyro, 2015). With this procedure, I estimate $\kappa = 0.008$. This value is slightly smaller but similar to the one estimated by Ahlfeldt et al. (2015) ($\kappa = 0.01$).

Another important parameter is ρ, the routing idiosyncratic preference parameter. This param-

[25] They estimate this parameter following Ahlfeldt et al. (2015), by matching the standard deviation of the log wage distribution in the data. Moreover, they use the 2002 wave of data from the same travel survey used in this paper. Their model of household preferences is consistent with my model.

[26] Note that commuting costs, τ, are an exponential function of travel time. So when I take logs in equation 9, we get log commuters as a function of travel time (as opposed to log travel time).

eter controls how elastic people's routing decisions are to changes in travel time in a given edge. Hence, it impacts how much traffic flows reorganize in the network in response to changes in the infrastructure. I set this parameter to $\rho = 150$. This value assures that I satisfy the conditions stated in Allen and Arkolakis (2022), mainly that the spectral radius of the matrix $\mathbb{A} \equiv [d_{k\ell}^{-\rho}]$ is less than one. My choice for ρ is significantly larger than the one used by Allen and Arkolakis (2022) ($\rho = 6.83$).[27] Note that, as $\rho \to \infty$, the routing procedure converges to the least cost path route. Hence, using a large value of ρ implies that idiosyncratic noise plays a small role in households' routing decisions.

The parameter μ controls the substitutability across cities of the upper nest: it affects the variance of the idiosyncratic preference shocks between the city and other locations in the country, namely other cities or the countryside. From the nested preferences structure, we know that $\mu < \theta$, which implies that households' idiosyncratic preferences play a larger role when choosing among cities than among neighborhoods within the city. Monte, Redding, and Rossi-Hansberg (2018) estimate the heterogeneity in location preferences across counties in the U.S. They estimate $\mu = 3.3$, and their model of household preferences is consistent with mine.

Exogenous locations characteristics

From the tax authority's data on land use, I compute the available floorspace for residential purposes, $\bar{H}_{Ri}$, and for productive purposes, $\bar{H}_{Fi}$, for each location. Figure A.2 shows the distribution of floorspace by purpose in the city. Note that in the model, $\bar{H}_{Ri}$ and $\bar{H}_{Fi}$ are measures of land and not floor space. However, as the model doesn't include a housing construction sector, we can map land in the model to floor space in the data.

I follow the standard inversion approach in the literature, described in (Redding & Rossi-Hansberg, 2017), to estimate the exogenous productivity and amenities, $\{\bar{A}_i, \bar{B}_i\}_{i\in\mathcal{J}}$. I exploit the gravity equation implied by the model and the data on population and employment by location in the travel survey. That is, given a matrix of τ_{ij} and a value for θ, there is a unique vector of wages, $\{w_j\}$, that rationalizes the observed distribution of employment, $\{L_{Fj}\}$, and of population $\{L_{Ri}\}$. Once I invert the vector of wages, I can recover the implied productivity using

$$\bar{A}_j = w_j \Big(\frac{1-\beta}{\beta}\frac{L_{Fj}}{\bar{H}_{Fj}}\Big)^{1-\beta} \quad \forall j.$$

Similarly, given τ_{ij}, the vector of wages, w_j, and the population distribution, I can calculate the implied residential amenity that rationalizes the observed residential population distribution, namely,

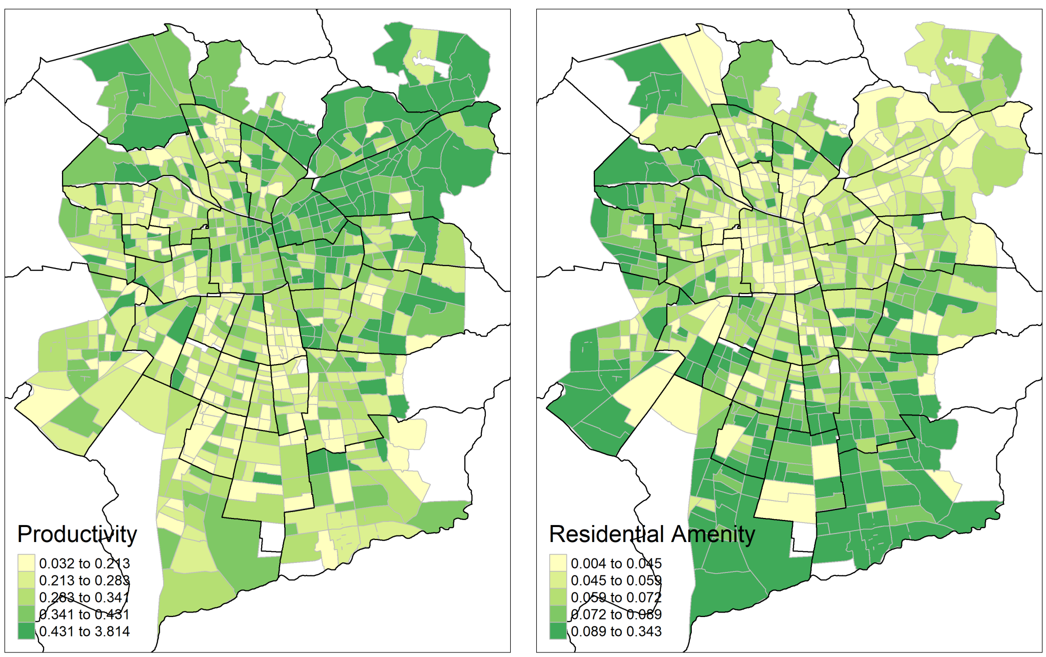
[27] Allen and Arkolakis (2022) choose a value of ρ equal to the value of the commuting elasticity, θ, for additional tractability in their framework.

$$\bar{B}_i = \left(\frac{L_{Ri}}{L}\right)^{\frac{1}{\theta}} q_{Ri}^{1-\alpha} \left(\sum_j (w_j/\tau_{ij})^{\theta}\right)^{-\frac{1}{\theta}}, \quad \text{where } q_{Ri} = (1-\alpha)\frac{L_{Ri}}{\bar{H}_{Ri}} \sum_j \frac{(w_j/\tau_{ij})^{\theta}}{\sum_k (w_k/\tau_{ik})^{\theta}} w_j.$$

Figure 13 shows the resulting distribution of productivity and residential amenities. Locations close to the center of the city and in the northeast have higher productivity, which is consistent with the pattern of employment shown in Figure 8. However, the implied differences in amenities are small.

Amenities are higher in the peripheral locations in the south and southwest. This is because these areas have significant residential population, although they are relatively far from jobs. Hence, the model rationalizes through higher residential amenities. In reality, these areas are quite poor (see Figure 7(b)).

Figure 13: Exogenous amenities and productivity



Note that the variance of productivity in space is much larger than the variance in residential amenities: $\mathbb{V}\text{ar}(\bar{A}_i)/\mathbb{V}\text{ar}(\bar{B}_i) \approx 68$. The variance in productivity and amenities in space is important for the implications of decentralization: First, it affects the size of spillovers and, therefore, the degree of underinvestment. Second, it increases the comparative advantage of some municipalities relative to others, allowing them to capture a larger fraction of the city's population by underproviding infrastructure and ultimately benefiting from decentralization.

Travel technology and network of edges

In the model, travel time in an edge (k, ℓ) is given by

$$\text{Travel Time}_{k\ell} = \bar{t}_{k\ell} \frac{Q_{k\ell}^{\sigma}}{\mathrm{I}_{k\ell}^{\xi}}.$$

I estimate the congestion elasticity, σ, using the real-time traffic flows and speed information described in Section 3.1. This data contains traffic flows and speeds every 15 minutes for 70 key intersections in the city. I estimate $\sigma = 0.14$. For more details on the estimation and the data, see Appendix A.5.

The value of the congestion elasticity will affect the size of the congestion externalities. Traffic congestion dampens the benefits of additional infrastructure and amplifies the distortions of decentralization through the indirect congestion force— municipalities fail to internalize the effect of their investments in traffic flows outside their jurisdiction.

I estimate the infrastructure elasticity, ξ, by exploiting the discontinuity in infrastructure at the border between municipalities documented in Section 3.3. In the same sample of grid cells around the municipality borders, I construct a measure of travel speed using Open Street Maps and a random set of origin and destination points within each grid cell.[28]

Figure A.8 shows the discontinuity in infrastructure and the corresponding discontinuity in speed. Using this variation, I estimate $\xi = 0.12$ by running a regression between log(Speed) and log(Infrastructure), where I instrument log infrastructure with the municipality border.

I build the network of edges using the shapefiles for the 700 locations from the travel survey. Locations that neighbor each other are connected by an edge in the network. I exclude neighbors that only touch in one point (for example, two squares that touch in a vertex rather than sharing a border). Figure A.4 shows the resulting network of locations and their connections (edges).

For every edge, I compute a proxy for the current infrastructure level, $\mathrm{I}_{k\ell}$, by using the information on the Open Street Maps road network. Similarly to how I approximate infrastructure to show the patterns of road density around the border, I take a buffer around the connecting line between the two centroids of the neighboring polygons and calculate the percentage of land allocated to commuting infrastructure in that buffer. I show an example for one edge in Appendix A.4.

Finally, with the constructed network of edges and their corresponding infrastructure levels, $\mathrm{I}_{k\ell}$, I use Google Maps to calculate the travel time for each edge during peak hours on a weekday. I then set the exogenous shifter, $\bar{t}_{k\ell}$, such that I perfectly match the observed travel times. That is,

$$\bar{t}_{k\ell} = \text{Travel Time}_{k\ell} \frac{I_{k\ell}^{\xi}}{Q_{k\ell}^{\sigma}},$$

[28] See Appendix A.6 for more detail on the measurement of speed and estimation.

where traffic flows, $Q_{k\ell}$, comes from equation (15). The travel demands, L_{ij}, are data observed in the travel survey. The link intensity, $\pi_{ij}^{k\ell}$, I construct using the observed edge-level travel times from Google Maps, κ, and ρ, according to

$$d_{k\ell} = \exp\left(\kappa \text{Travel Time}_{k\ell}\right), \quad \tau_{ij}^{-\rho} = (\mathbf{I} - \mathbf{A})^{-1},$$

where, following Allen and Arkolakis (2022), $\mathbf{A} \equiv [d_{k\ell}^{-\rho}]$. Given the matrix of d and τ, I compute the link intensity using equation (14).

Building costs

With all the estimated parameters, location characteristics, and edges characteristics, I use the structure of the model to obtain the infrastructure building costs. I use equation (22) and reorganize it as

$$\underbrace{\delta_{k\ell}^{\mathrm{I}}}_{\text{Building costs}} = \underbrace{\frac{1}{\mathrm{I}_{k\ell}^{g}}}_{\text{Data}} \underbrace{\xi \frac{\log d_{k\ell}}{1 + \rho\sigma \log d_{k\ell}} \left(Q_{\mathrm{R}k\ell} + Q_{\mathrm{F}k\ell} + Q_{\mathrm{Q}k\ell}\right)}_{\text{Estimated parameters + Model inversion}}.$$

I use the observed infrastructure in the data as $\mathrm{I}_{k\ell}^{g}$. That implies that the recovered building costs are such that the model perfectly matches the observed infrastructure in the baseline. We can think about these building costs as capturing not only traditional building costs but also any additional characteristic of an edge (link) that explains the level of infrastructure beyond the forces of the model. For example, suppose there is low road density in an area of the city because it is a protected area (for historical preservation, environmental considerations, etc). In that case, I rationalize the observed low level of infrastructure through high building costs.[29]

5 Centralizing Santiago

Using the estimated model, I consider two counterfactual economies where all infrastructure is decided by a metropolitan planner that maximizes the aggregate surplus of the city: aggregate land value net of building costs. In one counterfactual, I allow the metropolitan planner to increase or decrease the aggregate expenditure (budget). In the second one, I restrict the planner to spend the same budget as in the baseline decentralized equilibrium. By comparing the current decentralized

[29]One potential issue with this estimation strategy for the building costs is if these additional characteristics change in the centralized equilibrium. For example, suppose there is a high density of roads in areas that benefit the family and friends of the municipalities' mayors. If infrastructure decisions were centralized, then these personal incentives would disappear. However, my counterfactual analysis assumes that building costs would stay unchanged if the city was centralized.

equilibrium to these counterfactual ones, we can evaluate the infrastructure misallocation and welfare losses generated by the political decentralization of Santiago.

Table 1 shows changes to the aggregate variables of the model in the centralized counterfactuals relative to the baseline decentralized equilibrium. In the unconstrained centralized equilibrium, the aggregate infrastructure expenditure increases by 98%, i.e., it almost doubles, implying significant overall underinvestment in the baseline. By construction, aggregate expenditure stays the same in the constrained centralized equilibrium.

Table 1: Aggregate effects (%)

Variable	Centralized	Centralized|Budget
Population	6.9	4.3
Welfare	1.9	1.2
Surplus	4.9	4.3
Expenditure in infrastructure	98	0
Average commuting costs	-1.5	-0.8

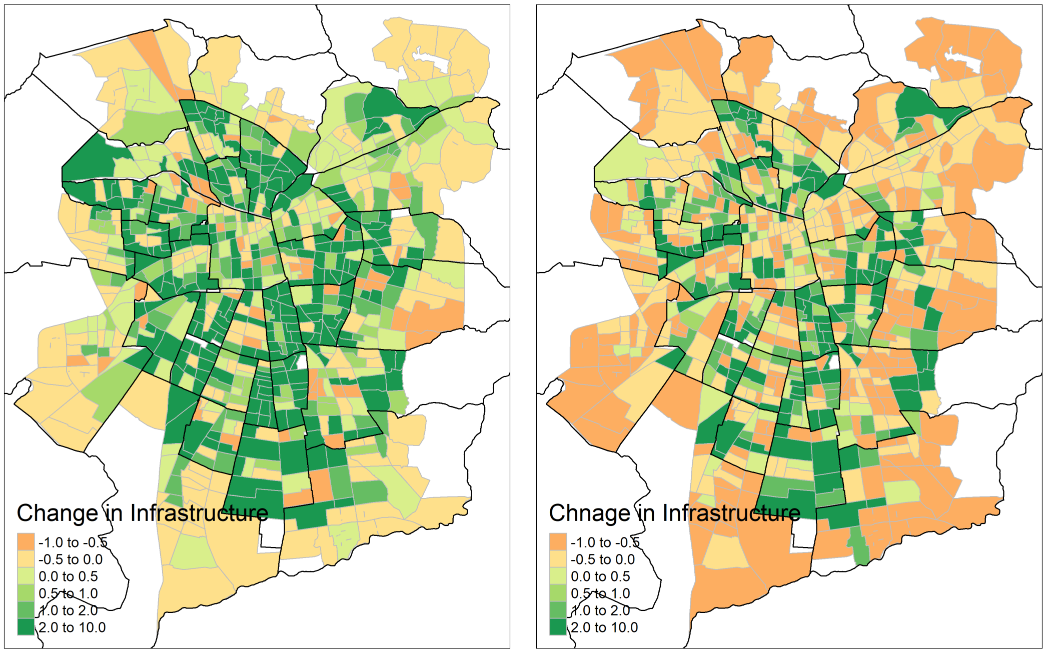
In the unconstrained counterfactual, even after the significant increase in infrastructure, overall commuting costs decreased by only 1.5%. This is due to the congestion forces, paired with the rise in population and reorganization of economic activity. As illustrated in the linear city, a higher concentration of employment in productive locations in this counterfactual leads to larger commutes and more traffic flows overall.

Perhaps interestingly, the counterfactual conditional on the baseline budget achieves a large fraction of the aggregate gains of centralization without increasing aggregate expenditure. Centralization reduces spatial misallocation in infrastructure investments. By shifting investment towards the municipalities that underinvest the most, we can improve connectivity and increase the city's aggregate land value and economic surplus.

Figure 14 shows the distribution in space of changes to commuting infrastructure relative to the baseline in both counterfactuals. Panel (a) shows the centralized counterfactual. The metropolitan planner invests more towards the city's center and less in the periphery than the baseline. The largest increases are concentrated in a ring around the central municipality. A large fraction of commuters in these locations are passing through: they live in the residential municipalities to the southwest of the city and commute to the center of the city and richer municipalities to the northeast of the city (see Figure 9 in the Appendix). Panel (b) shows the constrained centralized counterfactual, where we shift infrastructure from the periphery and central locations towards the inner ring, where there is more underinvestment in the baseline.

Figure 14: Changes to the city's infrastructure

(a) Centralized (b) Conditional on baseline budget



Note: In these figures, I show the increase relative to the baseline (decentralized) equilibrium. The change in infrastructure is calculated as $\Delta \mathrm{I}_{k\ell} = \frac{\mathrm{I}^{C}_{k\ell} - \mathrm{I}^{g}_{k\ell}}{\mathrm{I}^{g}_{k\ell}}$.

Figure 15 compares the distribution of changes in infrastructure for both counterfactuals. In the centralized case (in red), the metropolitan planner increases infrastructure for almost all locations. There is a reduction in infrastructure for roughly 30% of the links in the network, mostly located at the periphery of the city. In contrast, the constrained counterfactual reduces the infrastructure in more than half of the edges in the city (56%). This reduction goes towards increasing the infrastructure in the inner ring and improving the connectivity between the periphery and the city's core.

Figure 15: Distribution of relative increase in infrastructure

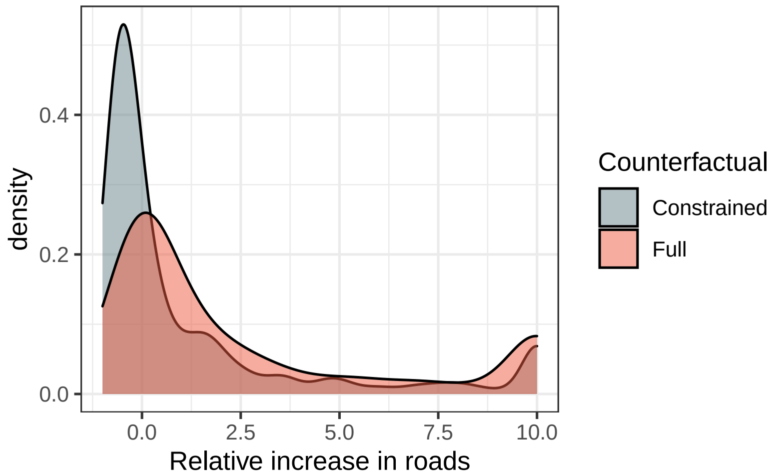
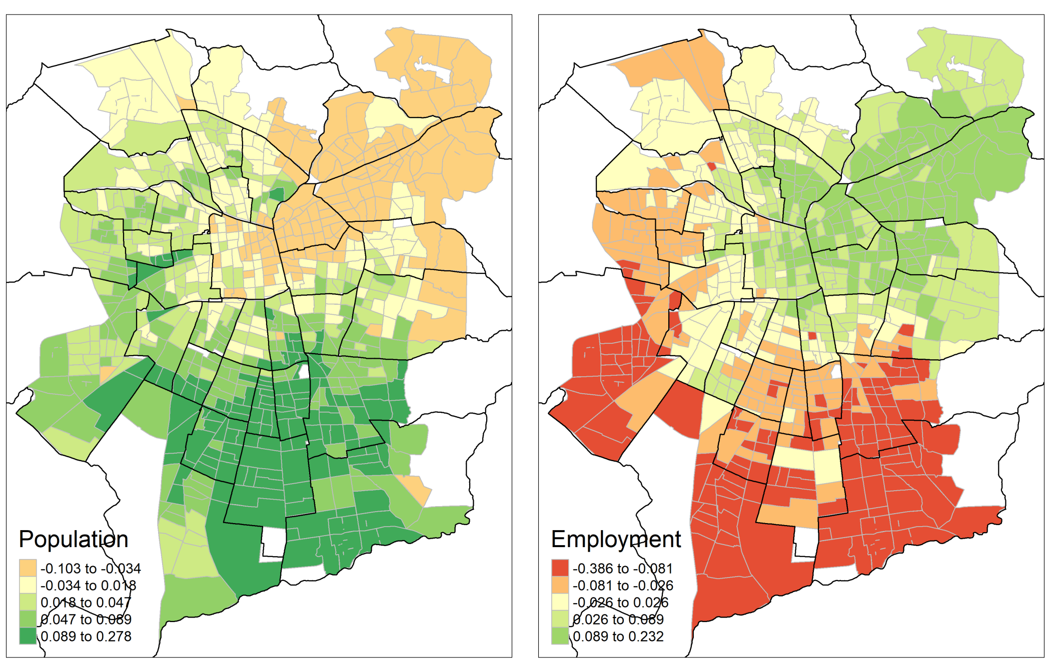


Figure 16 shows how the distribution of population changes in space for the constrained counterfactual. As in the line geography example, in the centralized (metropolitan) equilibrium, the employment shifts towards the productive areas within the city and becomes more concentrated. The residential population shifts towards areas with high amenities in the periphery. Hence, the city becomes more specialized: employment is more concentrated in productive locations, and residents are more concentrated in high-amenity locations, leading to longer commutes.

Figure 16: Constrained counterfactual - Changes to the city's population

(a) Residents (b) Employment



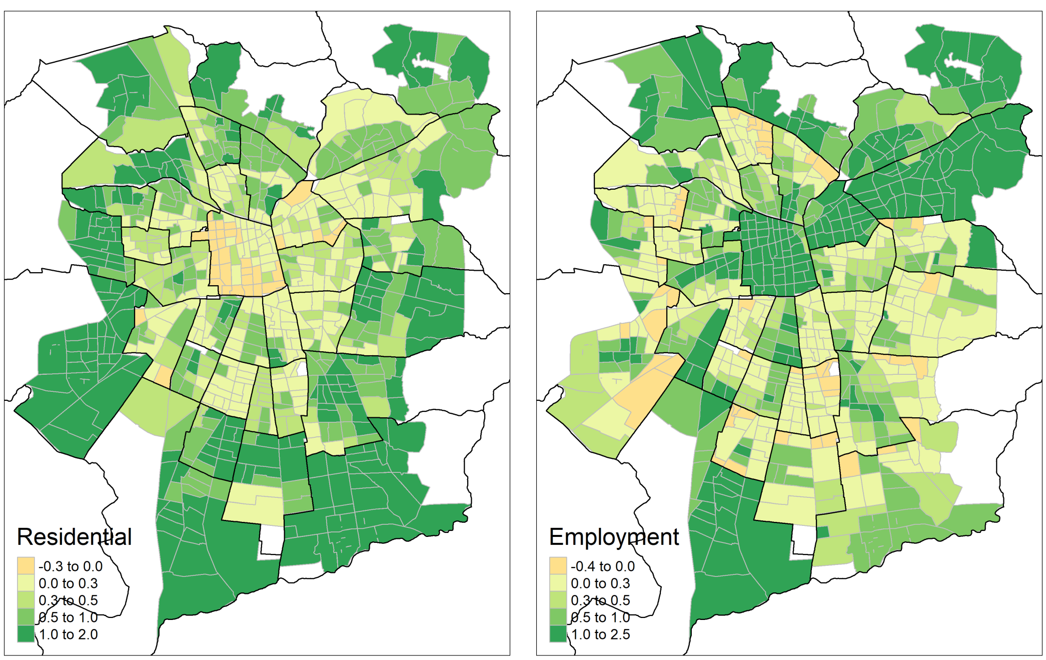
Note: In these figures, I show the increase relative to the baseline (decentralized) equilibrium. For example, the change in residents is calculated as $\Delta L_{Ri} = \frac{L^C_{Ri} - L^g_{Ri}}{L^g_{Ri}}$.

We can study the drivers behind the increase in infrastructure shown in Figure 14 by comparing the different forces defined in Section 2.2.1 under both equilibria. We can interpret these forces as weighted traffic flows, where the weights are a function of the government-specific Lagrange multipliers.[30] Figure 17 shows the ratio between the residential and employment flows in the decentralized baseline equilibrium and the centralized counterfactual. We can think of these relative flows as taking the ratio between the red and blue lines in Figure 3 in the linear city, the fraction of the total residential or employment benefits internalized by the municipality. Naturally, when calculating the relative flows, we consider the flows from the perspective of municipality g for edges in g's control relative to the metropolitan flows.

With this in mind, values smaller than one imply that locations outside the municipality capture some fraction of the benefits or costs. Values larger than one imply that the municipality increases its value by more than the city as a whole, i.e., the increase in land value is at the expense of value in other locations. Negative values imply that the location loses value in this dimension. For example, the central municipality has negative residential flows: additional infrastructure would translate into a loss in residents and land value for this municipality.

Figure 17: Relative flows

(a) Residential flows (b) Employment flows



Note: Relative flows are defined as $\frac{Q(\mathrm{R})^D}{Q(\mathrm{R})^C}$. The centralized flows are computed in the baseline equilibrium, i.e., with the empirical population distribution, but using the weights implied by the metropolitan planner.

[30]See Appendix B.1 for the derivation.

Let us focus first on the residential flows in figure 17(a). Areas around the city's center have low relative residential flows, even negative values; other municipalities capture a large fraction of the residential investment value in these locations. Improving its infrastructure causes residents to move from the city's center towards peripheral areas with lower housing prices and better amenities. In some locations at the center, the municipality loses overall residential value from investing in infrastructure. On the other hand, the periphery, especially the city's southwest, has large relative residential flows (higher than one). Investment in these locations increases residents and land value for these municipalities at the expense of residents in other jurisdictions.

Focusing now on the relative employment flows in figure 17(b), the central and eastern municipalities (areas with high exogenous productivity) have relative employment flows larger than one. Investing in infrastructure in these areas allows employment to concentrate in these productive locations, and these governments capture more land value at the expense of locations outside.

Note that the governments with the highest level of underinvestment in the baseline equilibrium are the governments with low relative residential and employment flows.[31] These governments have relatively low productivity and residential amenities to their neighboring jurisdictions. The benefits from infrastructure in these municipalities are mostly captured by their neighbors, as more people can travel to the work-intensive municipalities, and more households can move to the high-amenity peripheral locations.

Underinvestment is not as acute in governments that enjoy either a productivity or an amenity advantage. This is because the residential and employment forces go in different directions for these jurisdictions. When a productive municipality invests in roads, it loses residents and does not capture the full residential benefit of that investment. However, it gains employment at the expense of employment in other areas. It captures more than the total productive benefit of the investment, as it "steals" some business from other areas.

Winners and Losers of Decentralization

We now compute the differences in aggregate surplus by municipality. That is the change in their objective function defined in equation (18) in the centralized equilibrium relative to the decentralized equilibrium. This comparison allows us to study which municipalities currently benefit from decentralization and, therefore, might oppose a more centralized infrastructure planning strategy. For this analysis, I focus on the full centralized counterfactual, where the budget and aggregate investment adjusts and the aggregate gains in land value are the largest.

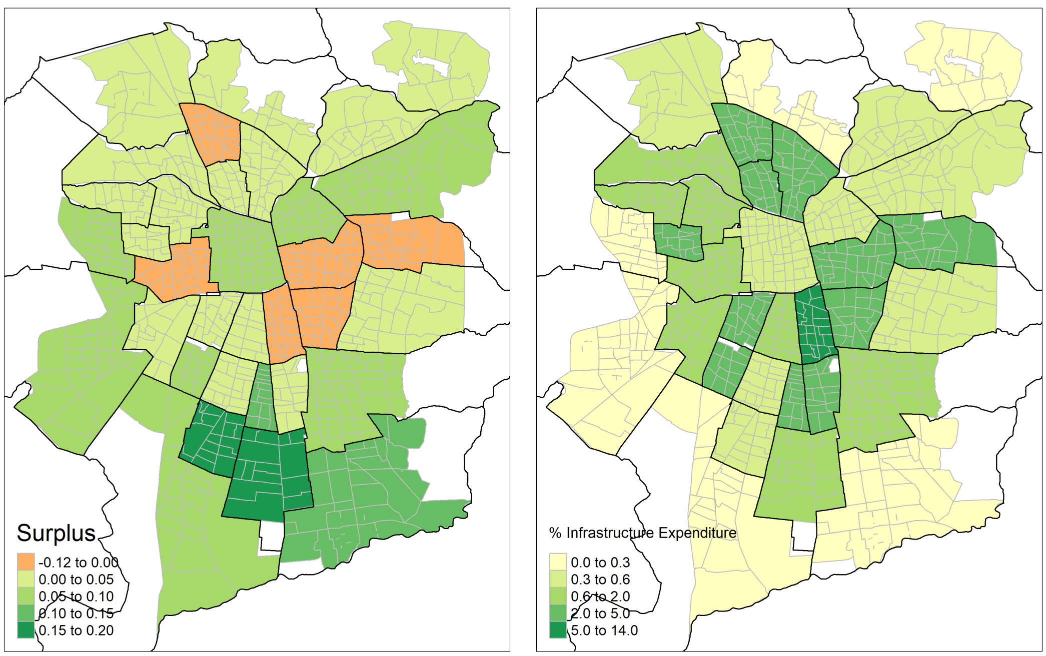
[31] We can see the overall level of underinvestment of a government in figure 18(b). This figure shows the overall increase in expenditure by government in the full centralized counterfactual, where the total metropolitan budget doubles. The municipalities in the ring around the core increase their expenditure the most and, therefore, are the ones that underinvest the most in the decentralized equilibrium.

Figure 18(a) shows the difference in surplus, and Figure 18(b) shows the difference in aggregate infrastructure expenditure by municipality. We can see that the peripheral municipalities in the south benefit the most from centralization. These municipalities don't increase their investment as much as those in the inner ring but benefit from the improved market access to the work locations. Similarly, the municipalities in the northeast benefit from the improved market access to workers, which raised their productive land prices.

The municipalities in red are the ones that benefit from decentralization and are losing surplus in this counterfactual metropolitan scenario. Intuitively, the worse-off municipalities coincide with those with some of the highest underinvestment in the baseline. They have to increase their expenditure significantly in the counterfactual, but most of the benefit is captured by other jurisdictions.

Figure 18: Full counterfactual - Change in surplus and socioeconomic status

(a) Δ surplus by government (b) Δ expenditure by gov.



Maybe surprisingly, the central municipality, called Santiago, is better off in the centralized equilibrium, even though improving its infrastructure causes a loss in residential land value compared to the baseline. This is because an increase in productive land value compensates for this loss.

6 Conclusions

This paper shows how political decentralization can lead to misallocation in infrastructure investment. I propose a quantitative spatial model where local governments invest in commuting infrastructure to maximize their land value. In equilibrium, local governments underinvest in areas near their boundaries, where a large fraction of the benefits from infrastructure accrues to locations outside their jurisdiction. Local governments overinvest in areas where they can increase their land value at the expense of land value in other jurisdictions. Moreover, the under-provision of infrastructure around the boundary leads to employment dispersion and residents moving closer to their work locations. This shift in the population distribution translates into lower overall commuting flows, lower aggregate population, and lower aggregate welfare.

I then test the predictions of the model in Santiago, Chile. I document a pattern of road density around the boundary between municipalities consistent with the model's predictions. I estimate the model's parameters and fundamentals with data from Santiago and use the estimated model to study two counterfactual economies where a metropolitan planner decides the infrastructure for every link in the network. This counterfactual analysis quantifies decentralization's aggregate welfare losses and reveals the pattern of misallocation.

The main result from this counterfactual exercise is that centralizing investment decisions would substantially increase investment: total expenditure on infrastructure would double. Importantly, the gains from centralizing are not only about building more but also about allocating the infrastructure more efficiently. By shifting infrastructure towards the locations that underinvest the most, the constrained metropolitan planner achieves 63% of the aggregate gains in welfare and population from the unconstrained counterfactual without increasing the total amount of investment.

The municipalities that most benefit from centralization are also the poorest. Figure 7(b) shows the city's baseline distribution of socio-economic status. Lower-income households are concentrated in municipalities in the city's south and west periphery. These locations are far from the productive areas where jobs are located and next to the municipalities that most underinvest in the baseline scenario. Hence, lower-income households currently commute longer and through lower infrastructure locations than their higher-income counterparts. Therefore, they would benefit more from the increased investment in their nearby municipalities. Accounting for these income differences across households in the theory and the empirical analysis is an interesting direction to explore in future research.

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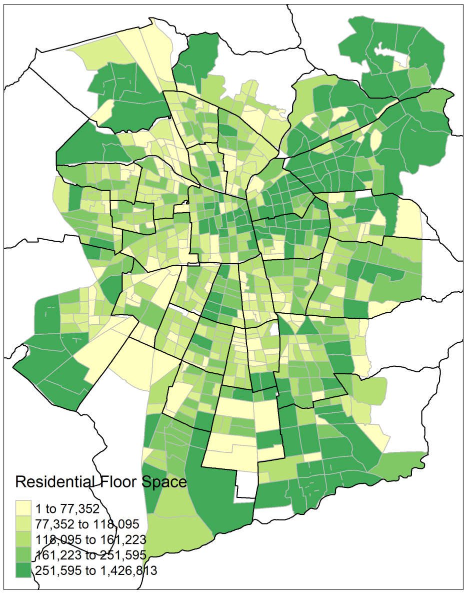
A Data and Estimation Appendix

A.1 Figures

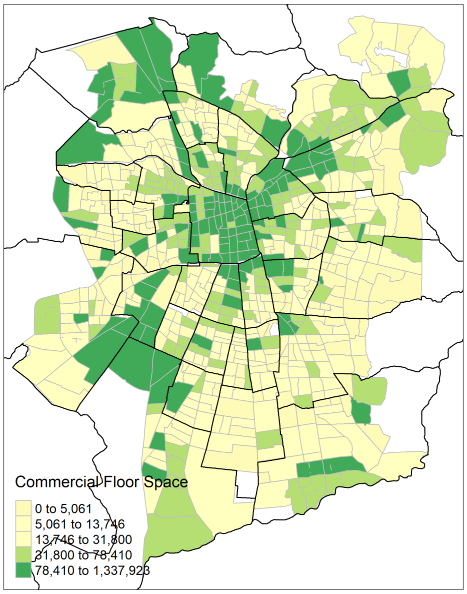
Figure A.1: Santiago's road network

Figure A.2: Available floor space by purpose in Santiago

(a) Residential

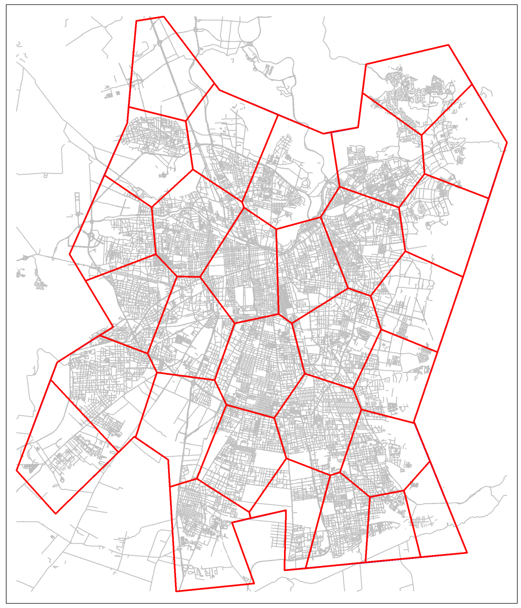


(b) Productive



Note: Constructed using the public database of real estate appraisals by the tax authority (2018).

Figure A.3: Example: Placebo Municipalities



A.2 Empirical patterns: Discontinuity in infrastructure

To estimate the size of the jump at the border between municipalities, I run the following regression:

$$\mathrm{I}_i = \beta \mathbb{1}(\text{Distance}_i > 0) + \gamma \text{Distance}_i + \mu \text{Distance}_i \times \mathbb{1}(\text{Distance}_i > 0) + \delta_{B(i)} + \epsilon_i$$

where i denotes an individual location, in this case, grid cell i. I control for distance to the border, where I allow for the slope to vary on each side of the border. As it is clear in Figure 11, the slope is first decreasing and then increasing with distance. Finally, I control for border (municipality-pair) fixed effects and cluster the standard errors at the border level.

I also run the above regression allowing for a quadratic function of distance, where I also interact the quadratic term with the border dummy. Table A.1 shows the estimated discontinuity; the average jump is 1.8% more infrastructure, which is approximated in the data as the percentage of area allocated to roads.

The sample's average infrastructure is 0.09, 9% of land allocated to roads. Hence, the estimated jump corresponds to approximately a 20% change in the infrastructure level.

Table A.1: Discontinuity in infrastructure at the border

	Infrastructure	
	(1)	(2)
	Linear	Quadratic
$\mathbb{1}$(Distance>0)	0.0194***	0.0175***
	(0.00357)	(0.00466)
N	10753	10753
Border FE	Yes	Yes

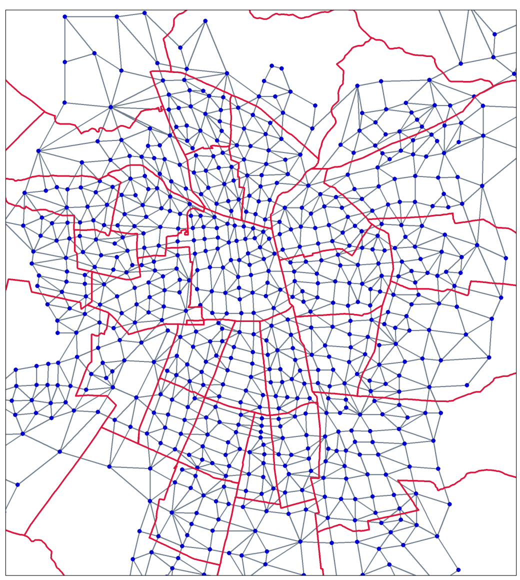
Standard errors in parentheses

Robust standard errors, adjusted for clustering by border.

* p¡0.10, ** p¡0.05, *** p¡0.01

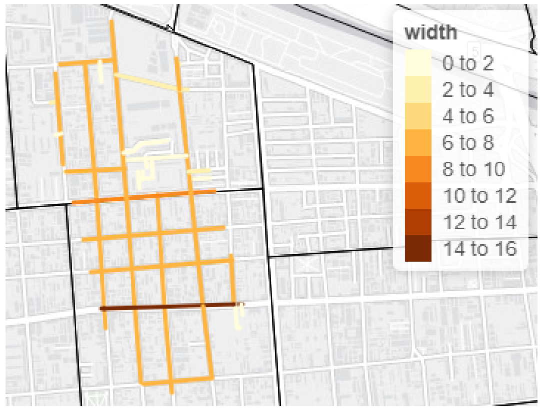
A.3 Estimation of the model's parameters

Figure A.4: Network of locations and edges



A.4 Computing $\mathrm{I}_{k\ell}$

Figure A.5: Example of one edge



$$\mathrm{I}_{k\ell} = \frac{\sum_r \text{width}_r \times \text{length}_r}{\text{Area}_{k\ell}}$$

A.5 Estimating the congestion elasticity, σ

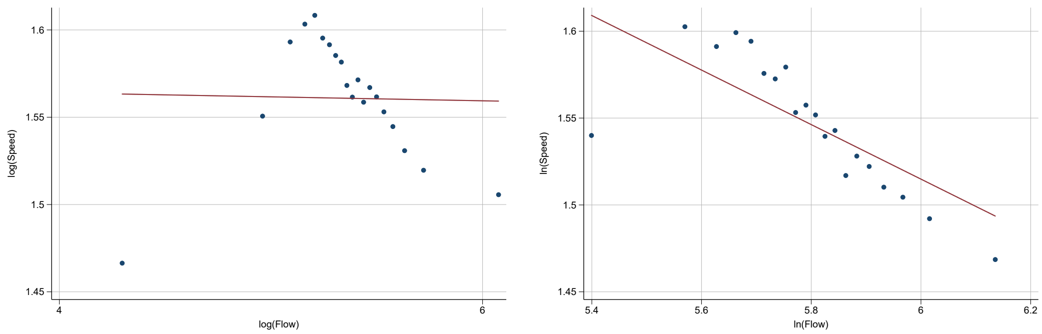
Using the Ministry's automatic readers data on traffic flows, and combining this data with my Google Maps data on real-time speed for the same intersection where the readers are located, I can study the relationship between travel times and traffic flows.

Figure A.6 (a) shows the binscatter of the relationship between log speed and log flows. We can see that for low levels of traffic, there is a positive relationship between speed and flows. On the other hand, as traffic increases and the road gets congested, the relationship becomes negative; driving speed slows down.

The increasing portion of the relationship is due to the following: When the road is uncongested, more speed by construction translates into more flow (more cars traveling in front of the reader). Intuitively, we can think about flows as a function of speed for this portion. Hence, I filter the data to capture the congested portion of the relationship.

Figure A.6: Speed as a function of traffic flows

(a) Full sample (b) Congested portion



Note: These binscatters include the following Fixed Effects: Hour of the day, day of the week, and intersection. For panel (b), I defined congested as having more than 160 cars in a 15-minute window.

I ran the following regression:

$$\ln \text{Speed}_{it} = \beta \ln \text{Flow}_{it} + \delta_i + \delta_h + \delta_d + \epsilon_{it}$$

where δ_i is an intersection fixed effect; the place where the automatic reader is located. Then, δ_h is an hour of the day fixed effect, and δ_d is a day of the week fixed effect. Note that $\beta = -\sigma$.

Table A.2: Regression Results

	ln(Speed)
ln(Traffic Flow)	-0.144***
	(0.0103)
Observations	35068
Adjusted R^2	0.617

FE: Hour, day of the week, intersection.

A.6 Estimating the infrastructure elasticity, ξ

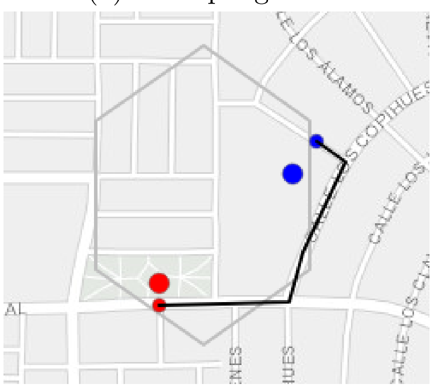
I estimate the infrastructure elasticity, ξ, by estimating the effect of more infrastructure on travel speed. I exploit the discontinuity in infrastructure at the border between municipalities as a plausibly exogenous variation on the amount of infrastructure and estimate the effect of that shift in infrastructure on average commuting speed.

First, the identifying assumptions behind this strategy are that unobserved omitted variables that might affect infrastructure and speed are continuous at the border. Second, the exclusion restriction for the instrument of crossing the border has to hold, that is that crossing the border only affects the speed of travel through the available infrastructure.

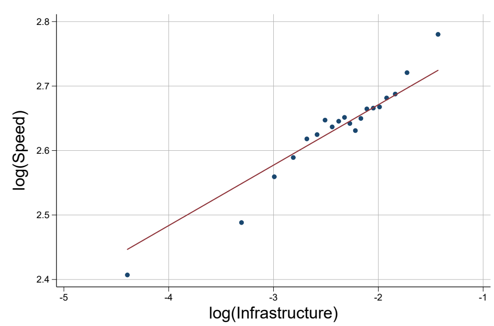
I compute speed using the same grid of hexagonal polygons used to calculate infrastructure in space. For each grid cell, I take a random sample of origin and destination points within the polygon and then use Open Street Map to calculate the travel time and distance between these two points in the road network. Finally, I add the walking time and distance from the origin and destination to the road network, assuming a walking speed of 4.5 km/hr.

Figure A.7(a) shows an example of a grid cell. The larger red and blue dots show the original random origin and destination points. The smaller dots are the closest points in the road network to the origin and destination. Open Street Maps provides the distance and time of traveling through the road network, highlighted in black. Finally, I add the walking time and distance to adjust for the fact that the original origin and destination are not in the road network.

(a) Example grid cell



(b) OLS relationship



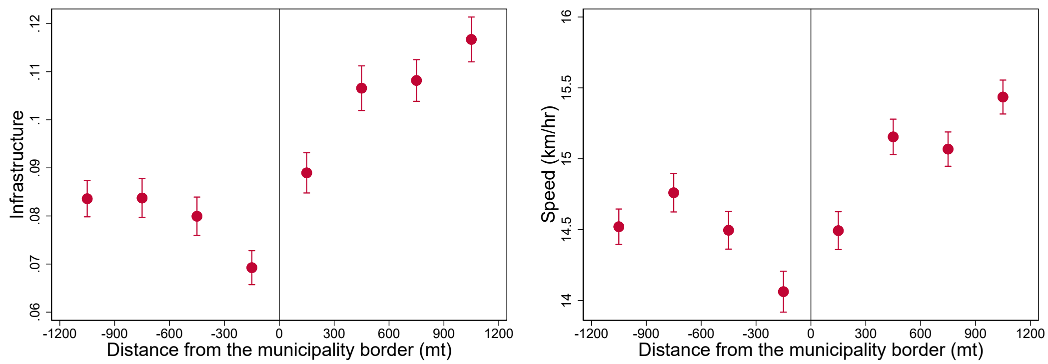
Note: In (b), I control for log(Flows), urban density, slope, and altitude.

Figure A.7(b) shows the OLS relationship in the sample of grid cells between the infrastructure, defined as the percentage of the area allocated to commuting infrastructure, and the speed calculated according to the above procedure.

Now, with a set of speed measurements for every grid cell in the 1.2 km buffer around the municipality borders, we can use the discontinuity in infrastructure at the border and relate that jump to the difference in speed around the border.

Figure A.8: Discontinuity at the border

(a) Infrastructure (b) Speed



I estimate ξ through the following 2SLS strategy

$$\text{First stage: } \log(\text{Infrastructure}_i) = \beta\mathbb{1}(\text{Distance}_i) + f(\text{Distance}_i) + X_i^{\text{Geo}} + \epsilon$$

$$\text{Second stage: } \log(\text{Speed}_i) = \beta \widehat{\log(\text{Infrastructure}_i)} + f(\text{Distance}_i) + X_i^{\text{Geo}} + \epsilon$$

where $\widehat{\log(\text{Infrastructure}_i)}$ is the predicted value from the first stage. I control for a flexible function of distance to the border and for geographical characteristics of the terrain, such as slope and altitude. Intuitively, we are running a regression of log-speed on log-infrastructure, where we are instrumenting infrastructure using the municipality border.

Table A.3 shows the results for different distance functions.

Table A.3: Spatial Regression Discontinuity

	Linear		Quadratic		Cubic	
	(1)	(2)	(3)	(4)	(5)	(6)
	<1200 mt	<900 mt	<1200 mt	<900 mt	<1200 mt	<900 mt
log(Infrastructure)	0.121**	0.122**	0.118**	0.122**	0.115*	0.141*
	(0.0486)	(0.0521)	(0.0480)	(0.0514)	(0.0621)	(0.0835)
N	129195	99300	129195	99300	129195	99300
Border FE	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses

* p¡0.10, ** p¡0.05, *** p¡0.01

B Theory Appendix

In this section, I show how I derive the optimal infrastructure from the government's problem. Then, I show how we can separate the government-specific forces behind the optimal infrastructure into the three effects described in the main text: residential, employment, and congestion. Finally, I'll show how we can interpret these as traffic flows weighted by government-specific weights.

First, government g's Lagrangian is given by:

$$\begin{aligned}
\mathcal{L} =& \sum_i \mathbb{1}[i \in \mathcal{J}^g]\Big\{\bar{H}_{\mathrm{R}i}q_{\mathrm{R}i} + \bar{H}_{\mathrm{F}i}q_{\mathrm{F}i}\Big\} - \sum_{k\ell} \mathbb{1}[(k,\ell) \in \mathcal{E}^g]\delta^{\mathrm{I}}_{k\ell}\mathrm{I}_{k\ell} - \\
& \sum_{ij} \lambda^g_{ij}\Big[L_{ij} - \tau_{ij}^{-\theta}\Big(\frac{\bar{B}_i}{q_{\mathrm{R}i}^{1-\alpha}}\Big)^{\theta} w_j^{\theta}\frac{L}{U}\Big] - \sum_i \lambda^g_{Wi}\Big[w_i - \bigg(\frac{\bar{A}_i}{q_{\mathrm{F}i}^{1-\beta}}\bigg)^{\frac{1}{\beta}}\Big] - \\
& \sum_i \eta^g_{\mathrm{R}i}\Big[q_{\mathrm{R}i} - \frac{(1-\alpha)}{\bar{H}_{\mathrm{R}i}}\sum_j L_{ij}w_j\Big] - \sum_i \eta^g_{\mathrm{F}i}\Big[q_{\mathrm{F}i} - \bar{A}_i\bigg(\frac{\beta}{1-\beta}\frac{\sum_j L_{ji}}{\bar{H}_{\mathrm{F}i}}\bigg)^{\beta}\Big] - \\
& \sum_{ij} \gamma^g_{ij}\Big[\tau_{ij} - \Big((1-A)^{-1}\Big)^{-\frac{1}{\rho}}\Big] - \sum_{k\ell} \epsilon^g_{k\ell}\Big[d_{k\ell} - \exp\Big(\kappa \bar{t}_{k\ell}\frac{Q^{\sigma}_{k\ell}}{I^{\xi}_{k\ell}}\Big)\Big] - \\
& \sum_{k\ell} \phi^g_{k\ell}\Big[Q_{kl} - \sum_{ij} L_{ij}\Big(\frac{\tau_{ij}}{\tau_{ik}d_{k\ell}\tau_{\ell j}}\Big)^{\rho}\Big] - \upsilon^g_L\Big[L - \frac{U^{\mu}}{U^{\mu} + \bar{U}^{\mu}_o}\bar{L}_c\Big] - \upsilon^g_U\Big[U - \Big(\sum_{ij}\tau_{ij}^{-\theta}\Big(\frac{\bar{B}_i}{q_{\mathrm{R}i}^{1-\alpha}}\Big)^{\theta}(w_j)^{\theta}\Big)^{\frac{1}{\theta}}\Big]
\end{aligned}$$

First order conditions:

$$
\begin{aligned}
[q_{\mathrm{R}i}] :& \eta^g_{\mathrm{R}i} = \mathbb{1}[i \in \mathcal{J}^g]\bar{H}_{\mathrm{R}i} - \frac{\theta(1-\alpha)}{q_{\mathrm{R}i}} \sum_j \lambda^g_{ij} L_{ij} - \upsilon^g_U \frac{U}{L} \frac{1-\alpha}{q_{\mathrm{R}i}} L_{\mathrm{R}i} \\
[q_{\mathrm{F}i}] :& \eta^g_{\mathrm{F}i} = \mathbb{1}[i \in \mathcal{J}^g]\bar{H}_{\mathrm{F}i} - \lambda_{Wi} \frac{1-\beta}{\beta} \frac{w_i}{q_{Fi}} \\
[L_{ij}] :& \lambda^g_{ij} = \eta^g_{\mathrm{R}i} \frac{1-\alpha}{\bar{H}_{\mathrm{R}i}} w_j + \eta_{\mathrm{F}j} \beta \frac{q_{\mathrm{F}j}}{L_{\mathrm{F}j}} + \sum_{k\ell} \phi^g_{k\ell} \Big(\frac{\tau_{ij}}{\tau_{ik} t_{k\ell} \tau_{\ell j}} \Big)^\rho \\
[w_i] :& \lambda^g_{Wi} = \frac{\theta}{w_i} \sum_j \lambda^g_{ji} L_{ji} + \sum_j \eta^g_{\mathrm{R}j} (1-\alpha) \frac{L_{ji}}{\bar{H}_{\mathrm{R}j}} + \upsilon^g_U \frac{U}{L} \frac{L_{\mathrm{F}i}}{w_i} \\
[\tau_{ij}] :& \gamma^g_{ij} = -\frac{\theta}{\tau_{ij}} \lambda^g_{ij} L_{ij} - \upsilon^g_U \frac{U}{L} \frac{L_{ij}}{\tau_{ij}} + \frac{\rho}{\tau_{ij}} \sum_{k\ell} \phi^g_{k\ell} L_{ij} \Big(\frac{\tau_{ij}}{\tau_{ik} t_{k\ell} \tau_{\ell j}} \Big)^\rho - \\
& \frac{\rho}{\tau_{ij}} \sum_\ell \phi^g_{j\ell} \sum_m L_{im} \Big(\frac{\tau_{im}}{\tau_{ij} t_{j\ell} \tau_{\ell m}} \Big)^\rho - \frac{\rho}{\tau_{ij}} \sum_k \phi^g_{ki} \sum_m L_{mj} \Big(\frac{\tau_{mj}}{\tau_{mk} t_{ki} \tau_{ij}} \Big)^\rho \\
[L] :& \upsilon^g_L = \frac{1}{L} \sum_{ij} \lambda^g_{ij} L_{ij} \\
[U] :& \upsilon^g_U = -\frac{\theta}{U} \sum_{ij} \lambda^g_{ij} L_{ij} + \upsilon^g_L \frac{L}{U} \mu \Big(1 - \frac{1}{U^\mu + \bar{U}^\mu_o} \Big) \\
[d_{k\ell}] :& \sum_{ij} \gamma^g_{ij} \frac{\tau_{ij}}{d_{k\ell}} \Big(\frac{\tau_{ij}}{\tau_{ik} d_{k\ell} \tau_{\ell k}} \Big)^\rho = \epsilon^g_{k\ell} + \phi^g_{k\ell} Q_{k\ell} \frac{\rho}{d_{k\ell}} \\
[Q_{k\ell}] :& \epsilon^g_{k\ell} d_{k\ell} \frac{\sigma}{Q_{k\ell}} \log d_{k\ell} = \phi^g_{k\ell} \\
[I_{k\ell}] :& -\epsilon^g_{k\ell} d_{k\ell} \frac{\xi}{\mathrm{I}_{k\ell}} \log d_{k\ell} = \mathbb{1}[(k,\ell) \in g] \delta^{\mathrm{I}}_{k\ell}
\end{aligned}
$$

Simplifying, the optimal infrastructure is given by:

$$
(\mathrm{I}^*_{k\ell})^g = -\phi^g_{k\ell} \frac{\xi}{\sigma} \frac{Q_{k\ell}}{\delta^{\mathrm{I}}_{k\ell}}
$$

We can simplify the system of F.O.C. equations:

$$
\begin{aligned}
[q_{\mathrm{R}i}] : & \eta^g_{\mathrm{R}i} = \mathbb{1}[i \in \mathcal{J}^g]\bar{H}_{\mathrm{R}i} - \theta\frac{(1-\alpha)}{q_{\mathrm{R}i}}\sum_j \lambda^g_{ij}L_{ij} - \upsilon^g_U\frac{U}{L}(1-\alpha)\frac{L_{\mathrm{R}i}}{q_{\mathrm{R}i}} \\
[q_{\mathrm{F}i}] : & \eta^g_{\mathrm{F}j} = \mathbb{1}[i \in \mathcal{J}^g]\bar{H}_{\mathrm{F}i} - \frac{1-\beta}{\beta}\frac{\theta}{q_{Fi}}\sum_j \lambda^g_{ji}L_{ji} - \frac{1-\beta}{\beta}\frac{1}{q_{Fi}}\sum_j \eta^g_{\mathrm{R}j}\frac{1-\alpha}{\bar{H}_{\mathrm{R}j}}L_{ji}w_i - \upsilon^g_U\frac{1-\beta}{\beta}\frac{U}{L}\frac{L_{\mathrm{F}i}}{q_{\mathrm{F}i}} \\
[d_{k\ell}] : & \phi^g_{k\ell}Q_{k\ell} = \Big(\frac{1}{\sigma\log d_{k\ell}} + \rho\Big)^{-1}\sum_{ij}\gamma^g_{ij}\tau_{ij}\Big(\frac{\tau_{ij}}{\tau_{ik}d_{k\ell}\tau_{\ell k}}\Big)^{\rho} \\
[U] : & \upsilon^g_U = \frac{1}{U}\Big(\theta - \varepsilon_L\Big)\sum_{ij}\lambda^g_{ij}L_{ij}
\end{aligned}
$$

where:

$$
\begin{aligned}
\lambda^g_{ij} &= \eta^g_{\mathrm{R}i}\frac{1-\alpha}{\bar{H}_{\mathrm{R}i}}w_j + \eta_{\mathrm{F}j}\beta\frac{q_{\mathrm{F}j}}{L_{\mathrm{F}j}} + \sum_{k\ell}\phi^g_{k\ell}\Big(\frac{\tau_{ij}}{\tau_{ik}t_{k\ell}\tau_{\ell j}}\Big)^{\rho} \\
\gamma^g_{ij} &= -\frac{\theta}{\tau_{ij}}\lambda^g_{ij}L_{ij} - \upsilon^g_U\frac{U}{L}\frac{L_{ij}}{\tau_{ij}} + \frac{\rho}{\tau_{ij}}\sum_{k\ell}\phi^g_{k\ell}L_{ij}\pi^{k\ell}_{ij} - \frac{\rho}{\tau_{ij}}\sum_{\ell}\phi^g_{j\ell}\sum_m L_{im}\pi^{j\ell}_{im} - \frac{\rho}{\tau_{ij}}\sum_k\phi^g_{ki}\sum_m L_{mj}\pi^{ki}_{mj} \\
\varepsilon_L &\equiv \mu\Big(1 - \frac{1}{U^{\mu} + \bar{U}^{\mu}_o}\Big) \quad = \frac{\partial L}{\partial U}\times\frac{U}{L}
\end{aligned}
$$

Then, replacing back into the optimal infrastructure Equation:

$$
(\mathrm{I}^*_{k\ell})^g = \frac{\xi}{\sigma}\frac{1}{\delta^{\mathrm{I}}_{k\ell}}\Big(\frac{1}{\sigma\log d_{k\ell}} + \rho\Big)^{-1}\underbrace{\sum_{ij} -\gamma^g_{ij}\tau_{ij}\pi^{k\ell}_{ij}}_{*}
$$

B.1 Weighted flows

In this section, I will show we can go from the residential, employment, and congestion effects to weighted flows. These effects map to the flow of commuters using the edge, weighted by government-specific weights.

Residential Effect

After some algebra and using the definitions of the Lagrange multipliers, we can simplify the residential force as

$$
\begin{aligned}
Q^g_{\mathrm{R}k\ell} &= \sum_{ij} \eta^g_{\mathrm{R}i} \frac{\partial q_{\mathrm{R}i}}{\partial L_{ij}} \frac{\partial L_{ij}}{\partial d_{k\ell}} \\
&= \sum_{ij} \eta^g_{\mathrm{R}i} \underbrace{\frac{(1-\alpha)}{\bar{H}_{\mathrm{R}i}} w_j}_{\frac{\partial q_{\mathrm{R}i}}{\partial L_{ij}}} \underbrace{\frac{L_{ij}}{d_{k\ell}} \left(\theta \pi^{k\ell}_{ij} - \frac{Q_{k\ell}}{L} (\theta - \varepsilon_L) \right)}_{\frac{\partial L_{ij}}{\partial d_{k\ell}}}.
\end{aligned}
$$

A reduction in d_{ij} will affect L_{ij} throughout the city, not only the origin-destination pairs that most intensely use the link $k\ell$, but also it affects L_{ij} through the effect in U and L. These population movements also affect residential (origin) land value across all locations. These changes in land value are multiplied by η^g_{R}, which transforms residential land changes to land value captured by the government g.

Now, reorganizing the above expression to express as a weighted traffic flow

$$
Q^g_{\mathrm{R}k\ell} = \sum_{ij} \pi^{k\ell}_{ij} L_{ij} \underbrace{\left(\theta \eta^g_{\mathrm{R}i} \frac{1-\alpha}{\bar{H}_{\mathrm{R}i}} w_j + \frac{\theta - \varepsilon_L}{L} \sum_h \eta^g_{\mathrm{R}h} q_{\mathrm{R}h} \right)}_{\equiv \omega^g_{\mathrm{R}ij}}. \tag{B.1}
$$

Recall that traffic flows are given by $Q_{k\ell} = \sum_{ij} L_{ij} \pi^{k\ell}_{ij}$. So we can interpret these residential flows as the commuters using edge $k\ell$, weighted by $\omega^g_{\mathrm{R}ij}$, which represents the value derived by the government g from changes to residential land value caused by a reduction in commuting costs for link $k\ell$, $d_{k\ell}$.

Employment Effect

After some algebra and using the definitions of the Lagrange multipliers, we can simplify the employment force to

$$
\begin{aligned}
Q^g_{\mathrm{F}k\ell} &= \sum_{ij} \eta^g_{\mathrm{F}j} \frac{\partial q_{\mathrm{F}j}}{\partial L_{ij}} \frac{\partial L_{ij}}{\partial d_{k\ell}} \\
&= \sum_{ij} \eta^g_{\mathrm{F}j} \underbrace{\beta \frac{q_{\mathrm{F}j}}{L_{\mathrm{F}j}}}_{\frac{\partial q_{\mathrm{F}j}}{\partial L_{ij}}} \underbrace{\frac{L_{ij}}{d_{k\ell}} \left(\theta \pi^{k\ell}_{ij} - \frac{Q_{k\ell}}{L} (\theta - \varepsilon_L) \right)}_{\frac{\partial L_{ij}}{\partial d_{k\ell}}}
\end{aligned}
$$

A reduction in d_{ij} will affect L_{ij} throughout the city, not only the origin-destination pairs that most intensely use the link $k\ell$, but also it affects L_{ij} through the effect in U and L. These population movements also affect commercial (destination) land value across all locations. These changes in land value are multiplied by η^g_{F}, which transforms residential land changes to land value captured by the government g.

Now, reorganizing the above expression to express as a weighted traffic flow

$$Q^g_{\mathrm{F}k\ell} = \sum_{ij} \pi^{k\ell}_{ij} L_{ij} \underbrace{\left(\theta \eta^g_{\mathrm{F}j} \frac{q_{\mathrm{F}j}}{L_{\mathrm{F}j}} + \frac{\theta - \varepsilon_L}{L} \sum_h \beta \eta^g_{\mathrm{F}h} q_{\mathrm{F}h}\right)}_{\equiv \omega^g_{\mathrm{F}ij}}. \tag{B.2}$$

We can interpret these employment flows as the commuters using edge $k\ell$, weighted by $\omega^g_{\mathrm{F}ij}$, which represents the value derived by the government g from changes to commercial land value caused by a reduction in commuting costs for link $k\ell$, $d_{k\ell}$.

Congestion Effect

Following a similar approach to the congestion effect, we can express the congestion force as a weighted traffic flow:

$$Q^g_{\mathrm{Q}k\ell} = \sum_{ij} \pi^{k\ell}_{ij} L_{ij} \underbrace{\left(\theta \sum_{k\ell} \phi^g_{k\ell} \pi^{k\ell}_{ij} + \frac{\theta - \varepsilon_L}{L} \sum_{mn} \phi^g_{mn} Q_{mn}\right)}_{\equiv \omega^g_{\mathrm{Q}ij}} \tag{B.3}$$

We can interpret these congestion flows as the commuters using edge $k\ell$, weighted by $\omega^g_{\mathrm{Q}ij}$, which represents the value (or cost) derived by the government g from changes to traffic flows caused by a reduction in commuting costs for link $k\ell$, $d_{k\ell}$.

B.2 Linear City

Table B.1: Example parameter values

Parameter	Description	Value
$(1-\alpha)$	Land share of utility	0.25
$(1-\beta)$	Land share of production	0.20
$\bar{U}_o$	Reservation utility	1
δ	Productivity dispersion	0.15
σ	Congestion elasticity	0.15
ξ	Infrastructure elasticity	0.10
θ	Commuting elasticity	7
μ	Migration elasticity	5