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Benjamin Carantino

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THÈSE

soutenue le 7 octobre 2021 à l'École d'Économie de Paris

pour l'obtention du grade de

DOCTEUR ÈS SCIENCES ÉCONOMIQUES

par Benjamin CARANTINO

Équité et Transports

Trois essais d'économie spatiale

sous la direction de Laurent GOBILLON et Miren LAFOURCADE

<i>Jury</i>	Pierre-Philippe COMBES	Dir. de recherche CNRS, professeur à Sciences Po
	Matthieu CROZET	Professeur à l'Université Paris-Saclay, CEPII
	Camille HÉMET	Professeur à l'École Normale Supérieure
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THESIS

defended on the 7th of October, 2021, in the

PARIS SCHOOL OF ECONOMICS

for the obtention of the title of

DOCTOR OF PHILOSOPHY

by Benjamin CARANTINO

Equity and Transportation
Three essays in spatial economics

under the supervision of Professor Laurent GOBILLON and Professor Miren LAFOURCADE

<i>Jury</i>	Professor Pierre-Philippe COMBES	CNRS & Sciences Po
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"Nous croyons que les tâtonnants essais d'application d'une pensée rigoureuse à la connaissance de l'homme, les excès mêmes et les erreurs manifestes qu'ils entraînent, méritent considération. Il est vrai la sociologie ne saurait être révolutionnée par la seule fantaisie, fût-elle géniale, d'un mathématicien. Faut-il admettre qu'elle le sera, ou qu'elle aurait pu l'être, par l'habileté conceptuelle d'un dialecticien ? On expulse les Géomètres au nom de la réalité sociale concrète et du caractère global du fait social. C'est bien. Mais la méthode de Galilée répugnait pour les mêmes raisons aux Théologiens et aux Alchimistes. le succès, même partiel, des Galilée, des Lavoisiers, montre que le fait physique " concret" des Paracelses, des Van Helmonts, n'avait rien à perdre par l'introduction de l'ordre et de la mesure. On conclura sans doute de cette comparaison que nous réduisons par avance les sciences du phénomène humain à un physicalisme vulgaire. Point du tout. Nous sommes convaincus de la spécificité des structures sociales et des organisations psychiques. Nous constatons seulement qu'une mathématique "bien tempérée" , adaptée à son objet, est l'instrument indispensable pour l'élaboration d'une science vraiment empirique et vraiment explicative."

Gilles Gaston Granger – *La mathématique sociale du Marquis de Condorcet*

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Abstract

Cities are highly unequal structures, being the site of a spatial competition for access to the benefits of density. Transportation infrastructures, and especially public transit, plays a major role in organizing spatial inequalities, since they provide distant land with access to urban agglomeration economies. Without transportation, one could not enjoy a full citizenship. It is therefore no surprise then that equity claims could take a spatial form and involve transportation. Two types of equity issues may be at stake in the spatial economy. Vertical equity, that regards equal treatment between households with different resources, is particularly salient within cities, since the housing market sorts incomes by distance to amenities and agglomeration economies. Horizontal equity, that regards equal treatment between households with similar resources and income, is of particular concern between cities, since the availability of transportation infrastructure, and especially public transport, conditions access to urban benefits for many urbanites. In a context of reinforced urban segregation, acceleration of the concentration of activity and jobs in large metropolis, and rise of transportation costs that could result of the generalization of the carbon tax, such vertical and horizontal equity claims may become more salient in the next decades, as shown by the fact that three of the largest social unrests of the last two decades in France – the 2005 suburban riots, the 2013 *Bonnets Rouges* and the 2019 *Gilets Jaunes* movements– were directly associated with claims for spatial justice. This thesis examines three aspects of spatial equity, through the particular scope of transportation infrastructure. The first two chapters assess whether public transit investment should be directed to mitigate vertical equity claims within cities or horizontal equity claims between cities. The third chapter applies the reflections of the first two chapters to the specific case of the fuel carbon tax acceptability and wonders whether urban policies that reduce spatial inequalities in fuel consumption.

In the first chapter, written with Antton Haramboure, we wonder whether by integrating social equity concerns and deviating from a traditionally more utilitarian design of transport networks, cities could answer vertical equity claims. We rely on an extensive multi-city tramway building program in the last two decades in France and a novel and comprehensive geocoded database of all unemployed from 2005 to 2018 to assess the effects of opening of a new transport option on individual unemployment trajectories and local social mixity in deprived areas. We find no evidence of any improvement in individual unemployment trajectories for the residents of the treated neighborhoods around the opening of the tramway line. In the medium term we find effects on the housing market consistent with capitalization of accessibility gains as well as a change in the income composition of renters, although gentrification is limited by the large share of social housings. The results indicate that, due to redlining and population mobility, connection of a deprived neighborhood to a public transit network does not improve much the situation of initial inhabitants. However, there

may be some room for a social housing policy coupled with public transport developments.

In the second chapter, written with Nicolas Jannin, we wonder whether a deviation from utilitarian perspective in the distribution of public good –typically, a public transit network– between cities towards horizontal equity criteria could be justified. To that end, we examine the interplay between scale economies in the consumption of public good and heterogeneous location preferences. Scale economies indeed constitute a factor of inequality between large cities and less populated jurisdictions, that one should compensate if mobility between cities is low. Using data on French cities, we present new stylized facts suggesting scale economies in the consumption of local public goods. We thus build a spatial equilibrium model with mobile workers and endogenous public goods and characterize the transfers from the central state implementing efficient population distribution. We show that heterogeneity in location preferences increases the equity cost of migration relatively to its efficiency benefits such that Pareto-improving reforms may not always exist. Investigating the Pareto efficiency of current French transfers, we empirically show that ignoring location preferences leads to recommending reforms that mistakenly redistribute towards the densest and richest places.

In the third chapter, written with Miren Lafourcade and Camille de Thé, we wonder whether the acceptability of the carbon tax could be increased by urban policies, notably the development of public transit. To do so, we investigate the impact of urban form on car usage and driving emissions within French metropolitan areas using a novel set of urban form metrics relying on the “3 D’s” typology proposed by Cervero and Kockelman (1997) : Density, Design and Diversity. In particular, we introduce a novel indicator of the Design, the fractal dimension of the built environment that captures differences in urban morphology likely to nurture car dependence in French cities. We find a strong impact of each of our 3D elements of urban form. The use of an Heckman procedure allows us to account for households’ preferences for driving, while historical and geological instruments allow to account for endogeneity issues. Our results allow us to reconstruct the relationship between city size and car emissions per household in France and find that it exhibits an unprecedented non linearity in the form of a bell-shaped curve, driven by Design and Diversity. In conclusion, it appears that the carbon tax may raise both horizontal equity issues – notably in medium size cities at the top of the U-shaped curve – and vertical equity issues –in poor neighborhoods stranded in car dependency that could threaten carbon tax acceptability. Our results suggest that there exists margins for urban policies to tackle such acceptability issues.

Résumé

Résultat d'une compétition pour l'accès aux bénéfices de la densité, l'économie spatiale comporte de fortes inégalités. Les infrastructures de transport, et notamment les transports en commun, jouent un rôle majeur dans la structuration de ces inégalités, puisqu'elles permettent d'accéder depuis des lieux éloignés aux espaces centraux bénéficiaires d'économies d'agglomération. Il n'est dès lors pas étonnant que les questions d'équité puissent prendre une forme spatiale et mettre en jeu les infrastructures de transport. Il convient de distinguer deux types d'équité. L'équité verticale qui correspond à l'égalité de traitement entre ménages disposant de ressources différentes et l'équité horizontale, qui correspond à l'égalité de traitement entre ménages disposant des mêmes ressources. La première est surtout en jeu à l'intérieur des villes, puisque le marché du logement y agit comme un mécanisme de tri spatial qui organise la position des ménages par rapport aux équipements et agglomérations en fonction de leurs revenus. La seconde est surtout en jeu entre les villes, puisqu'elles peuvent être différemment dotées en biens publics et en particulier en infrastructures de transport selon leur taille, à population similaire.

Dans un contexte d'accélération de la concentration des activités et des emplois dans les grandes métropoles, de renforcement de la ségrégation urbaine, et d'une possible augmentation des coûts de transport liée à l'augmentation de la fiscalité du carbone, ces enjeux d'équité pourraient devenir plus saillants dans les prochaines décennies. Il est ainsi à signaler que trois des plus importants mouvements sociaux des deux dernières décennies en France – les émeutes des banlieues de 2005, les Bonnets Rouges de 2013 et les Gilets Jaunes de 2019 – ont été fondés sur des revendications d'équité spatiale.

Cette thèse examine trois aspects de l'équité spatiale, à travers le prisme des infrastructures de transport. Les deux premiers chapitres évaluent si l'investissement dans les infrastructures de transport doit viser à satisfaire les enjeux d'équité verticale au sein des villes ou d'équité horizontale entre villes. Le troisième chapitre applique les réflexions des deux premiers autour de la question de l'acceptabilité de la taxe carbone, et s'interroge sur la possibilité de mobiliser des politiques urbaines, en particulier de transport et d'aménagement urbain, pour répondre aux problèmes d'équité spatiale liés à l'introduction d'une telle taxe.

Le premier chapitre, co-écrit avec Antton Haramboure, étudie s'il est possible de réduire les inégalités urbaines, en s'écartant d'une conception traditionnellement utilitariste des réseaux de transport pour leur faire prendre en compte les enjeux d'équité verticale. Il évalue empiriquement cette question en s'appuyant sur le vaste programme de construction de tramways exécuté dans une vingtaine de villes françaises au cours des deux dernières décennies, ainsi que sur une nouvelle base de données géocodées décrivant les trajectoires de l'ensemble des chômeurs en France entre 2005 et 2018, afin d'évaluer les effets de l'ouverture d'une nouvelle infrastructure de transport sur l'accès à l'emploi et la mixité sociale. Il ne met

en évidence aucune amélioration des trajectoires des chômeurs habitant dans des quartiers concernés qui soit liée à l'arrivée du tramway. A moyen terme, il constate que l'ajustement du marché du logement conduit à une capitalisation des gains d'accessibilité, à un départ des populations les moins aisées ainsi qu'à l'arrivée de nouveaux habitants aux revenus supérieurs. Cette gentrification est toutefois limitée par la part importante de logements sociaux. Ces résultats suggèrent que la discrimination qui touche les quartiers les plus défavorisés et la mobilité de la population limitent très fortement les effets attendus pour la population initiale du raccordement d'un quartier défavorisé à un réseau de transport public. Toutefois, une politique de logement social couplée à des développements des transports publics pourrait avoir des effets positifs sur le long terme.

Le deuxième chapitre, co-écrit avec Nicolas Jannin, étudie l'efficacité d'une approche inspirée par l'équité horizontale pour répartir les subsides de l'État central aux collectivités territoriales. Si une approche utilitariste voudrait qu'on subventionne la production de bien public là où il bénéficie du maximum d'économies d'échelle, c'est à dire dans les grandes villes, nous montrons qu'en présence de préférences intrinsèques des habitants pour certains lieux, l'équité horizontale pourrait s'avérer plus efficace. En effet, les économies d'échelle dans la consommation d'un bien public - typiquement, un réseau de transport - constituent une source d'inégalité entre les habitants des grandes villes et ceux des cités moins peuplées. Si la mobilité des habitants est faible, ces économies d'échelle constituent une justification pour des transferts plus importants aux villes moins peuplées. En utilisant des données sur les villes françaises, ce chapitre présente de nouveaux faits stylisés confirmant l'existence d'économies d'échelle dans la consommation locale de biens publics. Il construit ensuite un modèle d'équilibre spatial avec des travailleurs mobiles et des biens publics endogènes, puis caractérise les transferts de l'État qui permettent une distribution efficiente de la population. Nous montrons que l'hétérogénéité des préférences de localisation augmente le coût –en termes d'équité– des transferts visant la migration de la population vers les grandes villes par rapport à ses avantages en termes d'efficacité. En étudiant empiriquement l'efficacité des transferts en France, nous estimons qu'ignorer les préférences de localisation conduirait à recommander une redistribution excessive vers les zones les plus denses et les plus riches.

Le troisième chapitre, co-écrit avec Miren Lafourcade et Camille de Thé, étudie la possibilité de réduire les inégalités associées à l'augmentation de la taxe carbone à l'aide de politiques urbaines, comme le développement des transports publics. Pour ce faire, il analyse l'impact de la forme urbaine sur l'utilisation de la voiture et les émissions de gaz à effet de serre dans les zones métropolitaines françaises en utilisant un nouvel ensemble de mesures de la forme urbaine reposant sur la typologie des " trois D's " proposée par Cervero et Kockelman (1997) : Densité, Design et Diversité. En particulier, ce chapitre introduit un nouvel indicateur du Design: la dimension fractale du bâti urbain, qui capture des différences de morphologies urbaines susceptibles d'engendrer une dépendance à l'usage de véhicules in-

dividuels. Les résultats montrent un impact significatif des trois D sur la consommation de carburant, et sont robustes à la fois au traitement par une procédure de Heckman pour tenir compte d'éventuelles préférences inobservées, ainsi qu'à une instrumentation à l'aide de variables historiques et géologiques pour tenir compte des problèmes d'endogénéité. Finalement, la reconstruction de la consommation de carburant d'un ménage moyen dans différentes villes nous permet de mettre en évidence une non-linéarité inédite reliant la taille des villes et les émissions routières de CO₂ par tête sous la forme d'une courbe "en cloche".

En conclusion, si cette thèse confirme le risque que l'introduction d'une taxe carbone soulève des revendications d'équité spatiale, horizontales (notamment dans les villes de taille moyenne, au sommet de la courbe en cloche), et verticales (dans les quartiers pauvres dépendants de la voiture), les résultats du troisième chapitre suggèrent que la promotion de formes urbaines plus durables, réduisant l'étalement urbain, conçues autour des transports publics et des mobilités douces et moins spécialisées, pourrait contribuer à résoudre ces problèmes d'équité et d'acceptabilité.

Introduction

Among important waves of social unrest of the last two decades in France, three of the most striking ones had their roots in a claim for spatial equity: the 2005 suburban riots, which occurred in reaction to differences between affluent city centers and their deprived, discriminated suburbs, the 2013 *Bonnets Rouges* –Red Caps– who addressed the discrepancies between productive metropolis and plummeting small cities facing unemployment and a reduction of public services, and the 2019 *Gilets Jaunes* –Yellow Vests – who protested against the inequalities generated by a rise in carbon taxes between metropolitan centers that can adapt thanks to public transit and outer peripheries stranded in car-dependency through their urban form. It is actually no surprise that spatial justice and transportation are brought under the limelights : Spatial economics are a whole story of inequalities, and transportation largely structures it.

The existence of cities is indeed deeply connected to the presence of increasing returns to scale with density, due notably to agglomeration economies in production, driven by sharing resources, better matching of people, and accelerated learning from increased interactions (Duranton and Puga, 2004), and also due to the non-rival nature of public goods. The structure that results from spatial competition for access to these scale economies presents peaks and valleys of population and wealth – namely, spatial inequalities – that correspond to the spatial organisation of pre-existing inequalities. Though the structure of these inequalities is not always simple – cities are self-organized structures (Krugman, 1998), susceptible of multiple equilibria (Fujita and Ogawa, 1982) that may differ largely from the monocentric pattern fully structured by transportation costs exemplified by Alonso (1964), Mills (1967) and Muth (1969) – they are likely that to be organized in relation to transportation costs to the densest areas that benefit from returns to scale. By complement to this spatial structure of existing inequalities, the unequal access to the city center or subcenters through transportation could in turn generate inequalities of its own in access to urban services and markets. To put it in a nutshell, transportation infrastructure is not only the structure of initial inequalities, but could generate supplementary inequalities.

However, if the existence of spatial inequalities is established, the signification of "spatial equity" remains unclear. In the end, equity matters between people, not places. Population

mobility will thus obviously be key to determine which equity claims could actually be tackled through spatial policies. However, since the spatial economy is far from perfect mobility – it is largely frictional i.e. search for a dwelling come at a cost; built of location preferences i.e. households may have an idiosyncratic preference for some specific locations; and may even be plagued with housing constraints (Hsieh and Moretti, 2019) – one cannot reject *a priori* the validity of spatial equity claims. However, it is clear that due to the large agglomeration economies that gave birth to cities, any attempt to reach pure equality between territories will be vain. Spatial inequalities can only be reduced up to a point.

We can actually separate spatial equity claims into two aspects of equity, that translate into two scales of the spatial economy.

Within cities, since inhabitants and economic activities are competing for land with different characteristics and resources, the spatial equilibrium incorporates and reflects these differences. Using the metaphor of chromatography, a method used by chemists where differential migration of molecules over a solvent in a paper sheet reveals their nature by their differences in affinity for the non-moving paper and the moving solvent, one could say that competition for scarce urban land that benefits from agglomeration economies reveals characteristics of populations and activities, by the differences between their preference for dwelling surface or transportation time, and by their resources to get the better arbitrage between the two. Similarly to chromatography that makes different chemical substances instantly visible on a paper sheet, labor market clearing makes inequalities and preferences instantly visible on the map. In that respect, the housing market acts as an efficient sorting mechanism along the distance to city-centers, as exposed notably by Behrens and Robert-Nicoud (2014). Notably, in France, as exposed by Brueckner et al. (1999), the center of cities, that benefits from historical amenities, concentrates the wealthiest population, while the peripheries host the urban poor. Transportation plays a key role in the possibility of such sorting. Historically, it is actually the invention of public transport that gave birth to the modern structure of cities (Heblich et al., 2020a) that separates workplace from residence and thus rich neighborhoods from poor ones. The inequities embedded within the spatial structure generate spatial iniquities that can be defined as *vertical equity* issues, since it regards equal treatment between households with different resources.

By contrast, the housing market being less scarce at the national level, sorting with income is much less important between cities. However, transportation stock may be a factor of inequalities. Indeed, if space reveals inequalities, it also generates them, notably through spatial frictions in the access to the job market (Kain, 1968) or in access to education (see Maurin (2004) for a survey). Thus, access to transportation infrastructure, and especially the existence of a public transportation network can be large drivers of iniquity between cities, whatever the income or resources of inhabitants may be. More generally, transportation costs to access public goods and services and productivity gains associated with efficient urban

transport (see Lafourcade (1998) for a survey) can strongly differ between cities. Such iniquities can be defined as *horizontal equity* issues, since they regard equal treatment between households with similar resources in different cities.

Complementary to those static views of spatial iniquities, dynamical iniquities, both vertical and horizontal, may temporarily emerge due to the discrepancy between the inertia of the fabric of spatial life –buildings, roads, etc.– and a brutal change in the structure of the associated costs. Indeed, spatial equilibrium dictates that a location’s characteristics are finely tuned, in the long term, with the characteristics of its population. However, since buildings, infrastructure and local public goods are costly to build and modify, if a rapid change in economic dynamics or regulatory conditions were to affect housing or transportation prices, or local amenities, households could face difficulties to adapt to the new situation in the medium term. Therefore, if adjustment is guaranteed in the long term, existing spatial inequities may through this mechanism amplify disproportionately certain economic shocks.

In the wake of either the acceleration of the concentration of activity and jobs in large metropolis (Moretti, 2013; Davezies, 2012) that reduces resources to finance public goods in medium and small cities and may result in reinforced segregation within cities (Cassiers and Kesteloot, 2012; Musterd et al., 2015), or the perspective of the necessary rise in fuel prices for climate change action (IPCC, 2014) that could profoundly modify existing spatial equilibria, these three channels of spatial iniquities could constitute sources of major spatial equity claims in the next decades. The accelerated recurrence of social unrest associated with spatial equity in France provide evidence of the potential prevalence of these issues in developed countries. As signalled *supra*, the 2013 *Bonnets Rouges* blocked most of Brittany in reaction to the announcement of a tax on intercity road use for heavy duty vehicles (Spire, 2018). In 2018 and 2019, the *Gilets Jaunes* movement federated many more inhabitants from rural areas, medium cities but also peripheries of large metropolis to demonstrate each weekend in the center of each French major cities against a rise in the carbon tax of fuel and more generally of better spatial redistribution.

Urban policies are not generally destined to address equity issues. Due to population mobility, place-based policies generally appear as ill-founded (Neumark and Simpson, 2014) or tend to be ineffective (Briant et al., 2015), unless agglomeration economies or market frictions justify spatial distortions. In the case of transportation infrastructure, a long-lasting tradition, exemplified by the French school of engineer-economists such as Dupuit (1844) and Colson (1924-1928), sees infrastructure decision as the result of an utilitarian cost-benefit analysis¹. This perspective, that compares the expected utility of passengers and the cost of the infrastructure, would result, within cities, to prioritize connections from the denser population areas to larger employment centers or amenities, and between cities, to build a

¹Dupuit actually introduced the very notion of utility for the first time in his seminal 1844 article to tackle the issue of the allocation of public transport infrastructure.

public transit network only in cities whose population would be sufficient so that the aggregated utility that inhabitants would get from this transportation network would be superior to construction costs². These approaches are mostly incompatible with either vertical equity, since deprived peripheries are rarely dense population nor employment centers, or horizontal equity, since this latter may imply the presence of public transit even in small towns where fixed costs exceed aggregated utility. As emphasized by Allais (1973), in the case of perfect mobility, this utilitarian criterion is Pareto-efficient : any deviation from this principle would result, within cities, in a movement of the wealthy population to benefit from the new infrastructure and between cities, in less economies of scale in the consumption of the public good than it would have been in a larger city. However, these intuitions cannot be generalized in a more realistic framework of spatial frictions and agglomeration economies.

In the context of increasing claims for spatial equity, the question whether a deviation from utilitarianism in the distribution of public transit infrastructure, motivated by equity concerns, can be efficient constitutes an important policy issue for urban economics. This thesis examines this question on the three dimensions of spatial equity presented *supra*, both empirically and theoretically and taking the French case as an example. The first chapter builds on the important literature about the effects of a new transit option on the labor and housing market (see Redding and Turner (2015) for a survey) to examine the question in the wake of vertical equity. The second chapter crosses the large public economics literature on fiscal federalism (see Glaeser (2013) for a review) and spatial equilibrium models *à la* Rosen (1974) and Roback (1982) to examine the question in the perspective of horizontal equity. The third chapter builds on the large urban economics literature that examines the relation between urban form and fuel consumption³ to empirically assess the equity issues that may arise from a rise in the carbon fuel tax. In the light of the two previous chapters, it also examines potential policies to mitigate them.

The French situation appears as an interesting case study to assess this issue, for two main reasons. First, because of the history of French decision making on transportation infrastructures. It is not by accident that France is the birthplace of economic calculation and cost-benefit analysis for infrastructure projects : as recalled by Trannoy (2013), the legitimacy of infrastructure building decisions made by the central state in a highly centralized context after the French revolution was grounded in a demonstration of the efficiency of the infrastructure choice by the means of economic calculation. Dupuit (1844) approach of surplus has indeed been used in the nineteenth and twentieth for infrastructure decision making, and expanded in the second part of the twentieth century by Allais (1973), Boi-

²Construction costs often contain a large fixed cost (purchase of the rolling stock that is not strictly proportional to the number of passengers, due to the necessity of a high frequency, construction of the infrastructure, if any, etc.), which explains the absence of public transit in small towns.

³See the surveys and meta-analyses proposed by Ewing and Cervero (2001), Handy (2005), Ewing and Cervero (2010), Ewing et al. (2015), Stevens (2017) or Ahlfeldt and Pietrostefani (2017).

teux (1956) and Lesourne (1972) into a fully fledged framework to determine public good provision and pricing. For more than 50 years, this framework was the standard tool of centralized government bodies such as the *Commissariat Général au Plan* –General Commissary for Planning–, *Délégation Générale à l'Aménagement du Territoire et à l'Attractivité Régionale* – DATAR, General Delegation for Territorial Development and Regional Attractivity– or *Direction des Routes* – the Roads Directorate of the Transport ministry – to define the distribution of public good and especially transportation infrastructure in France. However, as exposed by Quinet (1990), this central planing efficiency-based approach gradually lost its grip on effective public good distribution under the influence of both a raise in equity concerns within the French society and decentralization that transmitted more and more decisions to local elected governments – the first decentralization act, the Defferre Bill, dates from 1983, and was followed by new steps in the 90's and 2000's. Gradually, transportation infrastructure and public good planning have transitioned from using utilitarian criteria to equity-based approaches, which constitutes a natural experiment to study whether such deviations from utilitarianism were efficient. Second, because spatial equity claims has been particularly vocal in France so far: the surge of spatial equity in the French public debate makes a study of their economic grounds particularly topical. Notably, in the perspective of the ecological transition, since urban sprawl is accelerating in France at the precise time when the European Commission proposes to expand the carbon quota system to road emissions ⁴, the design of spatial policies that could mitigate the equity impact of rising carbon taxes could become of continental interest.

Data and Methods

To address these questions, one cannot limit to a theoretical approach, nor to macro-level empirical evidence. The spatial economy being a complex landscape made of heterogeneous preferences and costs, one must dive into neighborhood-household level empirics to provide an adequate description of it. Similarly, urban models should take seriously the heterogeneity of the agents. This thesis tries to follow the footsteps of recent research in spatial economics and use both comprehensive administrative data and heterogeneous agents models to address urban equity issues.

The last decades have seen a drastic rise in the use of comprehensive administrative databases in econometry, through a movement that Angrist and Pischke (2010) coined as the "credibility revolution". This revolution has been made possible by an extensive effort by economists and statistical institutes to build individual-level databases and make them available to the public without breaking statistical secrecy. French *Centre d'Accès Sécurisé aux*

⁴See the *proposal to amend Directive 2003/87/EC and Decision (EU) 2015/1814 to strengthen the Emissions Trading System and extend it in line with the Union's increased climate ambition for 2030 issue on July 2021.*

Données (CASD) operated by the national statistical institute (INSEE) has been a notable part of this movement.

This thesis connects to this agenda by taking advantage of detailed administrative datasets to assess the questions summarized *supra*. Some of these datasets are regularly available to researchers, others have been accessed through securized environments such as INSEE surveys or socioeconomic characteristics of workforce (*Déclaration Annuelle de Données Sociales*) available on the CASD, others are internal administrative databases on which this thesis constitutes the first empirical work.

Geographic data Spatial economics requires precise geographic datasets. In this thesis, we use the comprehensive geographic database built by the French National Geographic Institute (*Institut Géographique National*, IGN) : the BD-TOPO. This metric-scale database gathers the trace of road and rail networks, but also the shape of buildings and their characteristics as well as information about land use. We had access to an internal journalized version of this database, never used yet in academia, that allows us to get yearly updates of transportation infrastructure and built area on the whole French territory. When necessary, we complemented this database with detailed geographic information such as tramway stop opening date or works beginning date, using administrative data obtained from the Ministry of Transportation which allows us to model weekly changes in accessibility, and thus contribute to the literature through better temporal and spatial precision than most of the existing works.

Labor market data The use of individual-level microdata has become a norm in labor economics. Similarly to most works carried out in France on this topic, we used the comprehensive administrative datasets built by the French social administration : the annual declaration of socioeconomic characteristics of workforce (*Déclaration Annuelle de Données Sociales*) and the daily report of the unemployed workforce (*Pôle Emploi's Fichier Historique*). These datasets contain respectively the characteristics (age, diploma, type of contract, etc.) of the whole workforce, through a annual questionnaire completed by firms to describe the social security status of their employees, and the characteristics of unemployed people (age, diploma, duration of unemployment, etc.) gathered by the national employment agency, *Pôle Emploi*. To supplement these datasets that report workplace and residence at the municipality level, we had been granted access to internal address table of the unemployed, which, coupled with a geocoding algorithm, allowed us to study unemployment in cities at an unprecedented metric-level.

Addresses and geocoding Geocoding of addresses necessitates an address database. We relied on the National Address Database (Base d'Adresses Nationale) developed by French

government's open data team (Etalab) together with the French post office. The use of a fuzzy matching algorithm that matches addresses phonetically allows for a larger matching rate when geocoding administrative data which was entered by hand by the unemployed and contains many orthographic errors. To our understanding, the approach developed in the first chapter is the first use of such techniques in spatial economics.

Housing market Housing market databases in France are notably imprecise (Eymeoud, 2018) since they are based on voluntary collection of local operations by notaries, and then gathered and sold without extensive treatments by the *Chambre des Notaires*. The INSEE estimates that they collect around 60% of real housing market operations, luckily without identified biases. If comprehensive administrative datasets have been set public by the fiscal administration in 2019, as well as real estate agents web-scraped data by Eymeoud (2018), these comprehensive databases are not sufficiently extended backwards for our usage. We thus relied on the notaries databases PERVAL and BIEN.

To track population and housing stock, we used the very comprehensive fiscal database of housing characteristics (FILOCOM) made available to us by the Ministry for Housing. It is constructed by the Ministry of Finance's Directorate General for Public Finances (*Direction Générale des Finances Publiques*, DGFIP) by merging registers used for the calculation of property taxes with the national income tax register. It contains information on each residential dwelling's characteristics (surface, number of rooms, etc.), occupation status and number of inhabitants. FILOCOM is hence a precise – and the only – source for comprehensive high-frequency information on population and housing stock.

Local public finance Local tax and spending data are necessary to understand public good production throughout the territory. We had access to the financial accounts of all French municipalities and municipal federations, the *Balance Comptable des Communes*, obtained from the *Institut des Politiques Publiques* and the Ministry of Finance for every year over the period 2002–2016. It provides detailed information on municipalities' assets and liabilities, spending items, tax revenues and more importantly, subsidies and transfers received from central state.

Fuel consumption By contrast with those comprehensive administrative dataset, we measure fuel consumption using a sample survey : the 'Family Budget' household survey (*Budget des Familles*) carried out by the INSEE. This survey has been conducted every five years since 1972 and aims to assemble the expenditures and resources of a representative sample of households living in French Municipalities⁵.

⁵It is the basis on which the INSEE determines which goods will be surveyed to compute the inflation rate.

Methods In the first chapter, we rely on the recent research in labor economics to build a staggered differences in differences estimator, based on a quasi-experiment of the opening of tramway lines in deprived neighborhoods, that allows us to identify simultaneously the effect of tramway line openings at different times and places in the same sample. This approach builds on both the event-study and causal differences in differences techniques increasingly used in public economics since the mid 1990's that allow to provide graphical evidence of the effects of a treatment. This set of techniques, coined as "the graphical revolution" by Currie et al. (2020), guarantees better identification of treatment effects since it provides a direct criterion on pre-trends to check potential identification biases. It also gives a better view on the dynamics of treatment effects. The time-span of the effects of a tram line opening on the labor market being key to discuss the underlying mechanisms, this approach is particularly needed in the first chapter.

In the second chapter, we build a comprehensive spatial equilibrium model combining Rosen (1974) and Roback (1982) classical approach with novel optimal city size theoretical approaches, summarised in the vast synthesis of Fajgelbaum and Gaubert (2018). We inform and calibrate this model through the successive estimation of reduced-form relationships drawn from the model on comprehensive administrative data. We then derive empirical conclusions from this model and our administrative data, making an extensive use of the "sufficient statistics" approach developed notably by Chetty (2009) whose use in public economics has risen dramatically in the last decade. It proposes an elegant way to estimate in a non-model-dependent, robust way the welfare effects of marginal policy changes using only a reduced set of observables, high-level parameters and elasticities. It notably allows to drive empirical conclusions without having to fully specify the model. However, it has shortcomings, since the method is based on full differentiability of the model and can only account for small reforms departing from an equilibrium situation.

In the third chapter, we rely more classically on textbook linear regression methods such as instrumental variables and Heckman correction to identify a causal relation between urban form and fuel consumption. Nonetheless, a particular descriptor of urban form we use, the fractal dimension of the built-up areas, constitutes the primary use in spatial economics of a metric introduced by quantitative geographers two decades ago by Frankhauser (1998). It appears particularly useful to describe a urban morphology's impact on urban life, in a "function follows form" approach reminiscent of Jacobs (1961). The techniques used for the estimation of this particular variable are drawn from numerical physics (Liebovitch and Toth, 1989) and fractal geometry (Mandelbrot, 1967).

Outline and Summary

The first chapter, written with Antton Haramboure, takes advantage of the extensive multi-city tramway building program conducted in the last two decades in France, that resulted in the (re)construction of tramway networks in more than twenty French cities, to decide whether the integration of social equity concerns in the design of public transit networks is effective to reduce vertical inequities in French cities. To do so, it notably investigates potential reduction of spatial mismatch in the labor market and segregation in the housing market due to the new infrastructure. It contributes to the large spatial mismatch literature which questions the role of workers' physical disconnection from job opportunities to explain spatial inequalities in unemployment (Kain, 1968). While early studies found a correlation between job opportunities accessibility and unemployment in American (Stoll and Raphael, 2000; Rogers, 1997) and European cities (Dujardin et al., 2004; Matas et al., 2010; Gobillon et al., 2011), the rare natural experiments on population displacement held conflicting results (Kling et al., 2007; Åslund et al., 2006), and studies following a shock in public transit showed no effect either (Holzer et al., 2003; Åslund et al., 2017). The first chapter contributes to this debate by providing an extensive study over more than 80 neighborhoods and more than 20 tramway line openings and confirms the absence of any short term effect. It actually provides a detailed micro-level empirical evidence in support of recent macro-level theoretical views of Manning and Petrongolo (2017) who suggest using a structural model that spatial mismatch does actually explain only a small share of actual unemployment. This chapter also contributes to the conflicting literature on population sorting and home price capitalization in response to transportation infrastructure building, summarized notably by the review of Debrezion et al. (2007). We find evidence of gentrification in deprived neighborhoods, when the share of social housing is low, but no composition change when it is high. This result obtained on more than 20 cities contributes to reconcile a divided literature, in which some studies (Grube-Cavers and Patterson, 2015) find a positive effect of transit exposure on gentrification while others (Dong, 2017) found no gentrification or even movement of older and less-educated population into the newly connected neighborhood. The result of this chapter actually confirms the theoretical view of Tsivanidis (2018) who proposed recently a general equilibrium structural model that explains the contrasted responses of affluent and deprived populations to a new infrastructure and shows that population change only in connected areas that could be beneficial to high-skilled workers. In the perspective presented above, our results indicate that, due to redlining and population mobility, connection of a deprived neighborhood to a public transit network motivated by equity concerns is largely inefficient. However, it suggests that there may be room for a reduction of vertical urban inequities through a social housing policy coupled with public transport developments.

The second chapter, written with Nicolas Jannin, connects spatial economics and public finance by studying the normative implications of public good agglomeration externalities and heterogeneous location preferences. It wonders whether the introduction of these two features in an optimal city size framework *à la* Fajgelbaum and Gaubert (2018) could not lead to optimal spatial policies redistributing public good towards small cities, in an approach consistent with horizontal equity. It notably contributes to the optimal city size literature initiated by Flatters et al. (1974) that generally concludes to optimal spatial policies that concentrate population in large cities, but recognized the difficulty to implement optimal spatial policies when heterogeneous preferences of households are not observed (see Wildasin 1980; Starrett 1980; Boadway and Flatters 1982; Boadway 1982; Watson 1986; Zodrow and Mieszkowski 1986). If recent theoretical frameworks take into account such preferences (Albouy et al., 2018), their results (Fajgelbaum and Gaubert, 2018) crucially hinge on the government's ability to offer city-type specific transfers which evacuates the equity-efficiency trade-off. This chapter proposes a more realistic approach, where government can only observe the chosen location as a spatial evidence of type of the households, and shall decide spatial policies based on the existing spatial equilibrium, and not an ex-ante *tabula rasa*. In this framework, because the government is unable to observe location preferences, both efficient transfers that correct for public good externalities and transfers that achieve redistributive objectives are necessarily place-based and distort migration decisions. In this context, we show that heterogeneity in location preferences increases the equity cost of migration — transfers — relatively to its efficiency benefits — agglomeration gains — so that Pareto-improving reforms only exist when preference dispersion is small enough. We then give a general sufficient statistics characterization of the transfers implementing efficient population distribution using a reduced set of variables and parameters. We derive a computable efficiency test for observed allocations and apply it to French data: ignoring location preferences leads to recommending reforms that mistakenly redistribute towards the densest and richest places. In the perspective presented above, this strongly speaks in favour of better accounting for the normative implications of geographic preferences, i.e. for spatial policies between cities inspired by horizontal equity criteria.

The third chapter, written with Miren Lafourcade and Camille de Thé, connects the two previous questions on a topical issue : the acceptability of the carbon tax in terms of both vertical iniquities within cities and horizontal iniquities between cities. As the *Gilets Jaunes* social unrest underlined, fuel consumption is highly determined by urban form. This chapter takes advantage from a survey of fuel consumption over more than 15,000 households in different cities and neighborhoods to assess which characteristics determine fuel consumption. From this point of view, it contributes to a large literature following Newman and Ken-

worthy (1989) that characterise empirically fuel consumption with respect to city size and characteristics (See the surveys and meta-analyses proposed by Ewing and Cervero (2001), Handy (2005), Ewing and Cervero (2010), Ewing et al. (2015), Stevens (2017) or Ahlfeldt and Pietrostefani (2017).). It mixes this city-level literature with the neighborhood level approach initiated by Cervero and Kockelman (1997), that focuses on local determinants of car use and underlines notably that land-use Diversity and pedestrian-oriented Designs encourage local neighborhood non-auto travels, while the density of transport stops encourages to use public transit for city-wide travels Bento et al. (2005). This chapter contributes to both these streams of literature by providing a cautious estimation of the effect of the “3 D’s” typology of urban form proposed by Cervero and Kockelman (1997) : Density, Design and Diversity. The use of an Heckman procedure allow to account for households’ preferences for driving, while historical and geological instruments allows to correct endogeneity issues. Moreover, we introduce a novel indicator of the Design, the fractal dimension of the built environment that captures differences in urban morphology likely to nurture car dependence in French cities. We find a strong impact of each of our 3D elements of urban form that indicates that strong inequalities in fuel consumption exist within city between neighborhoods, depending on local urban morphology and not only global urban size. Such inequalities could generate vertical inequities in the case of a fuel price increase due to a carbon tax. This local result expands at the city-level since our results allow us to reconstruct the relationship between city size and car emissions per household in France. We find that this relationship exhibits an unprecedented non-linearity, in a bell-shaped form, driven by Design and Diversity. This bell-shaped curve indicates that horizontal inequities could also happen in the event of a carbon tax on fuel. in such case, medium cities would remain stranded in car dependency by a bad design –too specialized households, too large distances to city center – and be unable to benefit from the adaptation margins present in large cities, notably public transit. Projection on recent census data suggest that current population growth in France being concentrated to medium cities, the french mean-household fuel consumption due to driving rose in the last decade, which increases the potential equity issues. However, the contribution of each of the 3D’s to fuel consumption reduction in households suggests spatial policies to reduce this potential issue at a controlled cost : notably, the Design of cities could be largely improved with more public transit and better urban planning to make new neighborhoods more "fractal" and incite to more often local trips by foot or bike.

Chapter 1

A Streetcar Named Opportunity: Can Rail Foster Social Integration ?

1.1 Introduction

Investment in urban public transport¹, which amounts to 16% of annual public investment in the OECD (CEMT, 2019) and more specifically to 20% in France over the last 20 years, ranks among the largest investments made by local authorities. The resulting public transport infrastructure deeply shapes the urban economy : first, it allows for the separation of workplace and residence² and thus plays a key role in the functioning of urban labor markets; secondly, it connects high density centers to the less-dense peripheries and are therefore instrumental to creating access to urban services and amenities for suburbanites, in particular for the most deprived ones³. Since it conditions access to both workplaces and urban services, public transport availability constitutes a key factor of social integration. In a context of urban segregation, policy makers and urban planers are usually asked to take into account social justice concerns when designing and operating urban public transport networks. However, these investments are usually subject to explicit utilitarian planning through cost-benefit framework dating back to Dupuit (1844) and Hotelling (1938) that ignored social jus-

¹This chapter is based on a joint work with Antton Haramboure.

²See Hebllich et al. (2020b) for a historical study of the emergence of this divide, that defines the modern metropolis.

³See Ahlfeldt et al. (2015a) for an explicit modelling of the interaction between endogenous density-driven amenities and public transportation infrastructure. Glaeser et al. (2008) shows that this type of public transport is especially valued by the urban poor.

tice criteria⁴. By integrating social equity concerns and deviating from a traditionally more utilitarian design of transport networks, could cities reduce spatial inequalities ?

This chapter contributes to an empirical assessment of this question by investigating the changes in labor market integration, housing prices and population composition in deprived neighborhoods in response to the construction of a public transport network explicitly meant to connect the urban poor to the affluent city center. The French "*tramway revival*" over the last 20 years indeed offers a unique opportunity to empirically test the relevance of integrating social equity concerns when designing a transportation network. Between 1998 and 2018, 25 French cities have built or extended their networks to the point where 27 of the 30 biggest cities in France are now equipped. One of the main stated aims of this policy was to fight the large, long-lasting urban inequalities that characterize French cities.⁵

Indeed, when spatial segregation sorts deprived -or unemployed- urbanites into isolated neighborhoods, a positive shock in accessibility to urban opportunities in those neighborhoods supposedly fosters social integration, notably through better matching on the labour market or improved social diversity. However, the effect on the labor market is not straightforward. If better access to new job opportunities may result in more effective job search, effective employment will also depend on skill-matching, that may have been affected by previous spatial isolation. Moreover, better connections to the city center may even make local jobs more accessible for other deprived urbanites, reducing the rare local opportunities. Similarly, as newly connected locations become more attractive, housing and labor markets adjustments affect this direct positive effect in an ambiguous way. Housing prices capitalization and population change in response to such an accessibility shock may either result in the displacement of the most deprived out of the newly connected neighborhoods, which would deprive them of accessibility gains, or in an improved social diversity that will eventually be beneficiary to employment and social integration in the long term through positive peer-effects.

We use the phased construction of French tramways to identify effects of transportation on the fate of the most deprived urban areas and their residents. To empirically assess the social effects of tramway networks, we combine several rich administrative datasets in a unique way that crucially allows to locate each individual's residence to precisely measure the impact of a new transport infrastructure. First, we recovered a unique and comprehensive dataset of the unemployed registering in their local job agency in 20 French cities from 2005 to 2019. This dataset includes addresses which we geocoded at a metric scale. Such infra urban precision has been missing so far in the literature to properly measure the impact of urban transportation on individual outcomes. Second, we further complement our

⁴In France, for instance, the law stipulates that every public infrastructure must be evaluated ex-ante through economic modelling. The project cannot be authorized if social profitability, computed through a utilitarian framework, is not above a certain threshold. See Quinet (2013) and Boiteux (1994) for details.

⁵See ? for a more precise description of French spatial segregation.

analysis with transaction data on housing price and income composition at the block level.

We do not find any evidence of a change in individual unemployment trajectories around the arrival of tramway. Our estimation strategy, which relies on quarter to quarter change in unemployment outcomes around the arrival of the tramway, shows that treated and never treated areas were similar before and ultimately after the arrival of tramway in the most deprived neighborhoods. Examining several relevant city and individual dimensions of heterogeneity confirms such results on every sub population. Importantly, such null effect is precisely estimated, leaving little room for economically relevant undetected effects. In our most precise estimates, the effect of tramway on the probability to have found a job after 6 months of unemployment is an insignificant 0.5 percentage point while the minimum detectable effect would be 0.8 percentage point. Crucially, while having no effect in the short term on unemployment outcomes we show that in the medium term tramway does have a strong effect on housing prices hinting at a substantial gain in accessibility. Interestingly this rise in housing prices induces the displacement of low-income renters in the private sector but does not affect the large part of the population living in social housing. Taken together, these results show that a large part of the population of treated neighborhoods have benefited from a gain in accessibility while gentrification has been limited by the important and growing numbers of social housing structures.

Main contributions

This chapter is linked to the spatial mismatch literature that underlines the role of the physical disconnection of workers from job opportunities to explain spatial inequalities in unemployment outcomes (Kain, 1968). Such a mismatch is notably reinforced by urban segregation for ethnic minorities and deprived households. Using observational data, several early studies find a correlation between job opportunities accessibility and unemployment in American (Stoll and Raphael, 2000; Rogers, 1997) and European cities (Dujardin et al., 2004; Matas et al., 2010; Gobillon et al., 2011). However, the rare natural experiments analyzing an exogenous change in household location hold opposite results on the existence of a causal link (Kling et al., 2007; Åslund et al., 2006). Our study builds upon this literature by focusing on deprived neighborhoods inhabited by populations of immigrant descent for whom spatial mismatch should be particularly acute. The results of this literature also guide our heterogeneity analysis of population for whom accessibility matters the most (Women, Non French Resident etc...). This chapter contributes to this literature by studying the effects of public transportation improvement, which is widely perceived as a potential solution to spatial mismatch. Indeed, theoretical contributions have proposed that shorter or cheaper transportation could positively affect job prospects by increasing the radius of search, reducing the net commuting cost wage (Coulson et al., 2001; Brueckner and Zenou, 2003), and

increasing the productivity of the worker (Zenou, 2002). However despite these theoretical mechanisms, few studies have brought causal evidence for such a link (Bastiaanssen et al., 2020). Two RCT show that reducing the cost of public transportation for cash-constrained individuals improve their job prospects in the short term in Washington and Addis Ababa (Phillips, 2014; Franklin, 2018). Closer to our work, three papers have aimed at studying the effect of the construction of a new infrastructure. In the American context Holzer et al. (2003) study the expansion of a heavy rail system linking Oakland to its southern suburbs and show that firm located near a newly built station tended to hire more Hispanic workers but not Black workers. Using French census data Sari (2015) study the effect of the opening of a tramway line in Bordeaux and shows that linked areas have seen a reduction in unemployment rate. However the nature of his data does not allow him to distinguish between composition effect and change in individual job accessibility. Closer to our work, using panel data and an Intention To Treat design Åslund et al. (2017) do not find any effect of a new commuter train in Sweden on the population present before the opening. We believe our study reinforces this result as we focus on larger infrastructure projects and vulnerable populations which are at the center of the Spatial Mismatch Literature. Our study also confirms a null effect in a multi-city design, thus avoiding the city-specific results that hinder the rest of the literature.

this chapter also participates in the literature studying population sorting and home price capitalization in response to transportation infrastructure. The effects of a new public transit option on population sorting are not straightforward. While many studies from Gibbons and Machin (2005) on late 1990s' London to Ahlfeldt and Wendland (2009) on 1890–1936s' Berlin through Fesselmeier and Liu (2018) in Singapore showed that households have persistently valued accessibility gains through rail⁶, which should result in attracting wealthier households in treated neighborhoods, Glaeser et al. (2008) argued that public transportation infrastructures could act as a poverty magnet, attracting the urban poor that place a far greater value in rail access than wealthier populations, due to their lower car ownership rates. However, if the effects of public transit on housing prices have been extensively studied (see Debrezion et al. (2007) for a review), empirical studies that examine neighborhood and social effects of public transit remain scarce and inconclusive⁷. In a study over American cities that built public rail transportation infrastructure, Kahn (2007) found contrasted effects of a new transit option on home prices and proportion of college graduates : six of the fourteen cities exhibit a positive and statistically significant effect, while two exhibit a negative one ; moreover, in most cities, the positive effect appears to be larger in neighborhoods whose prices were below the median before treatment. Such a phenomenon, usually

⁶Billings (2011) and Bardaka et al. (2018) study light-rail transit in the cities of Charlotte and Denver in the United States, and provides evidence of similar effects for tramway than from other commuter railways.

⁷See Padeiro et al. (2019) for a literature review

driven by a relative affluence of in-movers, is known as gentrification (Freeman, 2005). Using income, occupation, degree, ownership and rent to define gentrification, Grube-Cavers and Patterson (2015) found a positive effect of transit exposure on gentrification in two of three Canadian cities having recently invested in a new transportation infrastructure⁸. By contrast, Dong (2017) found no evidence of gentrification in Portland in response to the opening of a new public transit network, and even showed that public transport attracted older and less-educated population. More recently, Tsivanidis (2018) proposed a general equilibrium model that explains the contrasted responses of affluent and deprived populations to a new infrastructure depending on road congestion and jobs geography. He argues that although deprived households are dependent on public transport, high-skilled workers -who exhibit a high value of time- may put a higher value on public transport in case of high congestion. On the Bogota TransMilenio BRT case, he provides evidence of population change in connected areas beneficiary to high-skilled workers, consistent with this mechanism. The contribution of this chapter to this literature is thus two-fold : (i) it constitutes the first attempt to explicitly describe gentrification in the most deprived neighborhoods after the introduction of a new transit option, which offers an opportunity to further examine the preference of the urban poor for public transit signalled by Glaeser et al. (2008) (ii) it expands the growing but so far limiter corpus of European studies. Only two papers among the 73 reviewed by Debrezion et al. (2007) cover the European case, while only five out of 35 studies gathered by Padeiro et al. (2019) are not US-based. European cities nonetheless differ largely from their American counterparts, especially when it comes to public transportation, which is much more common and developed there. In particular, the French case is of interest since 23 tramway networks built in the last 20 years are French among the 138 built worldwide.

More generally, as a whole, this chapter exploits the specific focus on French public transport on deprived neighborhoods to assess the relevance of such a deviation from the utilitarian planning framework. It thus contributes to providing empirical evidence to feed a long-lasting discussion on the equity-efficiency trade off in public good location choice (Thisse, 2007). In a seminal paper, Morrill and Symons (1977) point out that an efficient location pattern *à la* Dupuit (1844) that maximizes system profits or minimizes travel costs may result in socially unacceptable inequality in access over space owing to area variations in density and income. By contrast, Glaeser and Gottlieb (2008) argue that, in a spatial equilibrium framework, equity-motivated place-based policies only contribute to moving populations to low-amenity places, and show that there is very little evidence of the efficiency of such policies. Thus, equity concerns should lead to people-based and not place-based policies, which supports the utilitarian approach. Finally, Tsivanidis (2018) empirically exposed that even when infrastructure is designed to connect the urban poor, welfare gains are better captured by high-skills, affluent workers, since improved connectivity led to travel time sav-

⁸A positive effect in Toronto and Montreal, but none in Vancouver

ings but also to a reorganization of residence and employment location choices. While the low-skilled use public transit the most, their value of time remains low and they may be replaced in newly connected neighborhoods by the high-skilled, who exhibit a higher value of time. However empirical, since we do not develop a theoretical framework to compute welfare gains for connected populations, our contribution to this literature is twofold : (i) it constitutes to the best of our knowledge the first empirical analysis to focus simultaneously on labour and housing market effects of public transit in the most deprived neighborhoods, which allows to clearly identify the sources of welfare changes for the most deprived populations; (ii) it constitutes the first study to explore a particular feature of European cities : the large presence of social housing, and the possibilities it offers for mixed public transport and housing policies.

1.2 Institutional Background

1.2.1 Deprived peripheral neighborhoods in France : a persisting issue for urban policy

Urban segregation in French cities has been a perennial issue for urban and social policymakers for decades. The post-war housing crisis lead to haphazard development of large housing compounds at the fringe of every French city in the 1950s and 1960s : *Les Grands Ensembles* (The Compounds), built for car-owners of the then-emerging middle-class with limited connections to urban transport networks or city centers (Newsome, 2004). Those housing complexes experienced important shifts in social composition in the 1980s when the middle class moved to city centers, followed by progressive relocation of low income populations in those ageing complexes, which left French cities facing large, spatially isolated deprived neighborhoods at the fringe of the major metropolitan areas.⁹

The Priority Neighborhood : a zoning policy Facing rapidly increasing urban inequalities, French policymakers have historically relied on zoning to define place-based policies. Among the many zoning policies defined since the 1990s, the most important and particularly well evaluated one, since it was used for local tax incentives and enterprise zones¹⁰, was the "Sensitive Urban Zone" (*Zone Sensible Urbaine - ZUS*) defined in 1996. It was replaced in 2016 by the "Priority Neighborhood" (*Quartier Prioritaire de la Ville - QPV*).

Contrary to the ZUSes that were determined jointly by local and state officials based on qualitative criteria (presence of *Grands Ensembles*, unemployment level, etc.), the QPVs are defined on quantitative criteria that aimed at both avoiding political interference and ensure

⁹For a comprehensive history of these neighborhoods, see also Burgel and Jullien (2014)

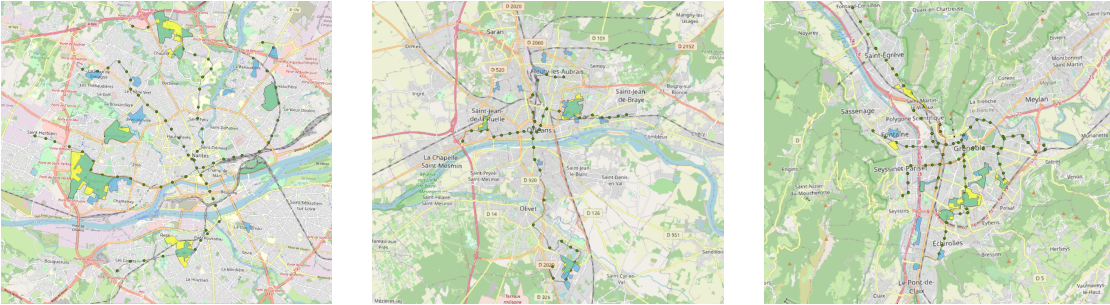
¹⁰See Briant et al. (2015) or Gobillon, Laurent and Magnac, Thierry and Selod, Harris (2012)

high similarity among the neighborhoods to allow for the evaluation of local policies. 1296 "priority neighborhoods" were defined by the French National Statistical Institute (INSEE) on the basis of the 2010 census. They regroup 5 million inhabitants in 702 different municipalities. They were defined using 2010 census data by

- a median income below a threshold defined by :
 - $S = 0,6 \times [(0,7 \times \text{NationalMedianIncome}) + (0,3 \times \text{CityMedianIncome})]$
for urban units larger than 5 million inhabitants
 - $S = 0,6 \times [(0,3 \times \text{NationalMedianIncome}) + (0,7 \times \text{CityMedianIncome})]$
for the others
- a population larger than 1,000 inhabitants

However different in their definitions, the similarities of these two zonings are striking : if QPVs are smaller and more numerous than ZUS, they cover very similar zones. In our cities of interest, 92% of the ZUS (299 of 326) defined in 1996 have a 2010 QPV in their perimeter as can be seen in Figure 1-1. Permanence of urban segregation and spatial isolation (Briant et al., 2015) may explain such persistence.

Figure 1-1: Nantes, Orleans and Grenoble tramway, QPVs and ZUSs



Note : QPVs are displayed in blue, ZUS are in yellow, tram stops are circles in green.

Source : BD-TOPO & Open Street Map

The inhabitants of Priority Neighborhood Population composition is very similar across these compounds due to the zoning definition. These urbanites face multiple obstacles in both the labor market and housing market. First and foremost is geography: most of these territories are located on the outskirts of cities and are often surrounded by physical barriers such as railway lines or highways as exemplified by Briant et al. (2015). Such spatial isolation, coupled with lower car ownership rates, translates into lower mobility and higher reliance on public transportation (Nicolas et al., 2018). A second obstacle is social. These neighborhoods’ inhabitants are more likely to have immigrant backgrounds and suffer from

a discrimination in the labor and housing market due to their origins and the bad reputation of their neighborhoods (Mathieu et al., 2016; Bunel et al., 2017). Finally, as documented by descriptive statistics in Section III, they are also less educated and skilled than the rest of the population. These difficulties translate into higher poverty rates, unemployment and crime prevalence that are higher in those neighborhoods than anywhere else in metropolitan France. More specifically, at the beginning of our period of interest in 2005, 22.1% of deprived neighborhoods' residents were unemployed compared to 11% at the national level.

Besides zoning and place-based policy, another lever to reduce spatial inequalities for local authorities has been transportation policy, which aims at reducing the isolation of deprived neighborhoods.

1.2.2 Tramways in France : a revival motivated by social equity concerns

Tramways as an urban policy toolbox If electric tramways were common in European and American cities in the early 20th century, they totally disappeared after World War II due to the combination of low fuel prices, the rise of individual cars and a correlated shift of public investment towards road construction (Goddard, 1996). At the end of the 1980s, French cities initiated a Light Rail Transit revival (locally known as *Tramways*) through an unprecedented nation-wide consistent program¹¹. In contrast with previous public transport infrastructure built in France, this *tramway revival* appears to have been largely motivated by increasing social concerns linked to urban segregation, which makes it of particular interest for our study.

Indeed, the tramway program represented a pivotal moment for the French doctrine on urban transportation decision-making. France transport infrastructure policy had been carried out across the whole territory since the 18th century by the central-state administrative body, the *Ponts et Chaussées* (Picon, 1992, 1994) whose decisions relied notably on utilitarian cost-benefit analysis following the tradition introduced by Dupuit (1844) and continued by Colson (1924-1928)¹². The 1982 Defferre decentralisation bill suddenly moved the authority on public transportation from the all-powerful hands of central state to municipal authorities, which paved the way for better assessment of local political priorities in infrastructure projects (Thisse, 2007; Offner, 2001), including social equity concerns. Lévêque (2017) showed for instance in the case of Lyons' metropolis that connection between deprived neighborhoods and the city center has been a constant goal of local transportation schemes since the mid-1980s. Similarly, the first tramway networks to be rebuilt in Nantes in 1985 and in Grenoble in 1987 were explicitly aiming to connect deprived peripheries to affluent city-centers. The popular success of these pioneer tramway made it one of the most

¹¹see Appendix A.1.1 for a brief history

¹²This framework introduced by French transport engineers (Roy, 1940) was popularized among English-speaking economists by Hotelling (1938).

popular urban planning tools among mayors nationwide to tackle the issues of congestion and urban segregation. Between 1998 and 2018, more than 25 cities in continental France built or extended tramway networks adding up to 600km of tracks and 800 stations (for a complete list of built lines and projected networks see figure A-3 in Appendix A.1.1). In most cities, tramway usage has exceeded the initial target by a wide margin.

Over the period in France, tramway constructions were the most important public investments by local authorities¹³. This national trend for tramway building is the most striking example of a global movement in which 138 new tramway networks were built worldwide in the last twenty years, more or less explicitly mirroring the French experience.

Table 1.1: Bus, tramway, and metro performances

	Bus	tramway	Metro
Max. flow (p/h)	700-1000	2000-5500	> 8000
Frequency (s)	600	180	100
Speed (km/h)	10-13.5	19,6	30
Cost (M euro/km)	5-10	15-30	45-100

Source: CEREMA (2019) study on 2002-2014 projects and FNAUT (2016)

tramway : comparative advantages The success of tramway with policy makers and commuters stems from its relative advantages compared to the bus and the metro. For mid-size, budget-constrained cities, it brings some of the advantage of the latter in terms of comfort and frequency but at a fraction of the cost. Faster, more frequent, and only 3 times more expensive than the bus, tramway circulate on their own tracks and benefit from right of way at crossings, which is particularly advantageous to avoid congestion. Table 1.1 lists these advantages. Unfortunately, there is no source of data which would allow us to easily compute the gain in travel time¹⁴. Anecdotal evidence shows that they often are substantial. A rough approximation can be drawn under the hypothesis that the tramway simply replaces a bus line. Given the difference in speed, traveling from two points on the line would take between 49% and 31% less time than with a bus. The time gain are potentially even more important at peak hours when tramway benefit the most from its corridor.

A common radial design Most of the networks are very similar in their design. Tramway lines are radial; they connect to each other in central district and run separately to the pe-

¹³For instance, the tramway of Dijon, considered as one of the least expensive, cost up to 400 million euros, which amounts to four times the annual investment budget of the whole metropolitan area of Dijon

¹⁴the decentralised administration of urban public transportation network by local transport agency makes the gathering of the information very costly. Some cities may have kept old matrices of distance in public transportation but it is not certain, and recovering them would require striking data access agreements with each agency individually

ripheries through large avenues¹⁵. The only deviations from this radial design are observed either in the polycentric suburbs of large metropolitan areas such as Paris (Ile de France network) and Marseilles (Aubagne network), or in a dense city network with no prominent center, as in the case of Valenciennes, in France’s northern mining basin. Table 1.2 reports some descriptive statistics about network design. Most (77%) tramway works can be considered as new line openings that exhibit a mean 18 stops per line, a 11.4km length and a mean distance of 630m between stops. This length typically corresponds to the distance between the city center and the fringe of the continuously built area. Those dense lines directly connecting the city center to periphery supposedly create a significant accessibility shock for the periphery neighborhoods and, depending on the existing network, the rest of the city. By contrast, line extensions are generally short and should be excluded from our analysis.

A deviation from a utilitarian objective The peripheries connected by these radial networks, though, are not random. They follow a common pattern by connecting both the main points of interest (POI) and the most deprived neighborhoods. Connected POI may be either central as the town hall, main hospital, train stations, or located at the urban fringe such as largest commercial malls and, if applicable, universities and airports, as shown by Table 1.3. However, the construction of tramway networks does not only aim at pursued a clear social equity objective: connecting the lower-income neighborhoods to the affluent city centers and to the rest of the city (Pissaloux and Ducol, 2012). Figure 1-2 exhibits maps of constructed networks that reflect such objectives : we can see that QPV are quasi systematically connected, even at the cost of a deviation from direct center to periphery route or extension to areas that exhibit no specific POI. Table 1.3 similarly suggests that tramway tend to be diverted from utilitarian objectives such as connecting POIs to connect deprived neighborhoods. Thirty years after the beginning of this nationwide trend, many *Quartiers de la Politique de la Ville* in large French cities were indeed connected to an tramway network as shown by figure 1-4. In cities where the network reconstruction started early (such as Strasbourg, Nantes or Grenoble), 80% to 90% of the QPVs are connected as of today.

Table 1.2: Descriptive statistics on realized tramway projects in the period of interest

	New Lines	Extensions
Distance between stops (m)	630	375
tramway line length (km)	11,4	-
Number of stops	18	5
Share	77%	23%

Source: BD-TOPO and authors’ own computations

Furthermore, heavily subsidised fares and generous mean-tested social pricing are tra-

¹⁵where they often follow the ancient tramway tracks

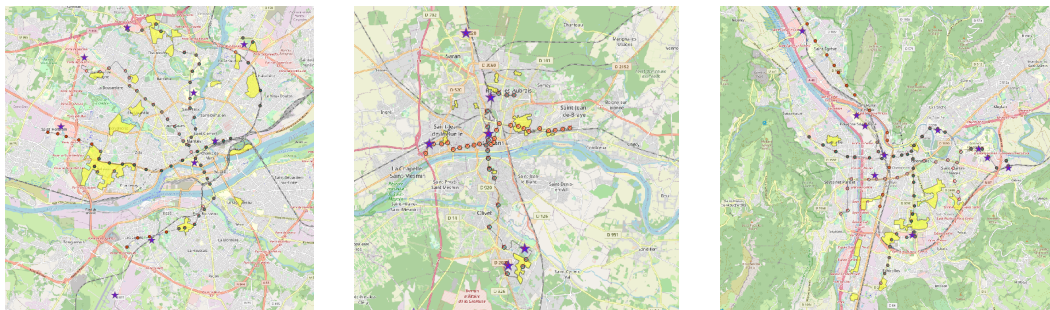
ditionally offered by local transport agencies to alleviate cost barriers for low-income users¹⁶. The French experience thus appears to be a case study of transportation infrastructure designed with equity concerns in mind, beyond classical public transport utilitarianism.

Table 1.3: Peripheral destinations reached by tramway lines connecting QPVs

Destination	Airport	University	Hospital	Rail	Stadium	City hall	Large Malls	Any
All Stops	6.5%	11.7%	10.3%	8.7%	3%	0.7%	37.3%	78%
Stops in QPVs	3.7%	6.7%	4.4%	4.4%	5.2%	0.7%	42.6%	67%

Source: Authors' own calculations from BD-TOPO.

Figure 1-2: Nantes, Orleans and Grenoble tramway, Priority Neighborhoods and POIs



Note : QPVs are displayed in yellow, tram stops are circles and stars stand for POIs.

Source : BD-TOPO & Open Street Map

The French public transport infrastructure decision process Since 1995¹⁷, every new infrastructure is indeed subject to a public debate. This typically corresponds to the first public information on the possible routing options. The chosen route, which must take into account the results of both the cost-benefit analysis and public debate, is then issued in the official gazette¹⁸, which makes it possible to then launch heavy work and necessary expropriations. The mean delay between the publication of the chosen route and the line opening is 3.48 years. The delay between public debate and line opening is more volatile, however the mean project is being completed 4 years after public debate¹⁹.

¹⁶In 2019, on average, the normal monthly fare was around 50 euros and the lowest social fare around 7 euros (for a summary of pricing by city see in A-1 in Appendix)

¹⁷Barnier Law of environment protection and local democracy, voted on February 2nd, 1995

¹⁸This "Déclaration d'Utilité Publique" (Declaration of Public Utility) can be issued either by central authorities such as the "Section des Travaux Publics" of the "Conseil d'Etat" or by regional state representatives, the "préfets".

¹⁹See Appendix A.1.3 for more details.

1.3 Data and Empirical Strategy

1.3.1 Data

We combine several comprehensive administrative datasets that describe job, transportation and housing markets at individual or city-block levels to assess the effect of an tramway network on deprived neighborhoods. This unique database extends over 14 years and exhibits granular spatial precision, which crucially enables us to document change around the arrival of tramway at an infra urban scale.

Unemployment data

Unemployed individuals Our unemployment data set contains the universe of unemployed individuals who were registered at their local unemployment office between April 2005 and December 2018 (corresponding to a total population of 123,161 unemployed people in our neighborhoods of interest, and more than 20 million nationwide), their socioeconomic characteristics, education, unemployment history, benefit eligibility, job search sector, maximal radius of search (expressed in distance or time) as well as postal addresses upon registration, drawn from *Pôle Emploi's* (French Unemployment Agency) *Fichier Historique* (FH) data set and completed with the outcomes of several internal working databases.

Censoring and Outcome of Interest Job seekers are required to notify their job agencies every month that they are still looking for a job to preserve their status. Additionally, local job agencies are only aware of the fact that job seekers find a job if they declare it when they terminate registration. As a result, a well-known shortcoming of this type of data is that we cannot always know for sure if job seekers stopped registering because they had indeed found a job or only because they failed/forgot to notify their job agencies. Job seekers entitled to UI benefit are strongly encouraged to remain registered as it is a necessary condition to receive their benefits but many are not eligible²⁰. Table 1.4 reports the motives for termination of registration.

Table 1.4: Motives for termination of registration

Motive	Share of all exits
Find a job	20%
Exit to non-employment	15%
Unknown destination	56%
Incomplete spells	8%

Source: Fichier Historique 2005-2018

²⁰In our population of interest many job seekers are only eligible to the unconditional welfare benefit

We address this shortcoming in two ways. First, to avoid cases in which unemployed people simply forgot to notify their agencies for a given month, we only consider a spell to be terminated if job-seekers do not register again at *Pôle Emploi* in the following month. Second, we define two individual outcomes that are not affected by censoring and a block-level outcome that corrects it. For each individual spell we compute both the probability to have exited unemployment after 6 months, irrespective of the exit type and the share of days spent registered in unemployment in the two years following a registration. The latter allows us to capture potential longer term effects of the tramway not only on the probability of finding a job but also on the quality and durability of the match. Finally, to take into account the information on the exit types, we estimate a simple Kaplan Meier estimator of survival at 6 months for each quarter of registration - block cells where we set all incomplete spells at the end of the period and unknown destination to right censoring while defining two competing risks for "finding a job" and "exiting to non-employment." We then define a corrected probability to have found a job with certainty at 6 months for an individual living in place j as $P(Job)_j = 1 - \hat{S}_j$ where \hat{S} is the Kaplan Meier survival into joblessness at 6 months.

Geocoding Although crucial to a precise identification of the effect of public transportation on the labor market, infra-municipality data remain scarce in the literature. To the best of our knowledge, we are the first researchers to use metric-scale geocoded data to describe urban labor markets. Using a phonetic string fuzzy matching algorithm on a comprehensive database of postal addresses, we are able to associate up to 85% of spells with the coordinates of the job seeker's residence²¹. Figure 1-3 reports the output of this process on a small neighborhood. The precision of the coordinates that were found is actually sufficient to identify not only the building but also the staircase of residence of the unemployed individuals.²². Geocoding makes it possible to measure individual distance to the closest tramway stop upon registration. It is to be noted that the data on job-seekers' addresses only exists for the job seekers registering in unemployment after April 2005. To put it differently, we do not know the location of the job seekers who are already registered for unemployment at this date, which prevents us from studying the effect of the tramway on the stock of job seekers in treated blocks.

²¹See appendix A.2.1 for details

²²Access to the exact postal addresses is restricted for legal reasons and has been possible thanks to the unemployment agency's general direction. The final data set contains only distance to tramway stops upon registration and not geographical coordinates

Figure 1-3: Unemployed geocoded at residence in Le Havre's eastern QPV.



Source : Administrative dataset, geocoding by authors algorithm, Open Street Map

Block level Data

To describe the mutations of a neighborhood's population induced by an tramway, we turn to block-level aggregated variables. We define a city block by the most precise spatial unit available in the French cadaster, the *Section Cadastre*.²³

Population Composition We retrieve population characteristics at the block level from a fiscal database on the universe of population and housing stock (*Fichier des Logements par Communes*, henceforth FILOCOM) available every two years over 2000-2014 at the French Ministry of Housing. It provides information on each non-commercial dwelling every two years between 1995 and 2015. It displays the location of each dwelling, its surface and whether it is rented, owner-occupied, or if it is social housing. It also contains the number of people who live in it, their age and income. Because of privacy constraints, the data set does not contain information on blocks of fewer than 10 households.²⁴ It allows us to

²³The median cadaster area is 257420.9 square meters which approximately corresponds to a 500*500 meters square

²⁴Such limitation is of little importance in our urban settings. In our population of interest, a median of 1105.5 individuals live in one block

recover income, age and household composition for each block, to document the evolution of the composition of the populations of deprived neighborhoods following the arrival of the tramway. The cadastral map is not constant over time and sections can be yearly redrawn by municipal authorities. However, the use of dwelling identification makes it possible to follow changes and to construct constant sections. Moreover, with dwelling identification being held constant over time, one can use it to characterize population flow at the block level.

Housing market We exploit the administrative PERVAL database from the French Board of Notaries (*Chambre des Notaires*) to further characterize the evolution of the neighborhoods in the housing market. It records transactions on the housing stock every two years from 2000 to 2014, localized at the block level and with detailed information on both the dwelling's characteristics and the buyer's and seller's status and occupation. Notary records provide a representative sample of the French housing market²⁵.

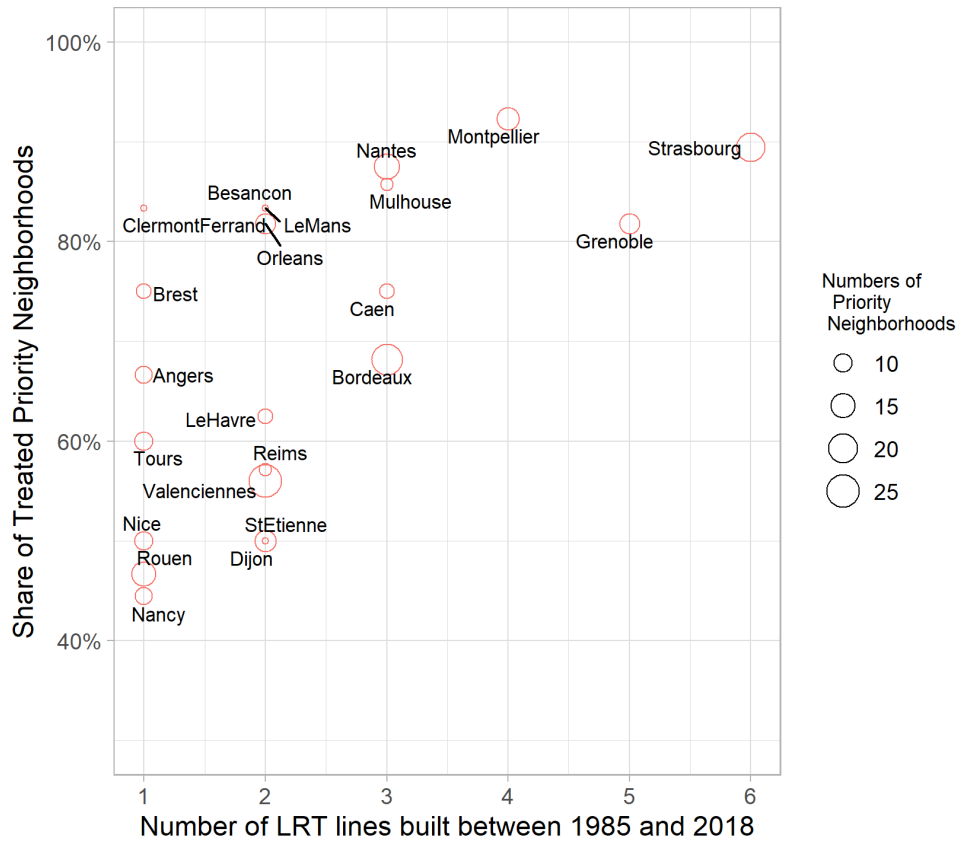
Tramways

Because tramway are dedicated to local transit, stations are closer than those of heavy rail networks and lines may be extended more gradually. Spatial and temporal precision is thus necessary to describe their phased development and its effect on urban labor markets.

Tramway networks To do so, we built a comprehensive GIS database of tramway stops' openings on a daily basis from 1985 to 2018. Geographic coordinates at a metric level are drawn from annual editions of the French National Geographic Institute (IGN) database BD-TOPO, supplemented and corrected when necessary with archival maps from local transport authorities. Timing of decision, construction and entry into service is very well documented thanks to the administrative process for infrastructure building. If each stop precise opening date can be easily drawn from local transportation authorities archives, we also have high quality data on the whole local decision process, which allows us to identify when the chosen route is known to the public. We built a panel of city blocks covering our period of interest, and compute the distance to the closest tramway stop at each time of the network's evolution. Figure 1-4 reports descriptive statistics on this development, on which it appears that the cities that pioneered the tramway renewal (Nantes, Grenoble, Strasbourg, Montpellier) exhibit a quasi total coverage of their QPVs by a tramway stop, while more recent networks, which only exhibit few tramway lines, are still in the process of achieving such coverage.

²⁵According to INSEE (2014) the data base covers more than 60% of the universe of transactions and constitutes an adequate sample that does not exhibit harmful biases.

Figure 1-4: City share of treated QPVs vs. number of lines built btw 1985 and 2018



Note: this graph represents the City Share of Priority Neighborhoods located at less than 500m from a tramway stop in 2018 for cities for which tramway and not the metro is the main historical mode of transportation

We included automated light subways built in the cities of Lille, Toulouse from 1983 to 2018 to our sample, even if they are slightly different on a technical basis from the majority of the French tramways that are non-autonomous surface streetcars²⁶.

Time-span and spatial extension of the analysis Considering the historical depth of these datasets, a common period of interest that allows us to compare the effect of an tramway on both unemployment trajectories, housing prices and population composition lies between May 2005 and September 2014. The revival of the tramway started in the 1980s and has lasted until today²⁷, as a result, many neighborhoods among French tramway cities have been connected before or after our period of interest. We do not consider these openings in our analysis.

²⁶These automated subways are based on *Matra's* VAL system, designed by the University of Lille in the 1980's, whose capacity, frequency and speed is similar to most of the tramways built in the 2000's

²⁷The last tramway line opening at the date of submission is Caen's new tramway, in July 2019

Moreover, to further ensure comparability between the different tram openings that we studied, we chose to exclude three cities: Paris, Aubagne and Valenciennes. This choice is notably motivated by the specific design of those networks. The Parisian tramway network is not radial and tends to link peripheries between themselves, which complicates the job market analysis. The Aubagne network is a subnetwork, but only a few kilometers long in a peripheral municipality in the larger Marseilles metropolis, which for local political reasons is not connected to the remainder of the metropolis's network. The Valenciennes network, by contrast, connects two cities of equal size and exhibits a 20km interurban section with no stops between two city centers of equal size, which makes it more similar to a commuter train than to a tramway.

1.3.2 Empirical Strategy

Identification

As showed *supra*, French tramway developments explicitly targeted deprived neighborhoods and especially QPVs in a redistribution-motivated deviation from utilitarian planning. However, as new infrastructure is costly, not every QPV has been connected to the city center during our period of interest. This offers an opportunity to estimate the impact of the connection of a deprived neighborhood to an tramway network by comparing connected and non-connected neighborhoods in a quasi event-study²⁸ specification at the individual, dwelling or block level.

Are these neighborhoods comparable? The selection procedure of the QPVs ensures high comparability between these neighborhoods. Moreover, our period of interest stands in the middle of tramway development roadmaps in most treated cities: potential bias arising from comparing the first connected neighborhoods, which may have been chosen out of local unobserved urgency, with the last connected or never connected ones, is thus tampered. Finally, Figure 1-6 shows that connected and non-connected QPVs during our period of interest are actually very similar in levels and trends over most outcomes before our period of interest. This parallel pre-trends identifying assumption is verified in practice on every outcome of interest as showed *infra*.

Discussion on Causality *Stricto sensu*, these estimates would be causal if the connection of a QPV to an tramway during the period of interest is quasi-random and does not correlate with unobserved characteristics of the neighborhoods that would have an effect on our outcomes of interest. Similarity of pre-trends between treated and non-treated QPVs stands in favour of this identifying assumption.

²⁸actually more a staggered difference in differences as exposed *infra*.

However, tramway developments are not random since we have seen they also aim at connecting train stations, hospitals, city hall, stadiums or large malls altogether. Far from threatening our strategy, this feature can actually be seen as a source of quasi random variation in tramway development since it is easier to provide tramway service to *QPVs* located between these points of interest, a location arguably unrelated to local neighborhood-specific unobserved characteristics. Table 1.5 shows that connected *QPVs* are more likely to be on a route to a *POI* than non-connected ones.

Table 1.5: Peripheral destinations reached by large radial roads connecting *QPVs*

Destination	Large mall	Airport	University	Hospital	Rail	Stadium	City hall	Any
Connected <i>QPVs</i>	35.6%	3%	5.9%	5.2%	5.2%	3%	0.7%	58%
Non c'ntd <i>QPVs</i>	5.4%	1.4%	3%	0.7%	0%	1.2%	0%	11.7%

Note: Authors' own calculations from BD-TOPO.

For a *QPV*, being closer to a convenient route from the city center to a *POI* increase the probabilities of connection to the tramway. Though, since we have seen the average tramway line is 11.4km long, being on a convenient route from the city center to a *POI* does not *a priori* imply better *ex-ante* access to the *POI* itself. It thus constitutes a factor of quasi-random variation in *QPV* connection unrelated to unobserved characteristics. However, it is not clear whether we shall use explicitly this exogenous variation to wield our results in the spirit of the inconsequential units approach developed by Chandra and Thompson (2000), since endogeneity issues may be different on the housing and the labor market. On the housing market, access to *POI* is not very likely to influence upwards the housing prices, but since we are sure that it influenced the design of the tramways network, we may want to restrict our analysis to the tramway lines that connect a *POI* and are most likely to connect the *QPV* located between the city-center and the *POI* only because of it inconsequential location. However, on the labor market, *QPV* located on the route to a *POI* are more likely to be *ex-ante* privileged since the benefit from a better connection to *POIs* that often constitute major employment centers (notably malls, airports, universities, hospitals). Thus, to mitigate this bias, one would prefer to restrict the study to the *QPV* that are not situated on any route to a *POI*. Moreover, any restriction of this kind would come at the cost of a large reduction of our set of pertinent tramway stops²⁹, which would threaten the precision of our estimators. However, we provide the results of such restrictions in section 1.4 as a robustness check.

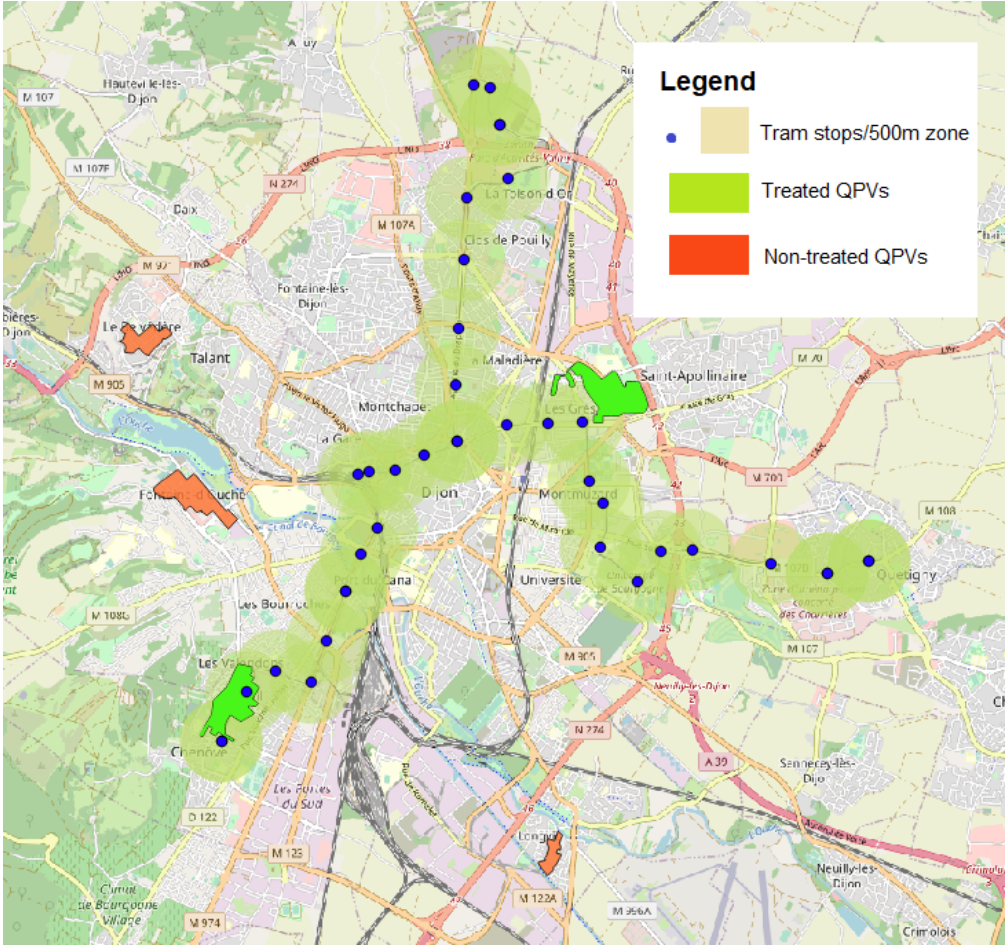
Treatment

We follow transport economics literature to consider a neighborhood and its residents treated when a tramway stop is opening fewer than 500 meters from its border. Our control group is made up of neighborhoods that are not treated at that time (no tramway stops have been

²⁹Actually fewer than half *QPVs* of interest are on a way to a *POI*.

built at 1000 meters from the border of the block). We exclude areas yet treated by another rail infrastructure, should it be subways (Lyon, Marseille, Toulouse and Rennes exhibit metro lines) or existing tramways. Figure 1-6 shows treated and never treated groups for the city of Dijon, Burgundy.

Figure 1-5: Treated and Never treated Neighborhoods in Dijon



Data: BD-TOPO & Open Street Map

To further take advantage of the precision of our data in the case of unemployed people, we consider them treated if and only if at the time of their registration into unemployment they lived in a treated block and their own individual distance to tramway’s next stop became lower than 500 meters. For the block analysis, we define as treated a block intersecting a priority neighborhood area and located at less than 500 meters away from a tram stop. This restriction aims at increasing the potential detected effect by focusing on the individuals and blocks which benefited the most from the new infrastructure.

These restrictions leave us with 195 treated blocks and 152 control blocks in 20 cities

Zoning discussion The use of zoning defined on the 2010 population census, during our period of interest could be a problem if tramway had a drastic short term impact on location decision of households. Descriptive statistics show that urban geography of poverty being quite persistent over time, treated and non-treated priority neighborhoods were already very similar and quite poorer than other neighborhoods in 2005.

Estimation Strategy

Our identification strategy relies on multiple tramway line openings in different cities at different times. We compare the evolution of several outcomes for the unemployed, households and transactions around the arrival of the tramway. We thus estimate the following individual and block level regression with a balanced panel :

$$Y_{i,t} = \sum_{-s < k < s} \beta_k D_{l(i),t,k} + \gamma X_i + \lambda_{l(i)} + \mu_{j(i),t} + \epsilon_{i,t} \quad (1.1)$$

$$Y_{l,t} = \sum_{-s < k < s} \beta_k D_{l,t,k} + \lambda_l + \mu_{j(l),t} \epsilon_{i,t} \quad (1.2)$$

Where $Y_{i,t}$ is the outcome of an individual i (unemployed, household, transactions) in period t , k is the difference between t and the date of opening of the tramway in the neighborhood, $\lambda_{l(i)}$ and $\mu_{j(i),t}$ are respectively a block l and a city j - year fixed effects and X_i is a vector of individual controls. $D_{l,t,k}$ is a dummy that values 1 if a tramway line was opened in the vicinity of block l in k quarters before time t .

We only use tramway openings for which we can observe the treated blocks for the full pre- and post-treatment window $-s$ and s . This insure that each coefficient β_k is estimated using the same set of control and treated blocks. More specifically, the analysis on population composition and housing prices (1.5) focuses on a $-6, +6$ year window. As we only have data from 2000 to 2014 on housing prices the openings we can study with those two data sets is limited to the openings occurring in 2006 and 2007. Meanwhile, the short-term analysis of unemployment outcomes (1.4) study the effect of the tramway in the 6 semesters before and after the opening of the infrastructure and rely on data available from April 2005 to January 2019. Taking full advantage of our data we carry the short-term unemployment analysis both for the entire period of availability of the data (reported in the main text) and for the common opening of 2006 and 2007 (reported in appendix).

Our estimations rely on within-city comparisons of blocks treated at the beginning of the period of interest with never-treated blocks, treated blocks, as well as to-be-treated blocks when available. Our estimation is akin to a "stacked" difference-in-difference (DiD). This class of two-way fixed effect specification has recently been the focus of a growing literature which highlights a challenge to the estimation of the average treatment effect (De Chaise-

martin and d’Haultfoeuille (2020); Borusyak and Jaravel (2017); Goodman-Bacon (2018). Intuitively, the β_k estimated in stacked DiD is a weighted sum of the average treatment effect of several DiD. In the presence of heterogeneous treatment effects across groups treated at different points in time, group average treatment effects are sometimes assigned a negative weight. In practice such bias will only affect our analysis of the labor market outcomes (1.4) for which we do have several treatment dates and our control group is made up of both never treated and to-be-treated job seekers. We re-estimate our β_k using the corrected DiD estimator proposed by De Chaisemartin and d’Haultfoeuille (2020) which is robust to negative weighting issues. For the analysis carried in the second part of the chapter, the restriction to opening of 2006 and 2007 and the biannual periodicity of our housing data amount to a unique date of treatment and no correction is needed. Hence, in this latter section the identification will only rely on the comparison of treated blocks with never treated blocks ³⁰.

The coefficients β_k can be interpreted causally under the common trend assumption: in the absence of the tramway, treated and non-treated blocks and individuals in the deprived neighborhoods would have evolved similarly. The specification allows us to examine such assumption by observing if the outcomes evolved differently between treated and never treated in the periods leading up to the tramway installation.

1.3.3 Descriptive statistics

Individual labor market characteristics Looking at relevant labor-market characteristics of the treated and never treated populations shows inhabitants of Priority Neighborhoods to be very comparable while reflecting the hurdles they face in finding a job. The Table A.2 presents some descriptive statistics for the job seekers entering unemployment before the arrival of tramway (in the second quarter of 2005) in the two groups as well as for the rest of the population living in our cities of interest. As expected unemployed people living in Priority neighborhoods are both less educated and less skilled than the general population. Only 15% and 13% of them hold a University degree and strikingly they were respectively 56% and 55% to have failed to validate their last diploma. At the same time, they are under represented in managing positions and over represented in the unskilled workforce. Finally, they less often hold French nationality than the general population, which hints at but understates the representation of workers of immigrant descent in Priority neighborhoods.

Block level characteristics Housing and income variables also support the comparability of our population and underline stark differences with the rest of the population. Housing prices and median income are very similar in treated and never treated blocks and respectively about 20% and 33% lower than for the rest of the population. Furthermore job seekers

³⁰for the list and date of tramway openings please refer to the appendix

Table 1.6: Population Mean (standard deviation) before LRT arrival

Group	Treated	Never Treated	General population
Age	30.4 (10)	30.8 (10.2)	30.8 (9.9)
Women	0.5 (0.5)	0.5 (0.5)	0.52 (0.5)
Years of Experience	2.46 (4.94)	2.86 (5.41)	3.09 (5.62)
University Degree	0.17 (0.38)	0.15 (0.36)	0.31 (0.46)
No degree	0.56 (0.5)	0.55 (0.5)	0.43 (0.5)
Managers	0.03 (0.18)	0.03 (0.17)	0.09 (0.28)
Skilled employees	0.5 (0.5)	0.52 (0.5)	0.57 (0.5)
Unskilled employees	0.47 (0.5)	0.45 (0.5)	0.35 (0.48)
French Nationality	0.81 (0.39)	0.85 (0.35)	0.89 (0.32)
P(Still registred after 6 mth)	0.44 (0.5)	0.45 (0.5)	0.44 (0.5)
P(Still registred after 2 y)	0.43 (0.32)	0.44 (0.32)	0.41 (0.32)
P(job with certainty 6 mth)	0.14 (0.07)	0.15 (0.09)	0.19 (0.12)
Housing Price/m2	1582.8 (463.5)	1674.5 (413.1)	1971.5 (473.8)
Median Income	7880 (2283.9)	7683.3 (2357.1)	10826.4 (2884.9)
Share social housing	0.47 (0.34)	0.51 (0.29)	0.19 (0.25)
Dwellings Surface	69.6 (15.9)	78.2 (17.5)	71.4 (19.4)
Number Transaction	29 (43)	18 (20.4)	23.5 (27.6)
Turnover rate	5,1%	3,2%	4,1%
Population	16176	7288	123161

Notes : Statistics from jobseekers registering in their local agency in the second quarter of 2005
Housing variables and Joblessness Survival are block level mean weighted by the number of unemployed living in the blocks in each group

in our population of interest live in blocks where almost half of the dwellings are social housing.

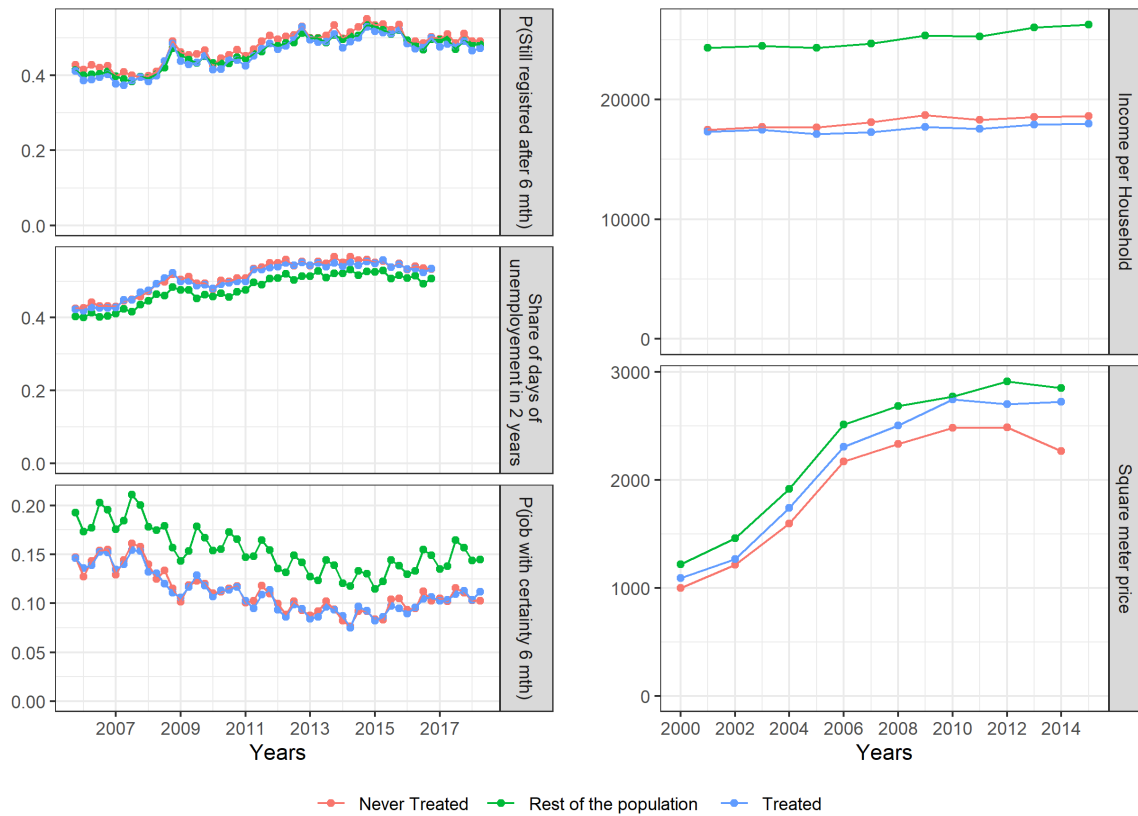
Outcomes of interest In addition to Table A.2, Figure 1-6 plots the evolution of the different outcomes throughout the period of interest. It confirms the similarity of the two groups and reflects the existing gaps in job market outcomes. The differences are stronger when looking at the block level probability to have found a job with certainty. Once the censoring was corrected in the second quarter of 2005, we find that only 12 and 13% of the job seekers have found a job with certainty whereas 17% of the general population have, which amounts approximately to a 30% difference. Both the never treated and the treated curves are almost conflated whereas the gap with the rest of the population remains big for the entire periods.

The gap between the share of days in unemployment of the two populations is smaller at the beginning of the period but proceeds to grow slightly, notably during the 2008 crisis. Interestingly, registration status at 6 months does not hold the same pattern between the three groups.

Housing outcomes show more interesting patterns, as the difference between treated and never treated groups, which was initially negligible, increases after the opening of the tramway in 2006 and 2007.

This first graphical analysis reinforces the comparability of treated and control groups.

Figure 1-6: Outcomes of interest through time



Left panel: Group mean for job seekers registering a given quarter from the 2005 to 2018 for the full sample of openings. Two calendar years of data being necessary to compute the share of days spent in unemployment we can only compute it up to the end of 2016. The probability to have found a job with certainty is equal to 1-Kaplan Meier survival in Joblessness.

Right panel: Group mean for households and transaction in a given year from the 2000 to 2014 for the openings of 2006 and 2007.

Source: FH 2005-2018 - Perval 2000-2014 - FILOCOM 1999-2015

It also shows that the scope for an average effect of tramway on labor market outcomes is limited while a mid-term housing market variable seems to respond to tramway connectivity in the descriptive stats.

1.4 An access to jobs ? Unemployment trajectories with a new transit option

Labor market integration in the most deprived neighborhoods constitutes a cornerstone of social effects of transport policies, since it may both be influenced by public transport availability and constitute a proxy for broader social integration.

1.4.1 Dynamic setting

Results

The figure 1-7 plots the results of the main regression for our 3 outcomes of interest. All outcomes exhibit a similar pattern. The profiles of the plotted lines are essentially flat. There are not differences in the periods preceding the tramway arrival which validate our pre trend hypothesis and our empirical strategy. Furthermore, There are no detected change in the unemployment outcomes after the arrival of the tramway in a neighborhood. The null effect suggested by the figure 1-6 is here confirmed by our regression results. The standard errors are fairly small, which leaves little room for an economically significant and undetected effect of the tramway on the entire population

Identification Hypothesis

Two potential identification concerns could have affected our analysis.

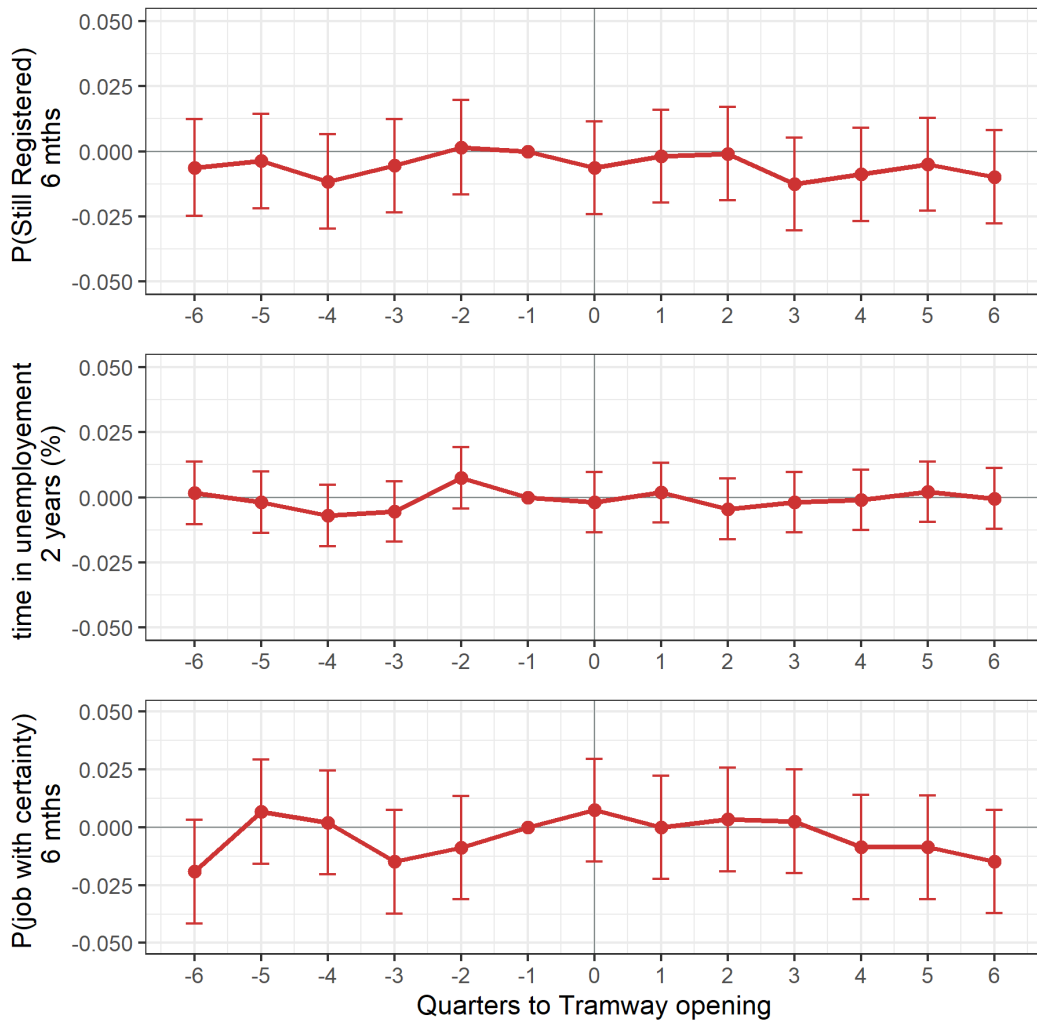
First, both the control and treated group are located in the same city, and an improvement in the accessibility and job prospect of one group could have a negative effect on the second group through spill over on the labor market, thus violating the Stable Unit treatment value assumption (SUTVA). Such violation would bias our estimates upward, overestimating the aggregated benefits of LWT on employment and is not much of a concerns given our null results.

A second concerns arise if an improvement in job prospect of the population living in treated block is due to a change in composition and not to the LWT per se. Our analysis controls for an extensive number of individual characteristics such as any bias would come from change in unobserved characteristics uncorrelated with observable. Furthermore, the literature and the second part of this article documents that gentrification is a long term process taking years if not decades to fully materialize ?. By comparison, the very short run nature of our analysis should shield us from big change in the population. Finally here again, if anything the bias should lead us to overestimate the effect of the LWT as more affluent households move in the treated neighborhoods.

1.4.2 Heterogeneity

Aggregated results point to a null effect of the arrival of tramway on labor market outcomes. But specific population, which theory or the empirical literature identifies as being more likely to benefit from increased accessibility, could benefit from tramway.

Figure 1-7: Labor market outcomes and tramway arrival



Notes: this graph plot the β_k of equation 1.1. Interpretation : the job seekers entering unemployment 4 quarters after the arrival of tramway in their neighborhood are 0.1 percentage points (non significant) less likely have found a job 6 months of unemployment than jobseekers living in untreated neighborhood.
 IC: 95% Confidence interval Source: FH - full sample

Estimation Strategy

To better assess the potential heterogeneity of our effect without losing too much precision we aggregate unemployment spells before and after the arrival of tramway and carry a simple difference in difference strategy.

More precisely, as we focus mainly on outcomes defined in the 6 first months of unemployment, job-seekers registering in the two quarters before the arrival of a tramway have access to this new transport mode at the end of their spell and are partially treated. We thus restrict our analysis to job seekers registering in 3, 4, 5 and 6 quarters before and 0, 1, 2 and 3 quarters after the arrival of tramway. The non treated group is here made of job seekers residents in never treated blocks or in blocks to be treated more than 12 quarters later.

We carry analysis along individual, block and cities dimension of heterogeneity. We thus interact an heterogeneity dimension dummy with the treatment dummy of the difference in difference specification as well as with city*quarter and block fixed effect. The coefficient associated with treatment is then interpreted as the deviation of treated job-seekers of group h relative to their city-heterogeneity group trends after the opening of the tramway.

Many block \times quarters cells contain few unemployment spells resulting in the impossibility to compute Kaplan Meier estimates for specific sub-groups. We thus do not estimate individual dimension of heterogeneity for this outcome

Dimension of Heterogeneity

We test for several relevant dimensions of heterogeneity :

Commuting potential A new transportation infrastructure could have an heterogeneous effect depending on the mobility potential of job seekers. During their registrations meeting at their local agency, job seekers are asked to state what is the maximum distance they are willing to commute to work. They answer a distance in km or a commuting time but do not specify what is their transportation mode. To test if the tramway affects differently job seekers depending on their commuting willingness we build city specific quartile of commuting willingness and run the regression for the different quartile (only top and bottom quartile specific effect are reported). To complement this analysis we also run the regression for two sub population that are known to be particularly limited in their commuting potential : Mothers ((Petrangolo and Ronchi, 2020)) and handicapped job seekers (result reported in section A.2 of the appendix)

Predicted outcomes The spatial mismatch literature hints that the population that has the worst predicted labor outcomes also tends to be the most affected by a low job accessibility (Labor outcome of low educated women in Barcelona and Madrid are more sensitive to job

accessibility compare to high educated women as showed by Matas et al. (2010)). To test if tramway affects differently job seekers depending on their expected labor outcomes we use our extensive set of control co-variates to estimate a predicted outcome and build city specific quartile groups.

Geographic Heterogeneity Change in transportation modes could have different effects in big and small cities. For example, congestion problems tend to increase with city size. tramway network are build to avoid part of the traffic jam at peak hours and could thus provide a bigger accessibility gains in bigger cities. Big cities are also by definition more geographically extended making the potential job accessibility gains more substantial. To test for such heterogeneity we divide our cities of interest in two groups depending on their size ³¹. We also run the analysis for treated blocks located at more or less than 5 km from the city center (see appendix)

Results

The results of the heterogeneity analysis of the effect of tramway are summarized in Figure 1-8 and in the Figure A-2. The left columns presents the results of the difference in difference estimation for the full population without heterogeneity dimension. The subsequent columns present the results of the estimation for the three heterogeneity dimensions previously defined. The results confirm the full population results. Most point estimates are very close to zero in absolute terms and relative to the mean of each outcome. Furthermore, At a 95% interval none of the coefficients are significant while the coefficient for small city is marginally significant at a 90% test. In Appendix A.2.2, Figure A-1 presents results for the DD estimation dis-aggregated per city, here again at 95% very few estimate are significant.

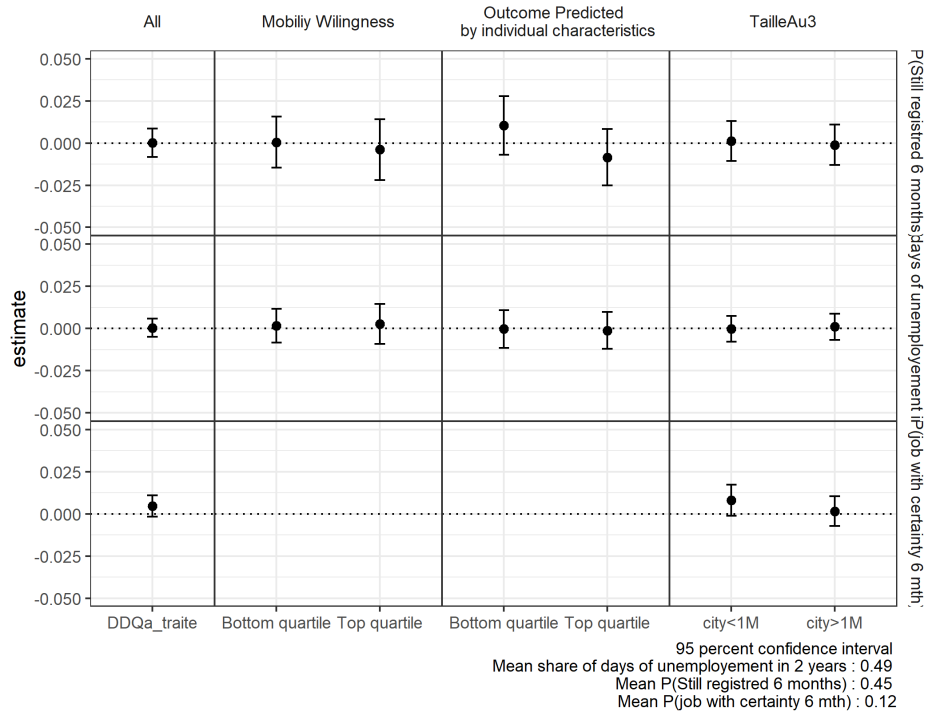
1.4.3 How precise is this zero ? A comparison

Table A.3 present the difference in difference point estimates and standard error of regression 1.1 on the entire population. The point estimates are very small, respectively representing 0.2%, 0,4% and 4.4% of the population mean and are insignificant at standard level. This null result is precisely estimated

Directly comparing the size of our results to the literature is not easily done as few contributions are closely linked to ours. Nevertheless given the level of preciseness of our estimates we would have been able to detect the effect presented elsewhere in the evaluations of programs designed to reduce unemployment duration. Closely related to us albeit in a different context, Phillips (2014) shows that the the job finding rate of job seekers who randomly received a public transit voucher in Washington increases by 5 percentage point after

³¹Size size is define using the Urban Area population (Aire Urbaine)

Figure 1-8: Heterogeneity analysis



Notes: this graph plot the *beta* of equation 1.1 for several dimension of heterogeneity.
 Scale and IC: scale are fixed at -10% and +10% of each outcome mean; 95% Confidence interval
 Source: FH

Table 1.7: Difference in Difference estimates

	Dependent variable:		
	P(Still r' gstd 6 mth) (1)	Nb of spells 1 year (2)	P(job certain 6 mth) (3)
LWT	0.0001 (0.004)	0.0004 (0.003)	0.005 (0.003)
Minimum Detectable Effect	0.011	0.007	0.008
Mean Outcome	0.45	0.49	0.114
Observations	255,849	255,849	5,985
R ²	0.135	0.141	0.418
Adjusted R ²	0.133	0.138	0.334

Note: *p<0.1; **p<0.05; ***p<0.01
 statistical significance $\alpha = 0.05$; statistical power (1) = 80 percent

3 months. In the French context and with a similar population of interest, Behaghel et al. (2014) find that an public intensive counseling programs reduce the number of days spent in unemployment in the year following registration of 20.6 days (4.8 percentage points) for those who entered the program and and by 6.5 days (1.8 percentage points) for those assigned to the program. More generally, active labor market policy tend to have bigger effect than our minimum detectable effects. Card et al. (2010) find that in average, counseling scheme increase the probability of finding a job by 2 percentage points in the medium term (1 to 2 year after program completion), training by 6,6 and private subsidy by 6.2 ³².

Even the most precise estimates would not allow us to conclude that tramway constructions do not have any effect on labor market outcomes in the short term. However if such positive effect existed and remained undetected its size would be of little economical relevance. This results complement the results of Åslund et al. (2017) while focusing on a particularly vulnerable population across many cities.

From a labor policy perspective our results underlines that improvement of public transportation, an intuitive and theory backed solution to spatial mismatch, does not always translate in better labor trajectories. As already stated, inhabitants of Priority Neighborhood face multiple challenges to labor integration and increasing accessibility to the rest of the city seems not to be enough to improve their unemployment trajectories.

From the lens of optimal public transportation design, this results show that deviating from an utilitarian design to take into account social fairness should not be founded on the sole expected gains in term of labor integration of the most vulnerable.

1.4.4 Robustness checks

Potential endogeneity issues may arise from the fact that some of the tramway lines that connect our QPVs also connect major employment centers such as large malls, hospitals, airports or universities. Such connection may bias either bias downwards our estimates, if it appears that these neighborhoods actually had access, before treatment, through their proximity to employment centers, to large job opportunities so that the new opportunities offered by connection to the city center would not widen job search so much; or it could bias upwards, if we consider that access to employment centers through the tramway connection not only reduces transport time to job offers but also gives residents of the connected QPVs a disproportionate advantage on the job market.

To evaluate such biases, we restrict our specification to the residents of the QPVs that are connected to a tramway line that does not connect any point of interest outside of city center. Figure 1-9 reports the results of this restricted specification. Figure 1-10 reports the results of the complementary restriction. Since neither of them is statistically different from zero, the

³²those estimates are averages of positive, null and even negative effect programs

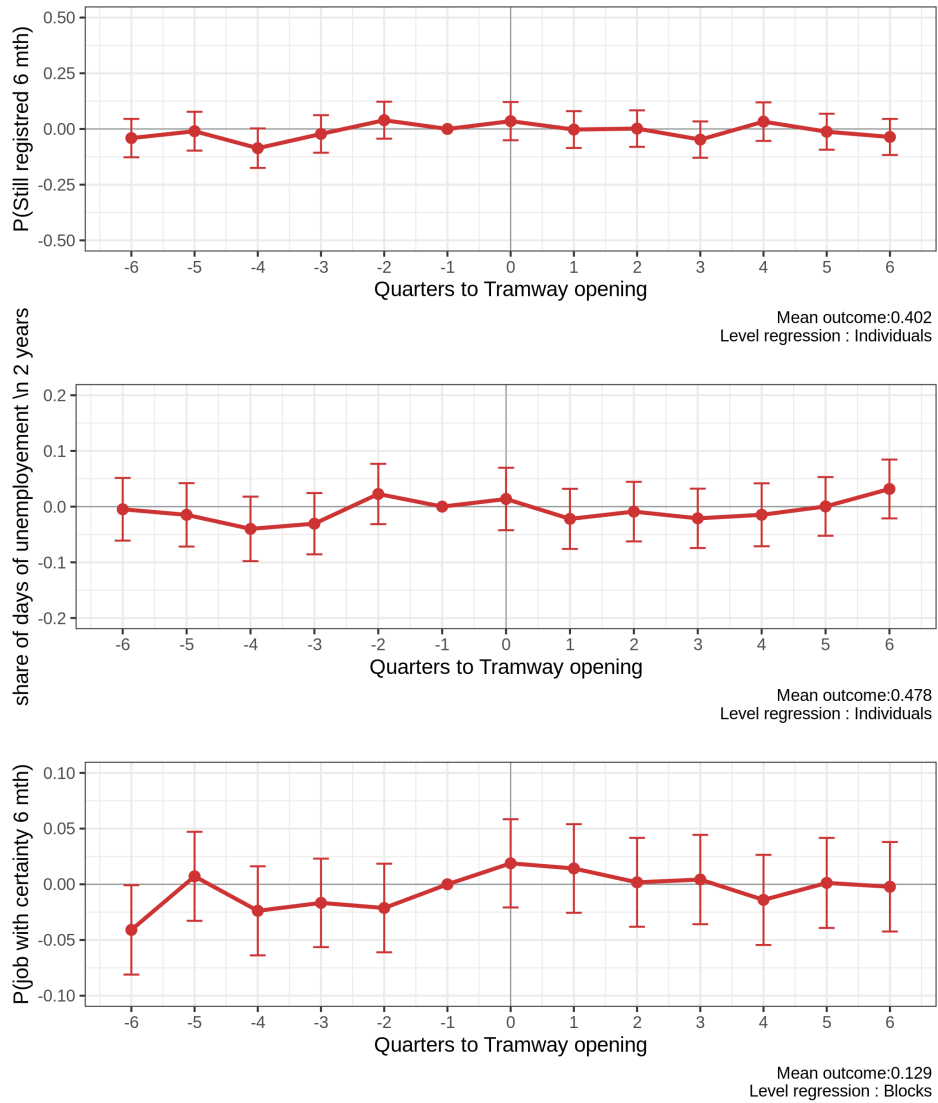
potential endogeneity bias appears not to be significant.

Table 1.8: DiD estimates restricted to QPVs never connected to a POI

	<i>Dependent variable:</i>		
	P(Still r'std 6 mths) (1)	Nbr of spells 1 year (2)	P(job certain 6 mth) (3)
LWT	-0.003 (0.007)	-0.002 (0.005)	0.019 (0.012)
Minimum Detectable Effect	0.018	0.011	0.016
Mean Outcome	0.41	0.45	0.14
Observations	92,378	92,378	2,453
R ²	0.159	0.160	0.296
Adjusted R ²	0.155	0.156	0.159

Note: *p<0.1; **p<0.05; ***p<0.01
 statistical significance $\alpha = 0.05$; statistical power $(1-\beta) = 80$ percent

Figure 1-9: Restriction to QPVs that are never connected to a POI

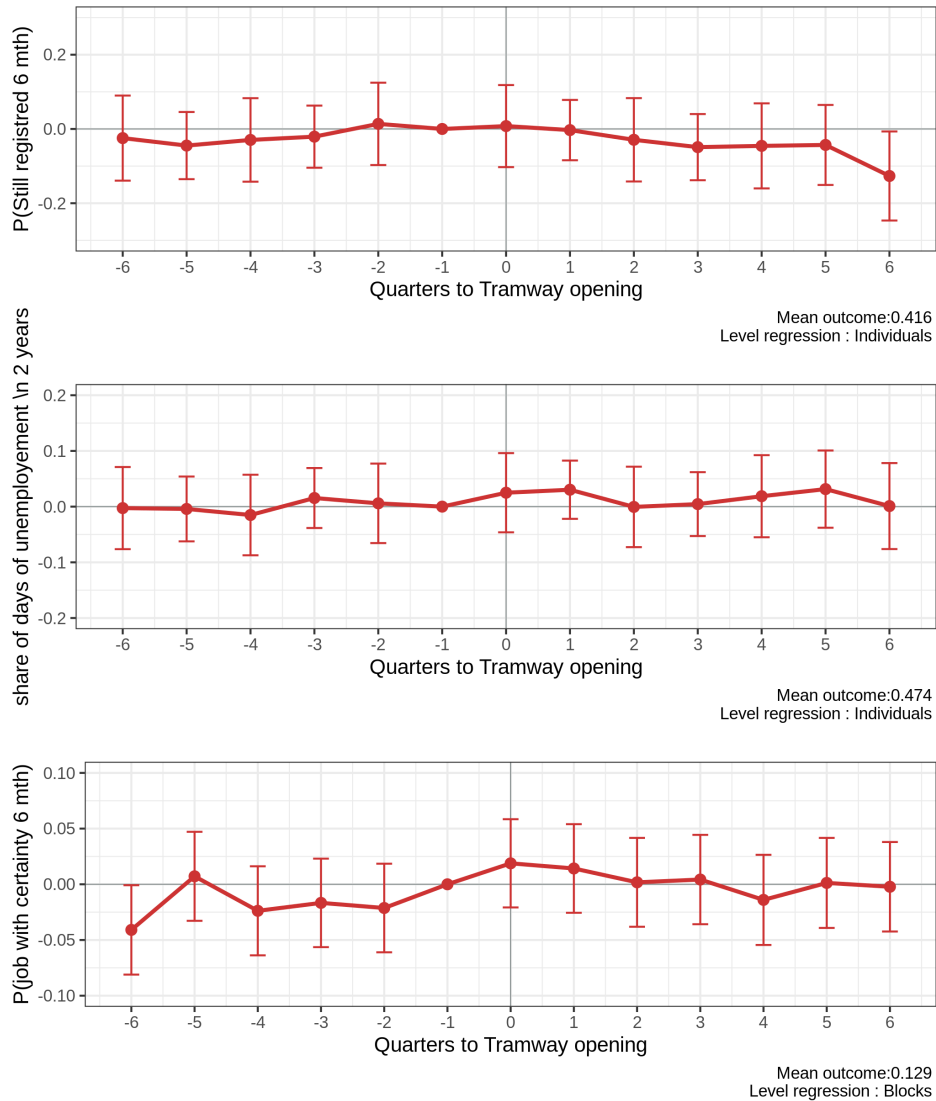


Notes: this graph plot the *beta* of equation 1.1 for inhabitants of QPVs that are never connected to an employment subcenter by a tramway line..

Scale and IC: scale are fixed at -10% and +10% of each outcome mean; 95% Confidence interval

Source: FH

Figure 1-10: Restriction to QPV that are connected to a POI



Notes: this graph plot the *beta* of equation 1.1 for inhabitants of QPVs that are connected to an employment subcenter by a tramway line.

Scale and IC: scale are fixed at -10% and +10% of each outcome mean; 95% Confidence interval

Source: FH

1.4.5 Long-term effects

Obviously, the absence of any evidence of effect of the connection to the tramway in the short time is not contradictory with the existence of long term effects of the tramway connection of labour market integration. Actually, in a long-differences setup, Sari (2015) finds that over 7 years, the connection to the tramway decreased unemployment rate in the most de-

prived neighborhoods by up to 5 points. However, most of the effect is washed out when all neighborhoods are taken into account, which is consistent with our choice to concentrate this study on the most deprived neighborhoods. Moreover, half of the effect seems explained by population change, that we chose not to observe to observe the sole effects of the accessibility shock on a constant population.

Actually, long term effects could be driven by three mechanisms :

- The adjustment of the housing market may induce population displacement that may lead the poorest –supposedly the less inserted in the housing market – to leave the neighborhood due to a rise in housing prices and employed households – or at least more inserted in the housing market– to enter the neighborhood.
- The access to central amenities could make professional training easier, and result in the long term in an improvement of the skills of the remaining population.
- Social mixity as well as access to better schools or universities could lead to the acquisition of better technical and social skills for the young generations, which could improve the insertion on the labour market

If our data on unemployment does not allow to reconstruct life trajectories long enough to determine which mechanisms are at play, population change and social mixity can be analyzed through the adjustment of the housing market.

1.5 Could tramway improve social mixity ? Capitalization and population displacement

Increased access to central amenities and jobs makes a previously isolated neighborhood more attractive. The net present value of all future benefits of this accessibility improvement (in terms of time, fuel, comfort etc.) shall reflect on a rise in the value of properties around the tramway stops. Such capitalization constitutes indirect evidence of the efficiency of the new transit network and that the zero-effect identified *supra* is not due to insignificance of the accessibility shock. Housing market adjustment could also induce population displacement that may impact social integration of the initial inhabitants of treated neighborhoods. Such population displacement actually reduces the aggregated welfare gains of the urban poor from the infrastructure but in the same movement improves social mixity, which may induce peer effects favorable to social integration in the long term. Even though the overall impact is far beyond the scope of this paper, it would be highly connected to the ability of the initial inhabitants households to capture welfare improvements linked to an accessibility shock. Housing occupation status, owner or social tenant rather than private tenant, is key to this issue. Our fiscal and transaction datasets allows to assess these impacts.

1.5.1 Estimation strategy

We follow the estimation strategy presented in Section 3 to assess housing market evolutions as well as changes in socioeconomic characteristics of occupants, buyers and sellers. Since the changes in the housing market appear more salient on the medium term, we study the effects of the introduction of a tramway along a two-year time span ³³.

Considering that we have extensive data on dwelling characteristics, we estimate an hedonic equation on all transactions, including lagged variables of time to and after treatment in a staggered differences in differences specification similar to equation 1.1. Indeed, hedonic price models are extensively used to examine whether home prices have increased in areas where public transit access has improved (Debrezion et al., 2007).

$$P_{i,t} = \sum_{-s < k < s} \beta_k D_{l(i),t,k} + \gamma X_i + \lambda_{l(i)} + \mu_{j(i),t} + \epsilon_{i,t} \quad (1.3)$$

Where $P_{i,t}$ is the price of a transaction i in period t , k is the difference between t and the date of opening of the tramway in the neighborhood, $\lambda_{l(i)}$ and $\mu_{j(i),t}$ are respectively a block l and a city j - year fixed effects and X_i is a vector of dwelling characteristics. $D_{l,t,k}$ is a dummy that values 1 if a tramway line was opened in the vicinity of block l in k quarters before time t .

We only use tramway openings for which we can observe the treated blocks for the full pre- and post-treatment window focused on the last and next six years with regard to treatment. This insure that each coefficient β_k is estimated using the same set of control and treated blocks. As we only have data from 2000 to 2014 on housing prices the openings we can study with those two data sets is limited to the openings occurring in 2006 and 2007.

To assess population displacement in response to treatment, we estimate this specification on the outcomes of interest available in fiscal data: inhabitants, newcomers and departing income as well as population flux. Occupation data in our transaction dataset offers complementary evidence. Eventually, we are able to focus on pertinent heterogeneity dimensions, such as social housing presence, distance to CBD and city size. In a second time, following the specification in equation 1.2, we are also able to estimate the impact on the size and status of the housing stock.

1.5.2 An accessibility shock that capitalizes into prices

A strong market capitalization Considering that QPVs rank among the most deprived and isolated neighborhoods in town, the expected rise of housing prices is not straightforward. Lower local amenities reflected by the initial deprived status could translate in a lower price increase than observed in the general case. However, due to higher previous spatial isolation

³³which corresponds to the seasonality of our data.

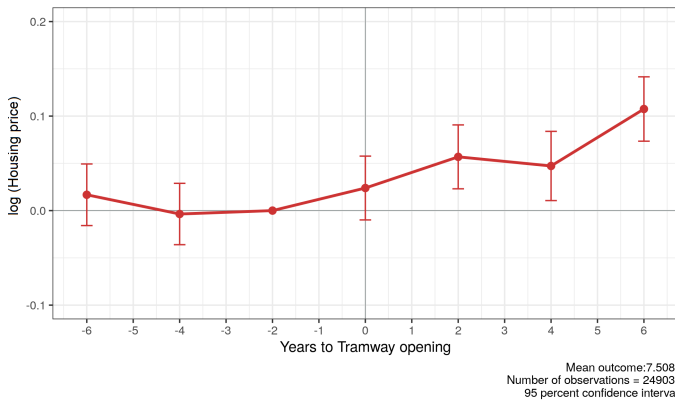
(as pointed out by Briant et al. (2015)), accessibility improvement after tramway connection could be larger and lead to higher price increase.

Hedonic prices estimates are presented in Figure 1-18. We find strong evidence of a capitalization of the accessibility shock, through a significant effect on housing prices as of the first year of operation, up to a 10% increase in housing prices six years after treatment. Absence of pre-trends is coherent with our common trends identification hypothesis. This immediate strong effect constitutes indirect evidence of the amplitude of the accessibility shock provided by the new infrastructure. The fact that, nonetheless, it did not produce any improvement on the labor market situation of treated inhabitants is thus very informative. To give a sense of comparability, Baum-Snow and Kahn (2000) find that decreasing distance to transit from 3 to 1km made housing prices rise by 4972 dollar per square meter in large US cities, whereas the meta-analysis by Debrezion et al. (2007) exhibits impacts ranging from -7% to +36%, with a +8% mean impact. Our 10% estimate is coherent with these findings, slightly larger than the mean point estimate in the literature, which would be coherent with the hypothesis of a large accessibility improvement due to tramway in QPVs.

Heterogeneous effects across cities If the rise in housing prices reflects a shock in accessibility to the rest of the city, it should vary accordingly across cities. In particular, it is expected that small cities where congestion is low exhibit higher substitutability between public transport and individual driving. By contrast, in large cities, high congestion and parking fees makes individual driving an option unavailable to the urban poor. We therefore expect accessibility gains to be larger for neighborhoods living farther away from the city centers of in large, congested cities. Table in Figure 1-18 reports the results of a difference in difference estimation following a similar specification as in section III. This figure provides complementary evidence of capitalization of an accessibility shock since we observe a larger rise in prices in the largest cities (more than 1 million inhabitants). Similarly, the increase of housing prices is higher in neighborhoods located more than 5 kilometers away from the city center.

Figure A-5 in Appendix A.3.2 exhibits the results of the same specification restrained to cities under 400,000 inhabitants, cities ranging between 400,000 and 800,000 inhabitants and cities beyond 800,000 inhabitants.

Figure 1-11: Prices and tramway arrival



Diff. in diff. estimates	Housing Price (per m^2)		
	(1)	(2)	(3)
tramway	0.063*** (0.015)		
< 1M hab		0.046 (0.030)	
> 1M hab		0.067*** (0.016)	
< 5Km CBD			0.069** (0.030)
> 5Km CBD			0.090*** (0.024)
Obs.	18,220	18,220	10,713
Adj. R ²	0.752	0.752	0.722

Notes: this graph plot the β_{t_k} of equation 1.1; 95% confidence interval

Source: Perval

Data : Perval *p<0.1; **p<0.05; ***p<0.01

Market activity To test whether this price increase is driven by an increase in demand, we turn to occupation duration and number of transactions reported in the Perval database. Figure 1-12 reports the results. We find a significant effect on the number of transactions on the year of treatment, and a non significant increase in the point estimate afterwards. More significantly, we find a negative and growing effect on occupation duration up to a 5 months reduction (-20%) after 6 years. Turnover on the housing market is thus significantly augmented by connection to the tramway. However, we also observe small pre-treatment negative trend, that may indicate the occupation duration has already been affected by construction works, for instance.

Since we do not have census data with a precise enough time-span to enable us to track urbanites in and out our tiny neighborhoods of interest³⁴, we have to make the hypothesis that the turnover on the housing market we reported is a good proxy for the migration flows. Therefore, we can use population inflows and outflows from the FILOCOM database as a proxy of real population displacement. Obviously, it comes at the price a small biases such as neglecting internal migration, however the small size of our neighborhoods of interest make such a migration quite uneven *a priori*. These figures motivate a closer look at the characteristics of households entering and leaving the newly connected neighborhood.

³⁴Census at the block level is only available in 2010 and 2015 at the date of publication

Figure 1-12: Market activity and tramway arrival



Notes: this graph plot the β_{a_k} of equation 1.2; 95% confidence interval

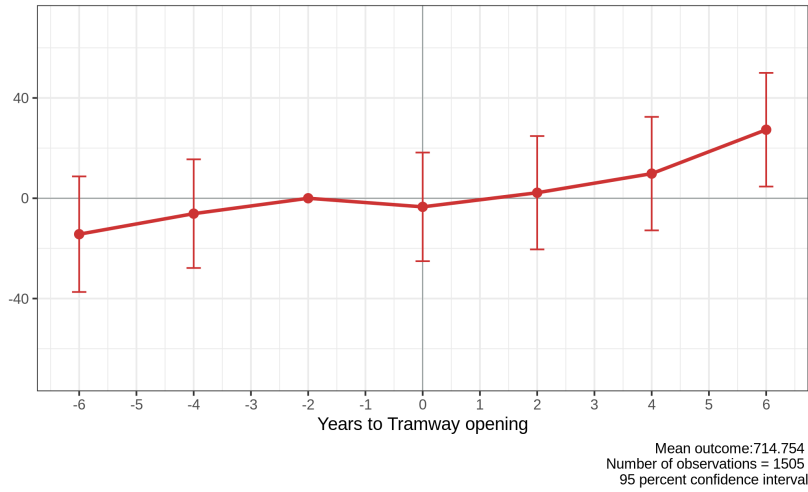
Source: FILOCOM

Housing stock Such a rise in transactions could be driven by the production of new dwellings by either public or private developers who would anticipate the entry into service of the tramway. In particular, since the QPVs are deprived neighborhoods, they benefit from a very extensive urban renewal programme, operated by a national agency known as "ANRU", that could translate in destruction and constructions in the social housing stock to improve the quality of the housing stock that would affect housing prices and population changes (Chareyron et al., 2019; Letrouit, 2020). If local authorities and ANRU had been discussing over the timing of tramway constructions, urban renewal could have been synchronized with tramway connection so that urban renewal benefits from the positive image of the tramway. Although improbable, considering the complexity of the decision process on both sides³⁵, such a synchronicity would bias our estimates of the effect of tramway connection.

We do not have data either on urban renewal programmes or on the quality of dwellings to control for this potential bias, however, we know that such a programme would translate in large flux in the housing stock, since dwellings would exit the market to benefit from renewal. Figure 1-19 reports the impact of tramway arrival on the number of dwellings. We observe a gross 3% increase of the total housing stock 6 years after arrival. This timing tends to indicate that housing developments are a consequence of the rise in housing prices after tramway connection and not a consequence of an unobserved urban renewal programme. Moreover, figure 1-14 shows no movements on the social housing stock. Urban renewal does not appear to be synchronised with tramways construction.

³⁵See Letrouit (2020) for a complete description of the ANRU decision process.

Figure 1-13: Housing stock and tramway arrival



Notes: this graph plot the β_k of equation 1.2; Source: Filocom

Figure 1-14: Social Housing stock and tramway arrival



Notes: this graph plot the β_k of equation 1.2; Source: Filocom

Appendix A.3.2 reports the results of the regressions examined *supra* on a sample restricted to existent housing, to wash out any possible effect of new buildings or increased quality. The price increase is robust to these restrictions.

1.5.3 Population change through migrations

As deprived neighborhood are better connected to the city centers, external households are willing to locate in the treated area. The amplitude of these flux, and whether this new population differs from the pre-treatment one are key questions to understand the effects of

social integration of the urban poor. Our dataset allows us to estimate income and profession variation in the flux of new dwellers, as well as to build population composition metrics.

Strong evidence of gentrification When travel time to the city center decreases in treated QPVS, we expect central affluent urbanites to relocate in them, looking for larger dwellings or proximity to natural amenities (when applicable to the large, high rises housing compounds that often constitute the QPVs). We thus expect newcomers to exhibit higher skill profile and income than incumbents. By contrast, the characteristics of departing population is key to understand the overall effects of this new infrastructure. We turn to the household income at residence retrieved from our fiscal dataset that corresponds to effective dwellers. Figure 1-15 report the impacts of an tramway opening on income of current inhabitants and income of new dwellers. We find a significant effect on income of new dwellers, that increases of 600€(2.7%) after 6 years. New dwellers differ strongly from existing population. A similar, but slower increase is observed on mean household income of 500 €(2.2%) after 6 years. This figure is consistent with labor market effects being null or small, which imply that any massive change of income will be due to newcomers higher income and not unemployed incumbents finding a job. It is also consistent with increased turnover (around a yearly 6% which gives around 35% change of population at the end of the period). By means of comparison, Bardaka et al. (2018) found a 18,6% increase in the first 10 years in the low-income blocks treated by a tramway in Denver. However, the literature is not straightforward, since Dong (2017) found a mean decrease of - 4440\$ (-12%) after 20 years, but no significant effect in the first 10 years in the neighborhoods connected to a tramway in Portland.

To complement this evidence, Figure A-1 in Appendix A.3 report the probability that a buyer is an executive³⁶ and a seller an employee. We find significant evidence of an inflow of executives in neighborhoods previously considered as ranking among the poorest, and an increase in the departure rate of employees that might substantiate the claim of gentrification. However, these figures are not conclusive since we have no information that buyers and sellers in PERVAL would be, or not, the residents. Inflow of executive buyers may simply reflect rental investment in a neighborhood considered as a new opportunity.

Interpretation in terms of social integration The interpretation of these figures in terms of social equity is not straightforward. Indeed, population displacement does not constitute a direct evidence of worse social integration in deprived neighborhoods. On the contrary, since housing stock remains constant, any improvement of social diversity will come at the cost of departing incumbents. Social diversity will be improved if this replacement is limited, and will be degraded if replacement extends to the quasi-total displacement of previous

³⁶Defined by aggregating all highly qualified categories in the french occupation category : namely senior civil servants, scientists and engineers, information and art producers, private sector executives, liberal professions

population. To study social diversity impacts of our tramway openings in QPVs, we must compute a diversity index on the population of our neighborhoods of interest. The Theil (1967) index is an entropy-based measure of diversity on income in a population, defined by :

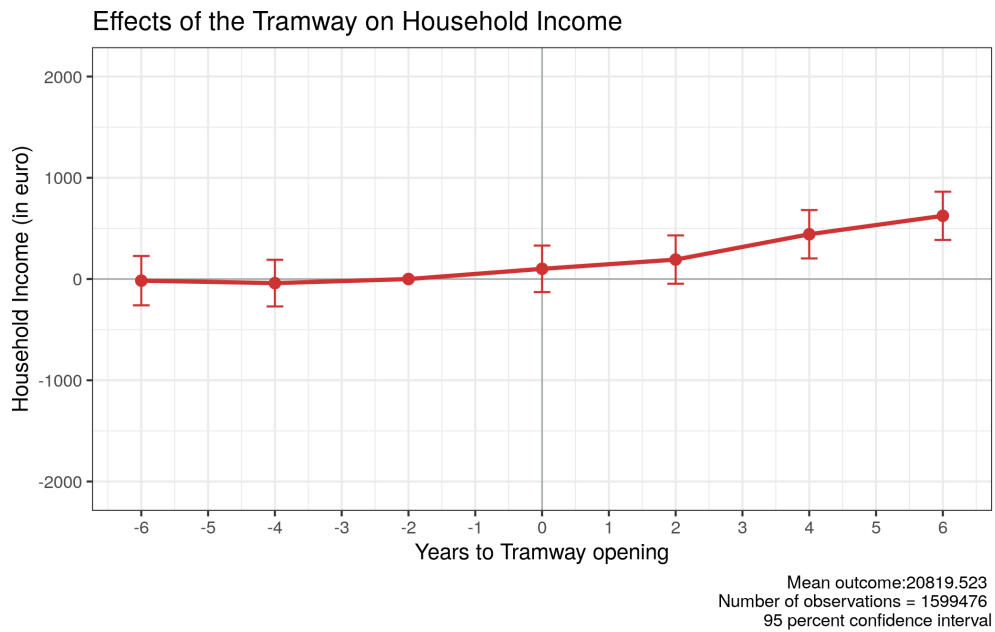
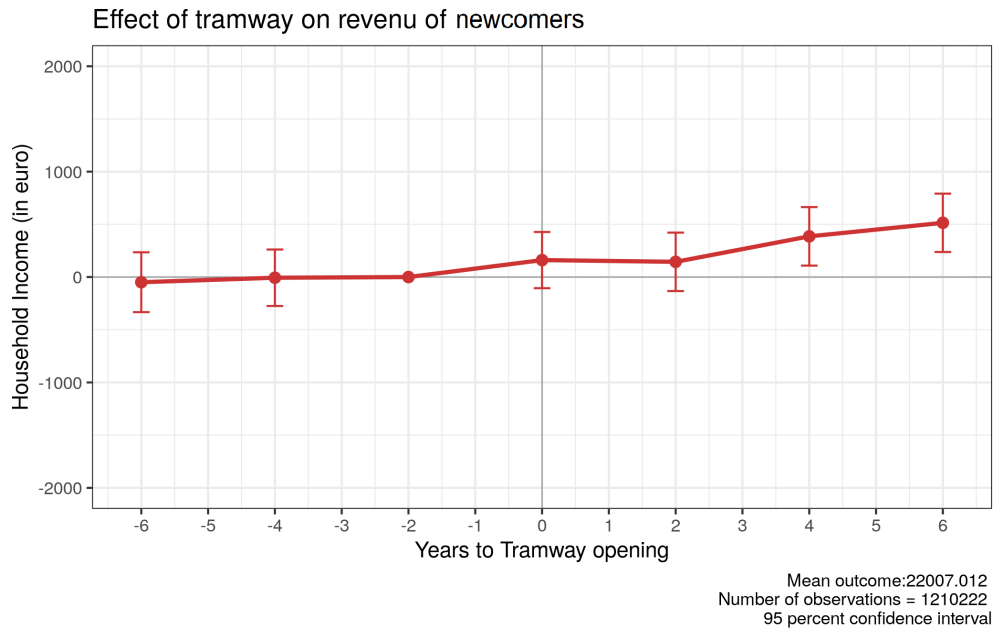
$$T = \frac{1}{N} \sum_{i=1}^N \frac{x_i}{\mu} \cdot \log\left(\frac{x_i}{\mu}\right)$$

where x_i is each inhabitant's income and $\mu = \bar{x}_i$ the mean income.

The result of our staggered diff-in-diff regression, estimated on block-level computed Theil indices is reported in Figure 1-16. It exhibits a strong positive effect of the opening of an tramway on Theil diversity index, which means that diversity of income has increased in the first six years after connection. At this time-scale, the effects of gentrification on social diversity and therefore integration appear to be profitable for the remaining initial dwellers, that should still represent considering the estimated turnover an approximate 65% of the population. However, the stability of this result in the longer term, which we cannot examine with our data, is highly questionable. It is arguable that it may depend on forces counteracting gentrification, which can be (i) an increased capacity of incumbents to stay in the neighborhood, that may come from rising income due to an increased labor market integration, which we showed to be unlikely; (ii) an institutional setting that reduces the pressure of rising prices on the urban poor location choice.

Actually, the long term impact of an tramway connection on social integration may heavily depend on occupation status of incumbents. For renters, an increase in rents consecutive to treatment would make a neighborhood less affordable and eventually induce migration out of the treated area, which would deprive them from the post-treatment accessibility gain.

Figure 1-15: Income of inhabitants / newcomers



Notes: this graph plot the β_k of equation 1.1; 95% Confidence interval

Source: FILOCOM

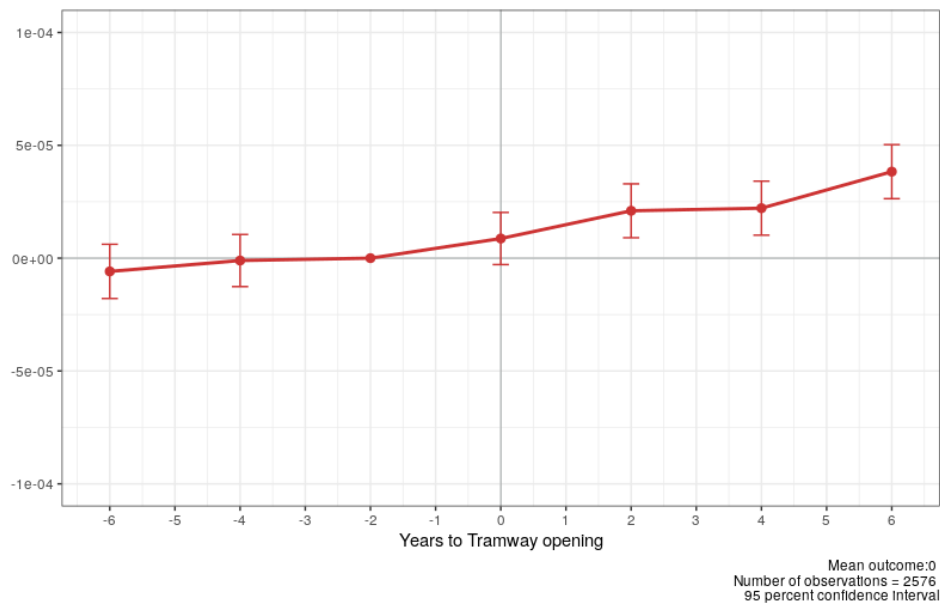
Table 1.9: Difference in Difference estimates by occupation status

	<i>Dependent variable:</i>			
	Occup. Dur'tn (1)	Income (inhab.) (2)	Income (newcom.) (3)	Income (depart.) (4)
Owner-occupiers	-0.58*** (0.060)	524.2*** (113.0)	930.4*** (261.1)	891.3*** (291.1)
Private housing tenants	-0.27*** (0.076)	714.2*** (158.8)	968.5*** (229.7)	897.3*** (246.3)
Social housing tenants	-0.13* (0.058)	205.8* (111.2)	530.4** (220.8)	291.3 (238.9)
Observations	1190500	1190500	288436	268424
Adjusted R ²	0.15	0.21	0.21	0.17
F-stat	148.2	308.3	59.1	43.7

Data : FILOCOM & Perval

Note: *p<0.1; **p<0.05; ***p<0.01

Figure 1-16: Theil index (income) and tramway arrival



Notes: this graph plot the β_k of equation 1.2;

Source: Perval

By contrast, owner-occupiers benefit, if they leave the treated zone, from the full value of the accessibility shock, capitalized into their dwelling's price³⁷. By contrast, social housing tenants face no increase in rents, thus reducing pressure from migration, but do not benefit from leaving. We shall thus study the heterogeneous effects of an tramway stop opening alongside occupation status.

1.5.4 The ambiguous role of social housing in preserving social mixity

Using the diff-in-diff specification, we study the heterogeneity of previous graphical results along occupation status. We expect social housing tenants to be less volatile than private housing market participants, since social housing authorities have no incentive to raise rents or facilitate turnover. However, increased attractiveness of newly connected neighborhoods should increase quantity and quality of the pool of applicants for social housing accommodation. We should thus expect a smaller but non-zero change in newcomers income in social housing.

Social housing as a support for social mixity Table 1.10 reports the effect of tramway on housing market variables by housing types. It appears that owner-occupiers are the most affected by the opening on an tramway stop. Their occupation duration decreases by 7,2 months, which constitutes a 33% drop. This spectacular decay may be linked to owner-occupiers willing to take advantage of their home's appreciation. Population changes are also quite spectacular, since mean income rises by 524.2 €, (2,3 %) and newcomers income by 930.4 (4,1%). More surprisingly, one cannot statistically reject equality between newcomers and departing owner-occupiers' income (the latter rises up to 891.3 €.). This may be interpreted as evidence that the market for owner-occupied dwellings has reached an equilibrium six years after the opening of an tramway. Private rental market appear as attractive for newcomers as the owner-occupiers one, with very similar increase in newcomer and departing income (actually the point estimates are even a bit higher, at 968.5 € for newcomers). However, private housing tenants seem well protected from increased demand and rising rents by their tenancy³⁸, which must explains their low drop in occupation duration (half the mean effect).

As for social tenants, their status protected them from the changes of the private housing market. The drop in occupation duration is hardly significant and we do not observe changes in the income of departing population. Everything happens as if incumbents willing to stay in the newly connected neighborhood could do so. Newcomers, by contrast, are

³⁷Their mobility should be less influenced by housing prices, even though there is an opportunity value of living in one's own dwelling

³⁸Tenancy Law is quite protective for tenants in France, since rents cannot be revised for the tenancy duration more than a national inflation rate, and terminating the rental agreement takes time.

a bit wealthier after connection to the tramway, as competition among applicants may have increased.

Social housing thus exhibits a protective function that preserve its tenants from the adverse displacement effects of gentrification. Social tenants appear as the true beneficiaries of the new infrastructure : they benefit both from its accessibility effect, that has a positive welfare impact on their travel time, even if it does not facilitate job matching, and from increased social mixity. By contrast, results on the private market indicate that, in absence of social housing, gentrification and population displacement would capture an important -but still to be determined- part of welfare gains from an infrastructure targeting the most deprived areas. These effects, that we have only been able to study in short term, may even wash out, if gentrification is complete, any benefit from the infrastructure for the poor primary inhabitants. Could a combination of social equity concerns in the design of transport networks and increased social housing therefore be effective in reducing spatial inequalities ?

Social housing as a obstacle for social mixity Catchy though it appears, this narrative must be tempered down by taking into account general equilibrium effects of an increase in social housing presence. An increase in social housing share in the housing stock may have adverse effects on surrounding housing market: (i) it may come at the cost of some 'redlining', since social housing concentrate the urban poor, and sometimes ethnic minorities that can be discriminated against. In that case, the mean income of surrounding inhabitants is not likely to increase with an tramway connection, and may even decrease as low-income households that value more public transport (Glaeser et al., 2008) may migrate to a well connected neighborhood that does not experience gentrification ; (ii) even without any discrimination, a large share of social housing in the housing stock could affect the surrounding market by reducing the pool of dwellings up to rental or sale, discouraging research in the area. However, with this mechanism, turnover may be slower but prices may rise eventually after an tramway connection.

Table 1.10 reports the result of a diff-in-diff specification on household income and housing price for neighborhoods above and below the national median of QPVs social housing shares. There is evidence that would support the first mechanism, since we find no significant impact on income in neighborhoods over the national median (the point estimate is even negative) concomitantly with a positive effect on prices (7% elasticity, in line with the price capitalization observed in neighborhoods under the national median).

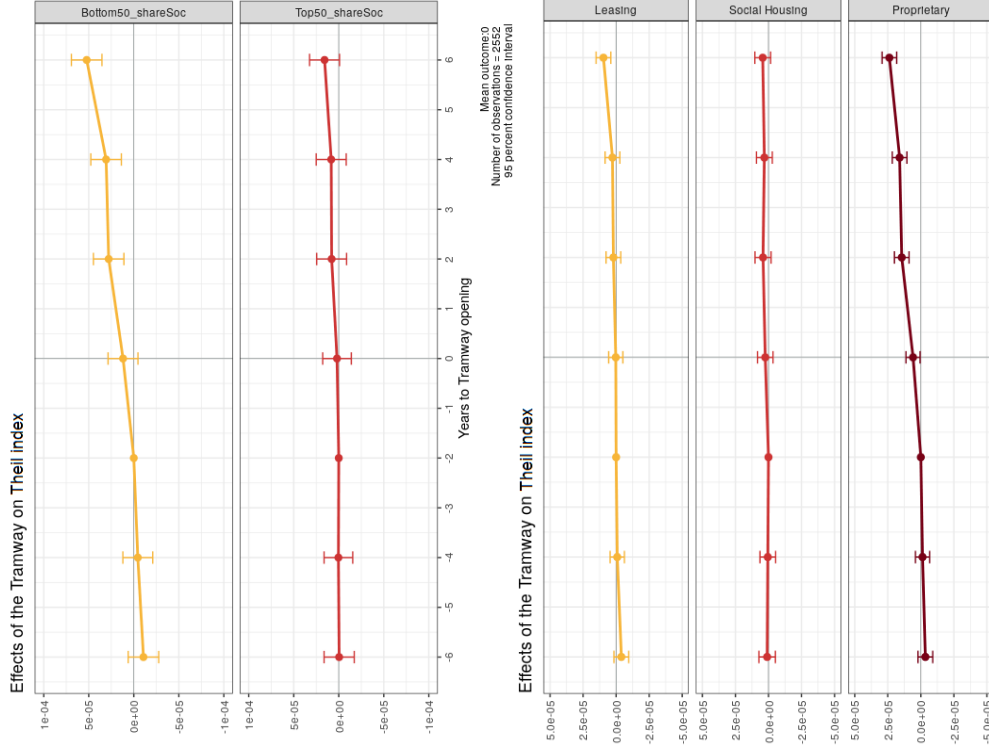
To complement this result, Figure A-2 and Figure A-1 in Appendix A.3 report the probability a buyer in a QPV is an executive, and the seller an employee . We find no significant effect in QPVs intensive in social housing, by contrast to QPVs intensive in private housing for which the estimates are in line with the mean case exposed in Figure A-1 (higher propor-

tion of executives among buyers). This behaviour constitutes another evidence of 'redlining' for the social housing intensive QPVs.

Such 'redlining' has two opposite effects : on the one hand, it reduces the capture of the welfare gains from increased accessibility by affluent urbanites, on the other hand, it does not increase social diversity, whose peer effects could prove necessary to improve durably the situation of the urban poor, peculiarly in a context where they face many obstacles on the job market. Figure 1-17 reports the increase in the Theil index between low and high social housing intensity neighborhoods.

We find no impact of a tramway stop opening on social diversity in social housing intensive QPVs, while the impact is strong and significant in private housing intensive ones. The second graph of Figure 1-17 shows that this effect is largely driven by owner-occupying newcomers, who concentrate the major part of total social diversity, and appear to be peculiarly rare in social housing intensive QPVs. Social housing thus appears as an ambiguous tool, that may participate to increase social isolation even in a context of public transit connection. In terms of policy recommendations, a public transit infrastructure deviating from the utilitarian decision criteria to remedy urban inequalities could thus have chances to be effective only if accompanied by a constant but moderate social housing construction policy.

Figure 1-17: Theil by social housing share and occupation status



Notes: β_{it_k} of equation 1.1; 95% Confidence interval Source: Perval

Table 1.10: DiD estimates by social housing prevalence

	<i>Dependent variable:</i>			
	Household Income (1)	Income (3)	Housing Price (in log) (5)	Housing Price (in log) (7)
tramway	441.7*** (74.8)	-	0.063*** (0.015)	-
< Med. Soc. Hous.	-	976*** (119.1)	-	0.064*** (0.020)
> Med. Soc. Hous.	-	-72.6 (105.8)	-	0.072*** (0.021)
Obs.	1,191,558	1,126,463	18,220	17,590
R ²	0.091	0.094	0.756	0.757

Note: PERVAL & FILOCOM (2006-2014) *p<0.1, **p<0.05, ***p<0.01

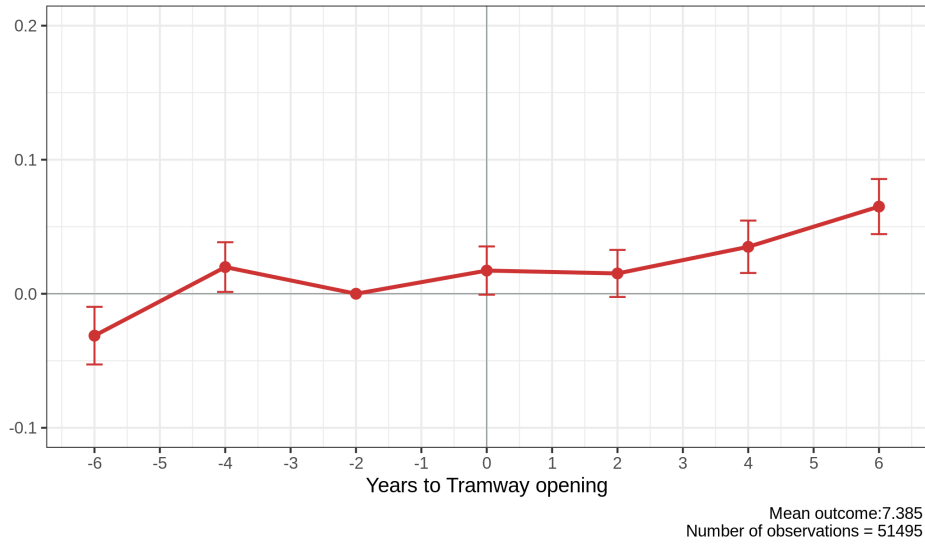
1.5.5 Anticipation or nuisance ? Effect of tramway construction works

As exposed in Section 2, complete pre-works information is given to local inhabitants through a public enquiry procedure, that gives way to the issuing of a *Déclaration d'Utilité Publique* (DUP) by state authorities. This document, which is necessary for any heavy works to be conducted, is generally issued in a mean 3.48 year delay before the tramway entry into service. From detailed information we get on some projects, it appears that construction works usually start right after the DUP is issued. These works typically take three years and imply heavy civil engineering : all energy, water and sanitation networks crossing the planned path of the tramway line must be deviated to avoid supporting the weight of the rail infrastructure; walkways and traffic lanes are usually reshuffled to take into account the presence of the tramway line; a catenary wire must be put in place and electric substations must be built, either in nearby buildings or under walkways, to power the line. Such works could constitute a nuisance for neighborhood inhabitants as well as a direct sign of the upcoming entry into service of the tramway line. We could thus expect anticipation in market capitalisation or evolution of the building stock, or a negative amenity effects on prices or population composition. Absence of anticipation could suggest that investors are not confident in the capitalization of accessibility benefits, which could be actually hampered by (i) persistent bad reputation; (ii) path dependency of neighborhood sorting as exposed empirically by Heblich et al. (2016) on English cities of the industrial era.

Prices The effects of the starting of construction works on prices is unclear. Indeed, construction works constitute an important local nuisance that should lead to a decrease in the housing prices in an hedonic model. However, these works also constitute a clear evidence of the future arrival of a tramway, that could increase value.

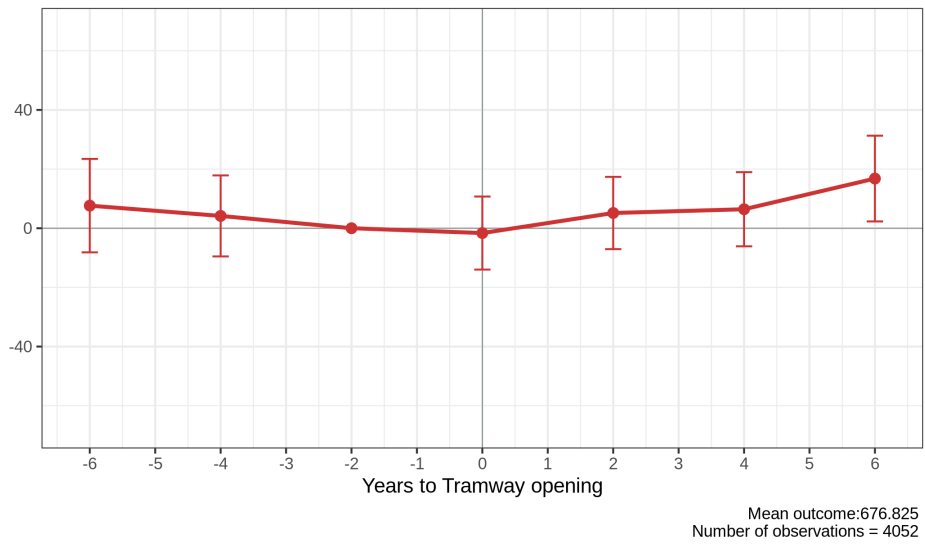
Figure 1-18 reports the results of equation 1.3 with a treatment at the date of the DUP. We do not observe any effect on price before more than 3 years, which is the time-span for the entry of the tramway into service. There is therefore no evidence of anticipation, which contrasts strongly with the existing literature on public transport that established regularly since McDonald and Osuji (1995) that the housing market anticipates the opening of new public transport options. The absence of anticipation constitute evidence supporting the idea of possible 'redlining' of these neighborhoods, that could partly explain their inhabitants persistent difficulties to labor integration even after connection.

Figure 1-18: Prices and construction works



Notes: this graph plot the β_k of equation 1.1; 95% confidence interval
Source: Perval

Figure 1-19: Housing stock and construction works



Notes: this graph plot the β_k of equation 1.2; 95% confidence interval
Source: Filocom

Housing stock As we shown before, we do not find evidence of a change in the housing stock in response to the opening of a tramway stop. We do not find new developments to happen simultaneously with the opening of the tramway line, but 4 to 6 years after. However, developers could have anticipated the opening, since the beginning of the tramway construction works is generally associated with a clear commitment to an opening date. Moreover, the development of new dwellings and the construction works could have been planned simultaneously if the city authorities see the tramway as an opportunity to further develop an area.

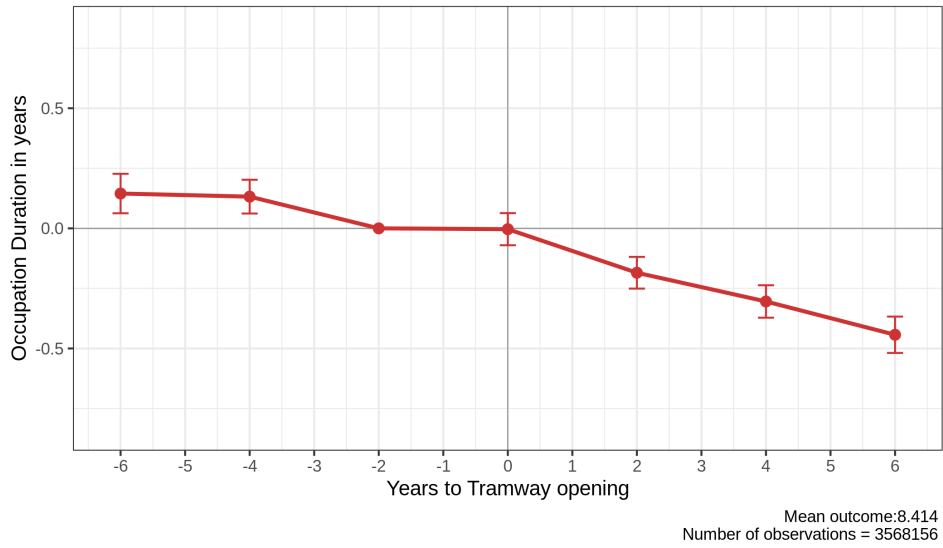
Figure 1-19 reports the results of equation 1.2 with a treatment at the date of the DUP. We do not observe any effect on the housing stock before 6 years, which corresponds actually to the delayed effect we observed on figure 1-19 . There is therefore no evidence of anticipation.

Market activity Even in the absence of any significant rise in prices, market activity may increase if the households most sensitive to disamenities associated to construction works leave to be replaced for instance by households who are anticipating a rise of accessibility or prices after the opening of the line, or

Figure 1-20 reports the effects of the beginning of the works on occupation duration. There is therefore a strong and significant effect of the beginning of construction works on market activity, which is consistent with the small pre-trends observed in figure 1-12. The same specification estimated for different occupation statuses in figure A-6 in appendix A.3 shows that this effect is only visible for owner-occupiers. This is consistent with speculation from owners that would anticipate a rise in prices.

Income Such market activity could lead to a change in population composition, notably in their income. Figure 1-21 reports the effect of the beginning of the works on the new income and suggests no effect. Newcomers that anticipate either a change in prices happen not to be wealthier than the initial population. This constitutes evidence to support the idea of possible 'redlining' of these neighborhoods.

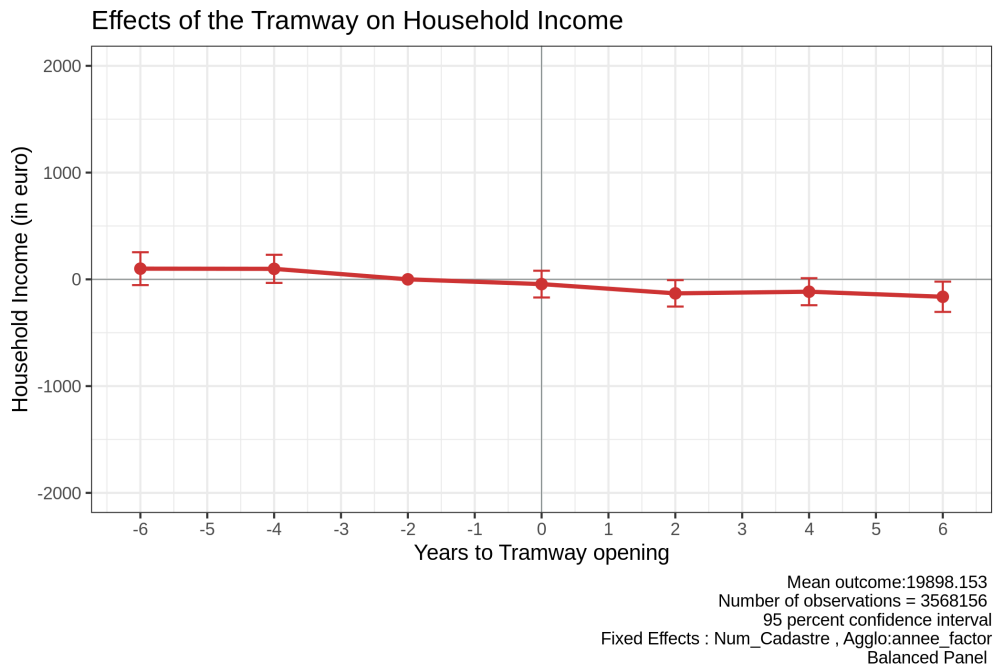
Figure 1-20: Occupation duration and construction works



Notes: this graph plot the β_k of equation 1.2; 95% Confidence interval

Source: Perval

Figure 1-21: Income and construction works



Notes: this graph plot the β_k of equation 1.1; 95% Confidence interval

Source: FILOCOM

1.6 Conclusion

This chapter takes advantage of the construction of tramway networks in most French city in the last 30 years to document the effect of a public transportation infrastructure aiming at connecting the most deprived neighborhoods on those area and their inhabitants. We rely on three administrative data bases with granular geographic precision to compare the evolution of unemployed, housing transactions and housing compositions around the arrival of tramway. To do so, We estimate a staggered difference in difference comparing linked neighborhood with similar neighborhoods in the same city.

The first part of our work focuses on the short term effect of tramway on labor outcomes of the job seekers. We do not find any change in unemployment trajectories between job seekers living in treated and control neighborhoods. This results is consistent for multiple relevant heterogeneity groups and ultimately estimated with great precision living no room for an economically significant effect. This results is particularly interesting through the lens of the spatial mismatch literature, while focusing on a population for which spatial mismatch ought to be particularly acute, we find no reduction of adverse labor trajectories. In fact, inhabitants of the poorest neighborhood face many hurdle in the labor market. If increased accessibility could well be necessary to improve their labor trajectories, our results suggest that it is certainly not sufficient.

The second part of the chapter provides evidences of change in housing price and population composition. It first highlight the amplitude of the accessibility shock brought by a new tramway infrastructure connected deprived neighborhoods. This shock capitalizes in a large local increase of housing prices in connected QPVs. A focus on population evolution after tramway connection allows to get more insights on the beneficiaries of this accessibility shock. Housing market adjustments often result in partial displacement of initial poor tenants following the rent increase, who do not benefit from the infrastructure. Owner-occupiers, by contrast, often migrate but benefit of the accessibility shock through capitalization in their dwelling's price. Social tenants have no incentive to migrate and can benefit from both the accessibility improvement and the peer effects induced by large social diversity. However, this mechanism does not take place in social-housing intensive QPVs, where we observe no in-migration of affluent urbanites.

Taken together, our results underline that even if tramway construction do not translate into better labor outcomes, the gained accessibility *per se* is beneficial to deprived neighborhoods residents if they are not too sensible to housing market adjustments. For policy makers looking forward to integrating social fairness criteria in the design of public transportation, this chapter shows that no benefit for the urban poor can be expected in the short term on the labour market, and that their benefits on the housing market are uncertain and mainly depend on the coupling of such a "social" transportation policy with a comprehen-

sive social housing policy, the amplitude of which depend mostly on the value granted to social diversity, since high density of social housing appears as a cause of 'redlining'.

Chapter 2

Optimal Spatial Policies with Local Public Goods and Unobserved Location Preferences

*“Vivre et travailler au Pays”*¹
Bonnets Rouges (Brittany, 2013)²

2.1 Introduction

Spatial transfers from the central state towards local jurisdictions represents a powerful lever of action in the hands of central authorities to organise the territory. In particular, since these transfers may be necessary to finance large public infrastructure – notably urban transportation systems – they may be key to the continued growth of small cities. Their allocation therefore raises important equity issues : should spatial transfers be decided so that every inhabitant in the actual distribution of population benefits from similar urban amenities, or should spatial policies be used to encourage a more efficient population distribution ? Population mobility and location preferences are obviously key aspects to study to answer these question. In the presence of scale economies in public good production or consumption, the second option would be privileged by an utilitarian planner who would encourage population movements to the large metropolis to take advantage of such scale economies. However, a planner may also take into consideration equity claims for a “right to stay” in

¹This chapter is based on a joint work with Nicolas Jannin.

²*“Living and working locally”*, a 1970’s trade union slogan about early de-industrialization, was revived in 2013 by the *Bonnets rouges*, a social unrest claiming for better spatial equity in central state expenditures and transfers.

low-density areas that should lead to transfers equating effective public good consumption per capita among jurisdictions. Such claims have actually been recently documented in France, notably by Spire (2018) who noted the above-quoted slogan during Brittany's Red Hats (*Bonnets Rouges*) 2013 recent regional social unrest. French central state indeed has a long tradition of using such transfers to shape the spatial distribution of population. Production of local amenities and design of an ideal distribution of population has been coordinated and controlled from 1963 to 2014 by a central state agency, the *Délégation interministérielle à l'aménagement du territoire et à l'attractivité régionale* (Interdepartmental committee for Territorial Organization and Regional Attractiveness) who encouraged the development of non-parisian cities and peripheral regions in a utilitarian perspective notably inspired by theories of the disamenities of agglomeration. This mission evolved with Pasqua (1995) and Voynet (1999) bills that introduced the concept of territorial equity and an *a priori* objective – never met to that day – to keep the differences in resources per capita between local jurisdictions under 20%. Recently, in recognition of the priority given to equity issues, this mission has been reorganized under a novel agency, the *Commissariat Général à l'Égalité des Territoires* (General Commissary for Territorial Equality). The change of terms underlines the deviation from the utilitarian ideal. French spatial transfer policies therefore constitute a striking example of the search for a compromise between utilitarian and equity criterion in the determination of optimal spatial policies. Are French spatial transfers following utilitarian or equity criterion? In the wake of claims for territorial equality, should such a criteria be actually used by central governments?

Public good being by nature at least partly non-rival, it largely benefits from scale economies in consumption. In an utilitarian perspective, such scale economies motivates the existence of spatial policies. Indeed, public good agglomeration forces raise obvious concerns about the efficiency of households' migration decisions. Because migrating households do not internalize their positive impact on cities' tax revenues nor the extra crowding they bring to existing public goods, migration comes with both a positive fiscal externality and a negative congestion externality. If these externalities do not offset each other, there may be room for government transfers that improve everyone's welfare by reaching more efficient population distribution and public good provision. Because agglomeration externalities are spatial in nature, efficient transfers correcting them will be place-based. However, when individuals have heterogeneous preferences for locations, one may fear that the overall effect of spatial taxes always be negative for those taxed residents that are strongly attached to their city. The interplay of geographic preferences with scale economies in local public good consumption thus likely determines which spatial policies are efficient and equitable.

The economic geography literature has given location preferences various interpretations, from capturing mobility frictions to representing genuine geographic tastes. While

mobility costs have decreased historically³ and may have become negligible over one's lifetime in developed countries, genuine preferences capture richer attachments to locations – e.g. to birthplace, social or natural amenities – and need not vanish in the long run. Indeed as highlighted by Lévy et al. (2018), unprecedented spatial liberty in contemporary high-mobility societies likely led to the prevalence of such idiosyncratic criteria in residential choices. Notably, Fauchille (2016) and Lévy and Fauchille (2017) showed through two inquiries in France and Switzerland that a very large majority of households mention their residence as an idiosyncratic choice among a wide range of available options, from city-centers to low-density peripheries. This would lead to interpreting them in this context as genuine location preferences.

The coexistence of persistent location preferences and scale economies in local public good consumption may help explain revived concerns for "spatial justice" and feelings of tax inequity in low-density areas⁴, a recent expression of which may be France's 2018 Yellow Vests (*Gilets Jaunes*) movement. Geographic transfers can achieve social justice goals, typically by redistributing towards low-income areas⁵.

If they are usually invoked to justify intervention on efficiency grounds, agglomeration forces may offer an additional justification for redistributive spatial policies. Individuals that are strongly attached to places destined to be low-density may consume less public goods than residents of high-density places when net agglomeration externalities are positive, sometimes for similar individual contributions to local budgets. If society values some form of horizontal equity for instance – e.g. workers with similar incomes or contributions should get similar public good benefits –, means-tested taxes and transfers will in general not be sufficient to carry out redistribution. Indeed, heterogeneity in population density conditional on income will require transfers that are expressly place-based to redistribute from high- to low-density places. Whether idiosyncratic geographic attachments and their welfare consequences are to be compensated for is obviously a highly sensitive question.

Because the government is unable to observe location preferences, both efficient and equitable policies are bound to be partly place-based. Spatial transfers create direct winners (infra-marginal residents of subsidized places) and losers (infra-marginal residents of taxed places). They symmetrically create indirect losers and winners through net agglomeration gains and changes in profits. Since the government cannot offer compensating transfers to potential losers without undoing its spatial policies, net gains from spatial transfers must be everywhere positive if welfare is to improve for everyone. It is then natural to investigate

³See Combes and Lafourcade (2005).

⁴Using data on 2900 French households, Spire and Bernard (2019) document that, *ceteris paribus*, the probability to view the tax system as unfair is 35% to 68% larger for inhabitants of small cities (2,000 to 20,000 inhabitants) than for inhabitants of large cities (200,000 inhabitants and more) and 40% for rural areas overall.

⁵Means-tested taxes and transfers can be viewed as implementing geographic equity objectives when location determines the wage (see Albouy 2009).

the circumstances under which Pareto-improving policies exist.

In this chapter, we study the welfare implications of the interplay between public good agglomeration economies and heterogeneous location preferences. We first present new stylized facts on scale economies in the consumption of local public goods by exploiting a unique combination of longitudinal administrative datasets on French cities with detailed information on municipal financial accounts, detailed tax revenues, local income data, municipal population and land use data over the period 2002-2014. Importantly and unlike existing studies, our data contain exact public asset position in addition to yearly public spending. Per capita public spending decreases with population with an elasticity of -0.32 . Although these patterns are better interpreted as associations in the data rather than causal effects, they suggest substantial gains from density through the public good consumption amenity.

We then develop an economic geography model with endogenous local public goods where mobile workers have heterogeneous preferences for various locations. As we wish to emphasize the spatial nature of efficiency and equity concerns, we assume away differences in other kinds of preferences, skills, endowments or ownership. Workers consume a freely traded private good and a local non-traded private good such as housing. Local jurisdictions provide public goods according to the outcome of a unanimous vote from residents. All three goods are supplied by locally competitive sectors. To have our model match empirical regularities, we assume that jurisdictions fund public goods through lump-sum taxes on resident households and property taxes on the outflow of local profits accruing to landowners nationwide. The central government taxes and redistributes across places and funds a national public good that depends on output produced in various locations. In our framework, exogenous local productivity and residential amenities stand for all dimensions of physical geography.

We give a sufficient statistics characterization of the spatial policies implementing all second-best allocations in this setup. We assume that the government does not observe location preferences. As a result, it is unable to offer type-specific lump-sum transfers and is limited to distortive place-based transfers. Importantly, we also assume that the welfare-enhancing nature (in a Pareto sense) of a potential reform is evaluated in the status-quo in which different workers already live in different places, a criterion we believe bears more political relevance than an ex-ante “veil of ignorance” approach⁶. Heterogeneity in location preferences opens the door to spatially differentiated welfare effects of spatial policies and to geographic infra-marginal winners and losers⁷. Since the government observes res-

⁶Precisely, we adopt an ex-post rather than ex-ante Pareto criterion. The ex-ante criterion neutralizes equity concerns by assuming that identical agents draw random preferences and that the planner’s objective is to maximize the common expected utility. The ex-post criterion assumes that reforms are evaluated from observed situations with heterogeneous agents already living somewhere who will be differently affected by spatial policies. The first approach weights equally all agents, while the second allows the planner to put different weights on different locations in the status-quo.

⁷In the standard framework with homogeneous preferences, discrepancies in living standards between cities

idential choices, it may weight differently these different groups of workers according to their status-quo location, which will be determinant for the existence of Pareto-improving reforms. We show that efficient transfers should be directed towards places where per capita public spending is higher, and away from places able to capture larger per capita amounts of local profits.

We then offer a fully computable efficiency test for observed allocations. We show that high enough preference heterogeneity makes the social cost of spatial redistribution encouraging migration too large compared to the agglomeration benefits such that Pareto-improving policies may not always exist in the laissez-faire economy. We then apply our framework to French data by investigating the efficiency of the current French transfer system. Among EU countries, France is the most striking example of large density discrepancies between urban centers and their peripheries and it has been documented that a large share of its GDP is redistributed from high to low density areas (Davezies 2012). We empirically illustrate that the efficiency diagnosis an economist would make strongly depends on the amount of preference heterogeneity she believes led to the observed situation, and that ignoring location preference heterogeneity mistakenly leads to advocating higher net transfers in already dense and rich places. This speaks in favour of a better accounting of the normative implications of geographic preferences.

Finally, we carry out a revealed preference exercise by empirically investigating the structure of the social welfare weights implied by the current spatial tax and transfer system. Our results suggest that the French planner is roughly utilitarian, but that it further compensates low-density areas in a way that is orthogonal to utilitarianism. This gives support to the idea that the government designs transfers tackling horizontal inequity in access to public goods, which we argue arises from the interplay of unequal density gains from scale economies and heterogeneous location preferences.

Main contributions

This chapter first contributes to the public finance literature on tax competition, public good provision and efficient spatial policies. In a seminal paper, Flatters et al. (1974) provide a formal treatment of efficient population distribution with homogeneous households and locally pure public goods financed by head taxes on residents. Efficient transfers should be set to equalize per capita contributions to local budgets. As for heterogeneous preferences, the authors “argue somewhat heuristically without such an analysis that the basic results derived from the simplest case (...) carry over to this situation” although they carefully highlight the difficulty for the government to implement type-specific taxes and transfers when these preferences are not observed. A rich literature singled out other inefficiencies in local

are arbitrated away by migration pressures so that utility is everywhere equal.

public good provision, such as “rent-sharing” migration externalities when local profits are taxed and paid out to residents and externalities from taxing local profits accruing to residents of other jurisdictions (see Wildasin 1980; Starrett 1980; Boadway and Flatters 1982; Boadway 1982; Watson 1986; Zodrow and Mieszkowski 1986). More recently, Albouy (2012) characterizes efficient transfers in the presence of public good externalities when the type of heterogeneous households (skill) is observed. The author assumes small if not zero public good scale economies so that spatial transfers predominantly correct the profit taxation migration externality.

More generally, this chapter contributes to the urban and economic geography literature on spillovers (Ahlfeldt et al. 2015b; Diamond 2016) and on optimal spatial policies (Fajgelbaum and Gaubert 2018; Albouy et al. 2018). We also relate to the literature on spatial misallocation (Desmet and Rossi-Hansberg 2013; Hsieh and Moretti 2019) and misallocation due to specific spatial policies like state or federal income taxes or firm subsidies (Albouy 2009; Fajgelbaum et al. 2015). In particular, Fajgelbaum and Gaubert (2018) characterize efficient transfers in a general framework encompassing production and residential agglomeration externalities that may vary by type (e.g. skill or tastes) and find that the laissez-faire is generically inefficient. However, their result crucially hinges on the government’s ability to offer city-type specific transfers which evacuates the equity-efficiency trade-off⁸.

We also relate to the fiscal federalism literature examining the optimal balance of powers between central and local governments in the presence of local externalities pioneered by Tiebout (1956) and followed by Oates (1972), Bewley (1981) and Gordon (1983) among others.

This chapter contributes to the empirical literature studying the determinants of local public good demand among which population density and urban sprawl. The seminal works of Borcherting and Deacon (1972) and Bergstrom and Goodman (1973) develop simple frameworks to disentangle the various forces driving local public spending. The authors typically find small if not zero net agglomeration gains in public good provision, although their cross-sectional identification, data limitation and incomplete micro-foundation warrants cautious interpretation of the results. A rich cross-sectional literature followed (Ladd 1992, 1994; Carruthers and Ulfarsson 2003; Solé-Ollé and Bosch 2005; Hortas-Rico and Solé-Ollé 2010) which finds negligible gains from more population, but does find that urban sprawl increases public good provision costs. However, Oates (1988) argues that cross-sectional studies severely under-estimate the impact of population because of threshold or “zoo” effects. Indeed, while more populated cities divide public spending among a larger pool of taxpayers and tend to spend less per capita, they also tend to spend more per capita because they reach the critical mass that makes possible the financing of large indivisible

⁸In an extension of their framework to unobserved preferences, Fajgelbaum and Gaubert (2018) consider that ex-ante homogeneous workers draw random location preferences and are equally weighted by the government, which evacuates equity concerns by letting the efficient allocation be the one maximizing the common (expected) utility.

facilities, like zoos, or more interestingly for our study, heavy public transit networks. This effect may have researchers conflate public good congestion with the existence of fixed costs, thereby mistaking agglomeration economies for agglomeration dis-economies.

Finally, one can view the normative arguments in this chapter as a geographic application of the literature on optimal taxation with discrete occupations (e.g. Piketty 1997; Saez 2002) and of normative public economics studying the ethics of redistributive policies such as Fleurbaey and Maniquet (2011) or Saez and Stantcheva (2016).

2.2 Data

We combine a series of rich administrative datasets obtained from various official sources. Detailed description of variable construction will be given in the text when needed. For data on local public spending and government subsidies, we use comprehensive municipal financial accounts (*Balance Comptable des Communes* henceforth BCC, used in Jannin and Sotura 2019) obtained from the French Department of Finance for all 36,000 French municipalities and all 2,000 municipal federations (or MF, which are administrative groups of neighbour municipalities) they belong to, for all years between 2002 and 2016. This rich dataset provides information on various spending items, asset positions, local tax revenues, user and business fees as well as various subsidies and transfers received from higher jurisdictions such as *départements* (counties), *régions* (provinces), the government or the European Union.

In order to have an in-depth understanding of local tax shares supported by residents, landowners and businesses, we supplement BCC with administrative local tax data (*Recensement des Éléments d'Imposition à la Fiscalité Directe Locale* henceforth REI) for every year from 2002 to 2016. REI contains data on all tax bases, rates and revenues at the municipal and municipal federation level for local household property and residence taxes, as well as local property and non-property business taxes.

We also use detailed data on natural and urbanized land area at the municipal level for each year between 2008 and 2014 from a government website managed by the French Ministry of Environment⁹. We construct a database on average m^2 house prices for every even year between 2000 and 2014 at the municipal level, combining housing transactions databases from the notary offices (BIEN for the Parisian region and PERVAL for the rest of France), and assume that house transaction prices are the net present value of unobserved rents.

We further exploit an administrative database on municipal population and housing stock (*Fichier des Logements par Communes* henceforth FILOCOM) available every two years over 2000-2014. We use it to construct our yearly municipality-level population measure as well as various useful indicators such as the share of owner-occupiers and alternative mea-

⁹See <https://datafoncier.cerema.fr>.

asures of urban sprawl. We also obtained access to yearly income tax data at the municipality level over 2003-2015 (*Impôt sur le Revenu par Commune* henceforth IRCOM) giving total municipal labor and pension income as well as total national income taxes paid (including tax credits to low-income households and various deductions).

We gather a series of publicly available datasets at the micro and national levels. We use census data to get municipality-level information on socio-demographic characteristics – age profile, education, industry, etc. – for years 1999, 2008 and 2013. We exploit data from the National Statistical Institute on various municipality geography indicators (municipal federation membership, history of municipal boundary changes, etc). Finally, we use higher-level yearly data on national accounts to measure aggregate capital income (including implicit rental income) to supplement our income tax data.

One objective of this chapter is to highlight the purely geographic determinants of unequal access to public goods. We construct a set of relevant variables netted of socio-demographic composition effects using hedonic regression methods. The universe is all mainland municipalities experiencing no boundary change – i.e mergers or separations – between 2002 and 2014, that is almost all of them barring a few percents. For outcome y_i at the *municipal* level we run

$$\ln y_{it} = X_{it} \cdot \beta_a + \lambda_{jt} + \epsilon_{it} \quad (2.1)$$

where X_{it} is a set of municipal composition characteristics – share of the population at various ages and education levels, share of university educated executives and share of owner-occupiers –, β_a is a metropolitan area specific vector of coefficients and λ_{jt} a municipal federation \times year fixed effect. We then use $\hat{\lambda}_{jt}$ and $\hat{\beta}_a$ to predict mean outcome at the municipal federation \times year level, replacing X_{it} by mean composition at the national level \bar{X}_t . Finally, we take the exponential of this prediction to obtain the composition-neutral outcome. We run this procedure on all relevant intensive variables such as per capita items in financial accounts, per capita local wages, pensions, national and local taxes, m^2 housing consumption – which we then scale back up by population size – and m^2 house prices.

2.3 Stylized Facts on Public Good Agglomeration Economies

To motivate our theoretical discussion, we present some stylized facts suggesting the existence of scale economies in the consumption of local public goods. Exploiting the panel datasets presented in section 2.2, we provide new evidence on the relationship between population density and per capita public spending and argue that existing evidence likely understate public good agglomeration economies.

2.3.1 Raw Patterns

In order to focus on scale economies separately from other local externalities¹⁰ and to account for spending by the municipal federation layer on top of municipal spending, we first consolidate all municipality variables at the municipal federation level¹¹ which leaves us with around 2,000 observations per year. Scale economies in public good consumption imply that public spending should increase less than one-for-one with population, hence we expect to see a decreasing relationship between per capita public spending and population. Figure 2-1 examines this naive cross-sectional relationship in the last available year 2014. In both panels, the explanatory variable is log population in the municipal federation. The dependent variable is log current expenditure per capita in Panel A and log capital expenditure per capita in Panel B. Current expenditure are constructed as the sum of annual staff expenditure, maintenance spending, payments for external services and operating subsidies to third parties. Capital expenditure – a *stock* position – are defined as the book value of durable facilities and constructed as the sum of all public assets minus the raw value of the land and financial assets. They include schools, transportation infrastructure, parks improvements, sports facilities, museums, art collections, investment subsidies to local clubs, etc.

Both panels of Figure 2-1 tell a similar story. Spending per capita follows a U-shaped pattern, overall slightly increasing with population for current spending and decreasing with population for capital expenditure. These cross-sectional patterns are reminiscent of results in Ladd (1992) and Ladd (1994). They are in line with overall agglomeration elasticity estimates being close to zero in existing cross-sectional studies, all the more since public capital is never properly accounted for. However, interpreting them through the prism of agglomeration (dis-)economies is biased in several ways. First, Oates (1988)'s "zoo effect" may explain in large parts why spending increases again at higher population levels as the *range* of services widens when cities reach critical population sizes¹². Then, while increasing population on a given urban land area is expected to increase population density and *decrease* the per capita cost of public goods, increasing population holding constant population density is expected to *increase* spending on local public goods as it gets more costly to maintain a given level of public goods benefits for new residents at the fringe of the city (see Carruthers and Ulfarsson 2003; Hortas-Rico and Solé-Ollé 2010). Last, local costs and per capita revenues

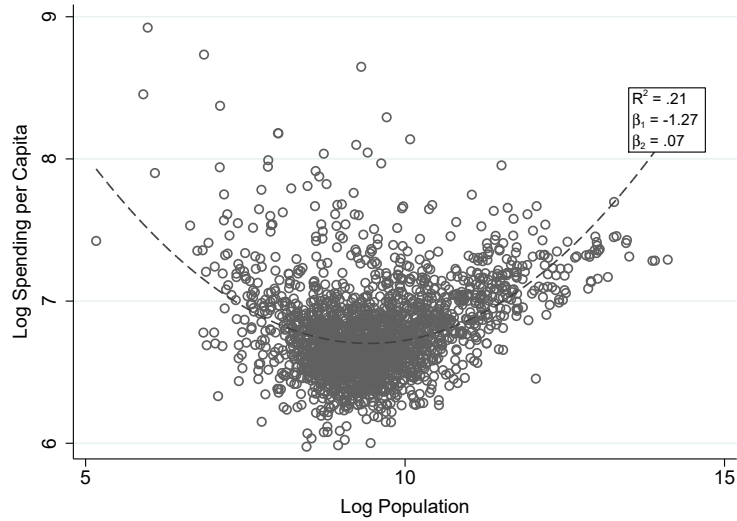
¹⁰Jannin and Sotura (2019) estimate strong public good spillovers between municipalities within municipal federations.

¹¹Membership to a municipal federations is not constant during the period covered by our panel. To circumvent this problem, we assign each municipality to its 2015 MF for the whole period when aggregating data at the federation level. This makes the consolidation of municipal and MF financial accounts possible because between 2002 and 2015, MF membership always evolved vertically towards more integration of 2002 blocks of municipalities. That is, isolated municipalities joined existing federations, formed federations with other isolated municipalities and some federations merged between them. No federation split, and almost no municipality changed membership. The underlying assumption is, for example, that an isolated municipality in 2006 already benefited from the total public spending – of both MF and member municipalities – of the MF it joined, say, in 2011.

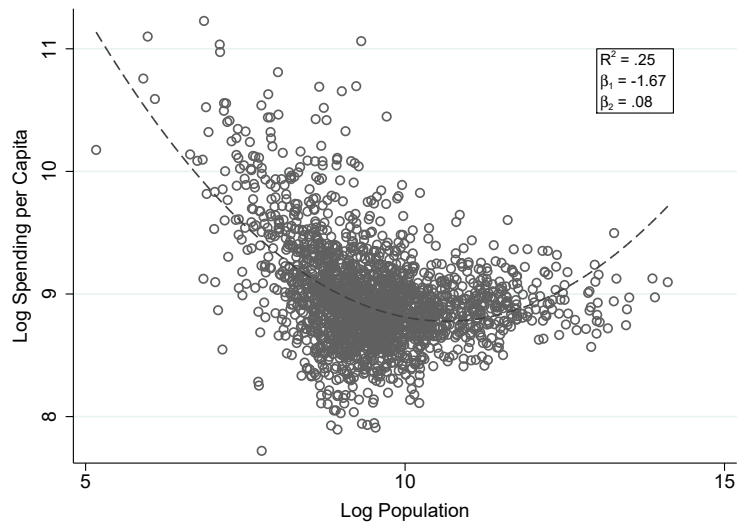
¹²The needs of populations in larger cities may also systematically differ from those of small city residents.

Figure 2-1: Spending per Capita vs Population

(a) Current Expenditure



(b) Capital Expenditure



Note: These graphs plot log spending per capita against log population across MFs in 2014 and a quadratic fit for which we report the coefficients and the R^2 . Current expenditure are the sum of yearly staff expenditure, maintenance spending, payments for external services and operating subsidies to third parties. Capital expenditure are the current book value of durable facilities and are the sum of all public assets such as schools, transportation infrastructure, parks improvements, sports facilities, museums, art collections, investment subsidies to local clubs, minus the raw value of the land and financial assets.

are expected to increase with density which bids up both local prices and demand hence increases per capita public spending.

2.3.2 Descriptive Regressions

Disentangling scale economies from the other mechanisms set out above would require causally estimating a fully-fledged quantitative model with exogenous migration shocks. Instead, we remain descriptive and provide simple regression evidence. All mechanisms mentioned above are expected to bias the interpretation of Figure 2-1 in the same way by making spending per capita increase again at higher population levels. Below we focus on smaller population variations to absorb discrete changes in the range of provided public goods and explore the role of urban sprawl.

As mentioned, the bundle of local public services is a mixture of yearly services (maintenance, subsidies to associations, staff payroll, etc.) and durable facilities (parks, transports, sports facilities, etc.). We account for this dual structure by assuming a Cobb Douglas shape for local public goods

$$\mathbb{G} = \frac{G_s^{1-\psi} G_f^\psi}{N^\kappa} \frac{1}{T^\gamma} \equiv \frac{G}{N^\kappa} \frac{1}{T^\gamma} \quad (2.2)$$

where G_s and G_f are the (unobserved) physical outputs, respectively the quantities of durable facilities and yearly services introduced above, and N is jurisdiction population. Urban sprawl T alters the usefulness of physical outputs at speed γ . Holding constant population size, more residential scatteredness diminishes how much households benefit from given public good outputs. We measure urban sprawl as the km^2 of urbanized land area in the municipality¹³. Parameter $\kappa \in [0, 1]$ is the speed at which public good quantities get congested by population N holding constant the scatteredness of dwellings in the MF, and $1 - \psi$ is the relative importance of durable facilities over annual services¹⁴. Assuming a price p_j^G for local public goods, per capita spending is $x_j^G = \frac{p_j^G G_j}{N_j}$.

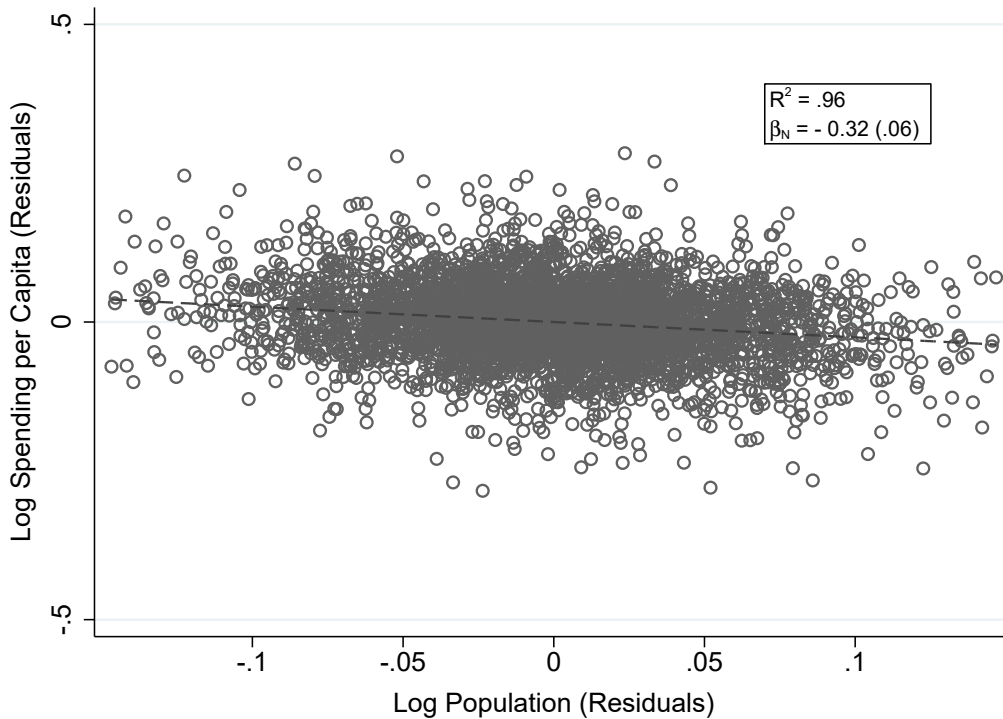
We first investigate the within-MF relationship between public spending and population. This should strongly attenuate the “zoo effect” as the range of services provided in a MF over our time period is unlikely to evolve dramatically. To mitigate measurement problems raised by looking at time variation (see Combes and Gobillon 2015) and problems raised by potential short-term rigidity in the supply of local public goods¹⁵, we look at the longest possible time difference allowed by our data i.e. the 12-year long difference between 2002

¹³Unlike Hortas-Rico and Solé-Ollé (2010), we control for absolute and not per capita urbanized land area. They are interested in the impact of population density on spending holding constant population size, while we are interested in the impact of population size on spending as measured by parameter κ holding constant the spatial extent of urbanization (see the discussion about density vs city size in Ahlfeldt and Pietrostefani 2019b).

¹⁴Appendix B.2.3 strongly supports this constant share assumption with $\hat{\psi} \approx 0.78$.

¹⁵Full rigidity would have per capita spending mechanically decrease one-for-one with population.

Figure 2-2: Spending per Capita vs Density (within regressions)



Note: This graph plots the log of our public spending index against log population at the MF level, both variables being first residualized with respect to two-way fixed effects using years 2002 and 2014, and a linear fit. We report the coefficient and R^2 of the two-way fixed effect model (2.3).

and 2014¹⁶. Unfortunately, data limitations prevents us to also look at changes in urban sprawl over 2002-2014¹⁷. We come back to urban sprawl in a separate specification. We run the following minimal specification aimed at capturing smaller changes in population over time across our 2,000 municipal federations using only extreme years 2002 and 2014

$$\ln x_{jt}^G = \beta_N \ln N_{jt} + \alpha_j + \lambda_t + \varepsilon_{jt} \quad (2.3)$$

where α_j and λ_t are MF fixed effects and year fixed effects respectively. Figure 2-2 visually inspects the relationship between log per capita spending and log population summarized by coefficient β_N , that is after both variables have been residualized with respect to α_j and λ_t . Strikingly, log per capita spending linearly decreases with log population with a reduced-form elasticity of -0.32 (0.06), invalidating the naive interpretation of Figure 2-1.

¹⁶Results would be quite similar using panel data, as showed in tables B.4 and B.5 in appendix B.3

¹⁷We also ran the specification over 2008-2014 adding log sprawl. As expected, the population coefficient is larger (0.43 (.07)) due to the shorter time-span, and that of urban sprawl is zero and insignificant (.00 (.04)) due to insufficient within-MF variation over time.

As complementary evidence, we run the following specification aimed at capturing density changes in a cross-sectional setting using only the last year 2014 across our 2,000 municipal federations. This time, we look at how per capita spending changes with both population and urbanized land area

$$\ln x_j^G = \beta_N \ln N_j + \beta_T \ln T_j + \sum_k \lambda_k^N + \varepsilon_j \quad (2.4)$$

where T_j is the urbanized land area in km^2 and the λ_k^N are dummies representing discrete MF population size groups. MF size groups help capture in a crude way discrete changes in the range of provided services, while residual population variation captures proportional scale economies. Results are given in Figure 2-3 for benchmark population steps of 13,500 inhabitants corresponding to 100 groups¹⁸. The reduced-form elasticity between per capita spending and population is -0.31 (0.04) and close to that of Figure 2-2. Per capita spending is also positively associated with urban sprawl conditional on population, with an elasticity of 0.13 (0.03). Overall, these results show that density is negatively associated with per capita public spending, suggesting scale economies in local public good consumption.

2.3.3 Preliminary Comments on Welfare Implications

Strong public good agglomeration economies have important welfare implications. To guide our intuition on the impact of agglomeration economies on spatial inequities, it is useful to compare the distribution of per capita local public spending and that of local public spending effectively enjoyed by residents. Panel (a) of Figure 2-4 shows the maps of per capita local public spending x^G , while panel (b) captures effective local public good availability obtained by discounting public expenditure by N^κ with an example value for congestion parameter of $\kappa = 0.5$. While per capita public spending is largely concentrated in mountainous and low-density areas, effective public good is much more evenly distributed in this example.

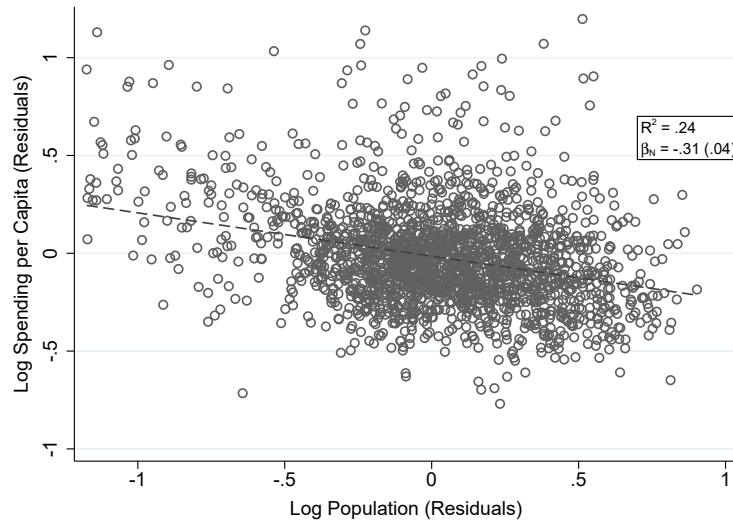
The only remaining pattern seems to be the concentration of effective public goods in large cities that may be explained by large indivisibilities in public goods financing – whose relevance for French municipal federations has been evidenced by Frère and Paty (2011) –. The apparently even distribution among the other locations suggest that the French spatial redistribution scheme embodies collective preferences for horizontal equity, very present in the French political discourse with the concept of "territorial equity" (*Egalité des Territoires*).

Thus, factoring in public good agglomeration economies dramatically changes the perceived spatial distribution of local public good consumption. A fully-fledged economic geography model helps clarify these intuitions in a more systematic way by accounting for

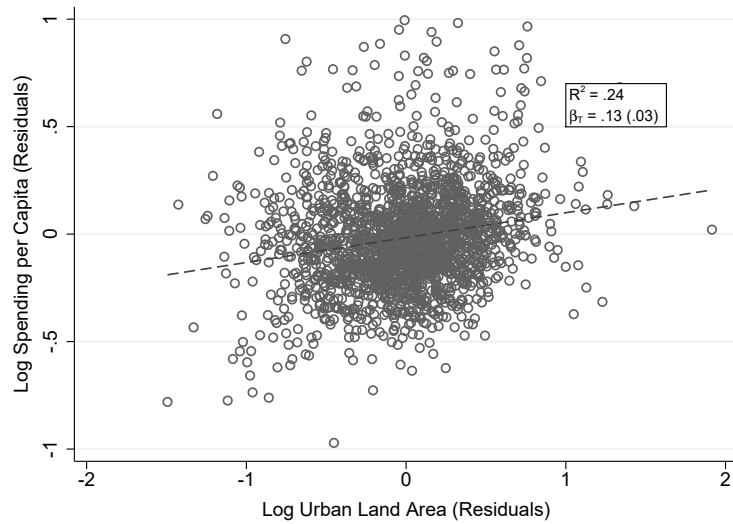
¹⁸Coefficient for urban land area is unchanged as we change the number of groups. As expected, coefficient for population varies between -0.22 (0.04) with 50 groups to -0.42 (0.09) with 500 groups as we further attenuate the zoo effect, and is stable beyond.

Figure 2-3: Spending per Capita vs Density (cross-sectional regressions)

(a) Spending per Capita vs Population (constant urban land)



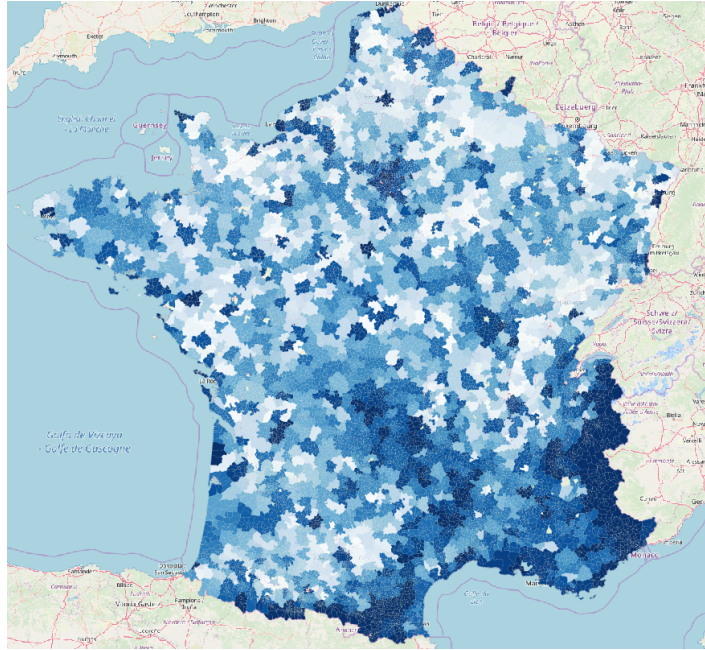
(b) Spending per Capita vs Urban Land Area (constant population)



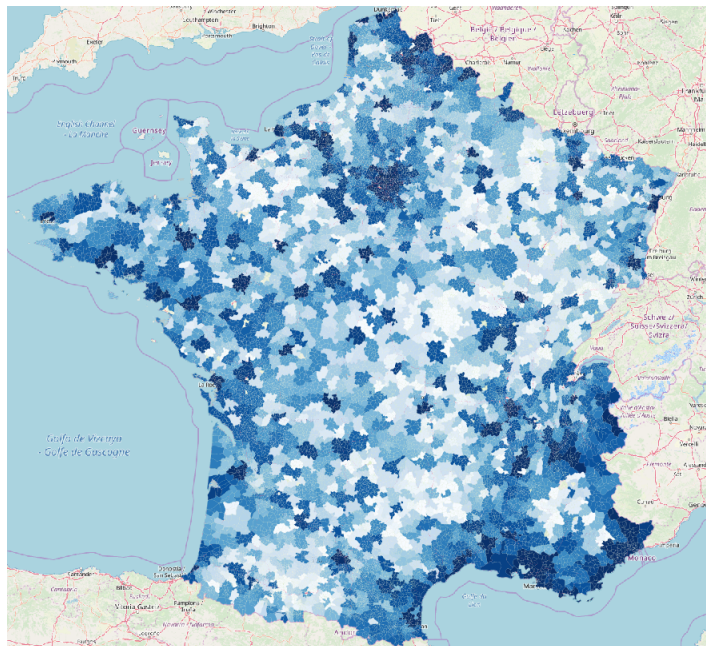
Note: These graphs plot log public expenditure per capita x^G against log population after residualizing both with respect to 100 city size dummies and log urban land area, and log public expenditure per capita against log urban land area after residualizing with respect to 100 city size dummies and population, with linear fits. Observations are the MFs in 2014. Coefficients and R^2 are that of model (2.4).

Figure 2-4: Per Capita Spending vs Effective Public Goods

(a) Per Capita Public Spending



(b) Effective Public Goods ($\kappa = 0.44$)



Note: These maps show percentiles of public spending per capita in (a) and of effective local public goods in (b). Effective public goods are obtained by multiplying per capita spending by $N^{1-\kappa}$.

efficiency and equity concerns more generally.

2.4 Economic Geography Model with Local Public Goods

Motivated by the evidence of section 2.3, we develop a Rosen (1974) and Roback (1982) type spatial equilibrium model with endogenous local public goods subject to agglomeration economies. The framework builds on the rich literature studying efficient population distribution (e.g. Flatters et al. 1974; Albouy 2012; Fajgelbaum and Gaubert 2018) and features the – we argue – more realistic assumption that idiosyncratic location preferences are heterogeneous and unobserved. We emphasize that these preferences need not disappear in the long run as they typically capture more than mobility frictions. Since this chapter wishes to highlight the spatial nature of efficiency and equity concerns in this context, the framework is kept simple by assuming that workers are homogeneous but for location preferences. Obviously, we could enrich the model with observed skills. As long as there is unobserved heterogeneity in location preferences conditional on skill, the arguments below carry through¹⁹.

The model works as follows. There are J heterogeneous jurisdictions indexed by j . There is a continuum of workers indexed by i , homogeneous in everything except location preferences. Workers freely choose the city where they both live and inelastically supply one unit of labor. They consume a freely traded good, a non-traded good (e.g. housing) and local non-traded public goods that are subject to agglomeration economies. All these goods are supplied by locally competitive sectors.

Demand for local public goods in each jurisdiction is the outcome of a unanimous vote involving its current residents. Jurisdictions compete between them through residence-based and source-based taxes. All households living in a given jurisdiction are liable to a residence-based head tax. Source-based taxes are property taxes levied on the outflow of local profits accruing to landowners nationwide.

Workers also consume a national public good supplied by the central government. We assume that the latter is a Stackelberg leader i.e. is able to commit to central policies that are determined prior to local governments' and workers' choices. The government taxes and transfers income across locations and supplies the national public good which is produced using output from different cities. Sections below describe how the equilibrium is determined in this setup.

¹⁹Figure B-3 in Appendix B.3 further justifies our focus on geography by showing the distribution across municipal federations of a Theil index capturing skill sorting, which is very low in France over the period studied.

2.4.1 Central Government

A national public good \mathcal{G} ($\{\mathcal{O}_j\}_j$) is supplied by the central government using a combination of local outputs $\mathcal{O}_j = F^{\mathcal{O}}(L_j^{\mathcal{O}})$ produced using local labor. The government makes local hiring decision $L_j^{\mathcal{O}}$ that will be paid the equilibrium local wage w_j , to produce a target level of \mathcal{O}_j in each jurisdiction. Spending on local labor is financed by a general tax and transfer scheme $\{T_j\}_j$ which also corrects migration externalities and redistributes between places in a zero-sum fashion.

Central policies $\{\mathcal{O}_j, T_j\}_j$ are considered fixed by workers and local governments in the spatial equilibrium described below. The government chooses $\{\mathcal{O}_j, T_j\}_j$ by backward induction among the set of policies that will make the central budget hold in equilibrium:

$$\sum_j N_j T_j = \sum_j L_j^{\mathcal{O}} w_j \quad (2.5)$$

where N_j is population in city j .

2.4.2 Demand for Cities

Worker i chooses to live in the city that maximizes her welfare. Her utility is

$$u_i = \max \{v_{ij}\}_j \quad (2.6)$$

where v_{ij} is the utility level that i gets when living in j . Let's introduce our first structural assumption. We impose that utility break down into a city component v_j indexed by j because of differences between locations in exogenous residential amenities, and an idiosyncratic individual-city specific term μ_{ij} that contributes in a multiplicative fashion i.e.

$$v_{ij} = v_j \mu_{ij} \quad (2.7)$$

City utility v_j depends on the consumption of the traded good c_j , the private non-traded good h_j , the local public good G_j and the national public good \mathcal{G}

$$v_j = v_j(c_j, h_j, G_j(G_j, N_j), \mathcal{G}) \quad (2.8)$$

with a slight abuse of notations. Note that (2.8) imposes that all workers in a given city consume the same amount of traded, non-traded and local public goods. Indeed, workers have homogeneous tastes and skills, and the government cannot offer ij -specific transfers since types are unobserved. In addition, local public goods are assumed locally non-excludable so that all residents of j equally enjoy G_j . We stay general and let $G_j(G_j, N_j)$ depend on total physical output G_j and population N_j contributing to output congestion. Importantly, we

assume that local land policies are such that urban sprawl is fixed over time so that density and population size are equivalent in our framework.

Type- i workers are fully characterized by location preferences $\{\mu_{ij}\}_j$. They are naturally thought of as representing one's attachment for one's city of birth or personalized enjoyment of a city's natural amenities. Section 2.6 discusses how the interpretation of μ_{ij} is central in shaping social preferences. The second structural assumption we make is that the logarithm of idiosyncratic preferences $\ln(\mu_{ij})$ be i.i.d across cities and workers and distributed Type-1 Extreme Value $(0, \sigma)$. The share of workers demanding to live in city j upon observing $\{v_k\}_k$ is then

$$N_j = \frac{v_j^{1/\sigma}}{\sum_k v_k^{1/\sigma}} \quad (2.9)$$

where $\sigma \in]0, \infty[$ captures the amount of heterogeneity in location preferences.

2.4.3 Demand for Private Goods

Conditional on living in j , workers

$$\max v_j(c_j, h_j, \mathbb{G}_j(G_j, N_j), \mathcal{G})$$

over $\{c_j, h_j\}$ subject to their budget constraint

$$p c_j + r_j h_j = w_j + \Pi + T_j - \tau_j^h \quad (2.10)$$

where p and r_j are the prices for traded and non-traded goods respectively, w_j is the local wage and Π is total net profits. As detail below, total net profits are redistributed equally to all workers which is why Π has no subscript. T_j is the net per capita transfer from the central government and τ_j^h is the head tax set by the local government, both taken as given by workers. Private optimization yields the usual first-order condition

$$\frac{\partial v_j}{\partial c_j} r_j = \frac{\partial v_j}{\partial h_j} p \quad (2.11)$$

2.4.4 Supply and Ownership

Since there is no individual heterogeneity other than location preferences, all workers living in j receive the same wage w_j .

Supply of the traded good The national good Y_j is locally produced using labor L_j^Y with constant or diminishing returns – because of a fixed factor e.g. land – and heterogeneous local productivity. Competitive firms' labor demand and traded good supply maximize profits

given local wage w_j and national price p

$$Y_j = F_j^Y(L_j^Y) \quad \text{and} \quad w_j = p \frac{dF_j^Y}{dL_j^Y} \quad (2.12)$$

Housing supply The local non-traded good H_j is produced using labor L_j^H with diminishing returns – because of fixed land – by locally competitive firms maximizing profits given w_j and local house prices r_j

$$H_j = F_j^H(L_j^H) \quad \text{and} \quad w_j = r_j \frac{dF_j^H}{dL_j^H} \quad (2.13)$$

Local public good supply Non-traded public good output G_j is locally produced using labor L_j^G with constant or diminishing returns by competitive firms maximizing profits given w_j and local price p_j^G

$$G_j = F_j^G(L_j^G) \quad \text{and} \quad w_j = p_j^G \frac{dF_j^G}{dL_j^G} \quad (2.14)$$

Ownership structure We assume that land is the residual claimant of local profits and that land ownership is evenly distributed among households. All households hence own the same fraction of total net profits. Total net profits are the sum of local profits accruing to land ownership net of local property taxes

$$\Pi = \sum_j \Pi_j (1 - \tau_j^p) \quad (2.15)$$

where

$$\Pi_j = p Y_j + r_j H_j + p_j^G G_j - w_j (L_j^Y + L_j^H + L_j^G) \quad (2.16)$$

is the outflow of local gross profits accruing to landowners nationally and τ_j^p is the local property tax.

Market clearing We complement equilibrium equations with market clearing conditions. Local labour market must clear i.e.

$$L_j^Y + L_j^H + L_j^G + L_j^O = N_j \quad (2.17)$$

where the elements of $L_j \equiv \{L_j^Y, L_j^H, L_j^G, L_j^O\}$ are defined above. The condition for local housing market clearing is

$$H_j = N_j h_j \quad (2.18)$$

Finally, the market for the traded good clears i.e.

$$\sum_j Y_j = \sum_j N_j c_j \quad (2.19)$$

2.4.5 Demand for Public Goods and Tax Competition

Demand for local public goods in j is set by the local government through a unanimous vote on a head tax τ_j^h imposed on all residents²⁰ and a property tax τ_j^p imposed on the outflow of local profits accruing to landowners nationwide. We assume that local governments take part in a Cournot-Nash competition i.e. set the head tax and the property tax taking other jurisdictions' policies as given²¹. Local governments also take the central government's policies $\{\mathcal{O}_j, T_j\}_j$ as given.

Importantly, we assume that local governments are non-myopic i.e. perfectly anticipate migration responses to own policies. Because migration responses impact local labour and goods markets, jurisdictions also foresee these changes. Being small, jurisdictions however do not anticipate how the price of the traded good p adjusts in equilibrium. A local jurisdiction maximizes the welfare of its current residents i.e.

$$\max v_j(c_j, h_j, \mathbb{G}_j(G_j, N_j), \mathcal{G})$$

over $\{G_j, \tau_j^h, \tau_j^p\}$ subject to equations (2.8) to (2.18) and local budget

$$p_j^G G_j = \tau_j^h N_j + \tau_j^p \Pi_j \quad (2.20)$$

taking as given p , other jurisdictions' policies $\{\tau_k^h, \tau_k^p\}_{k \neq j}$ and central policies $\{\mathcal{O}_k, T_k\}_k$. Although migration anticipation complicates the analysis, it ensures that local governments provide public goods efficiently from a social perspective by respecting a local Samuelson rule.

Proposition 1. *Each jurisdiction satisfies a Samuelson rule as an interior condition for τ_j^h*

$$\frac{p_j^G}{p} \frac{\partial v_j}{\partial c_j} = N_j \frac{\partial \mathbb{G}_j}{\partial G_j} \frac{\partial v_j}{\partial \mathbb{G}_j} \quad (2.21)$$

Proof. See Appendix B.1.1. □

²⁰Head taxes can be implemented through a variety of residence-based tax instruments (e.g. on wages and profits earned from land and capital property nation-wide) since households are homogeneous but for location preferences. This is true as long as these taxes are non-distorting conditional on residence (e.g. when labor supply is inelastic). We hence rule out taxes levied on consumption such as taxes proportional to housing as they would create local distortions that would require central intervention.

²¹We assume that the strategic instruments are taxes and that spending adjusts endogenously.

This Samuelson rule accounts for congestion through the term $\frac{\partial G_j}{\partial G_j}$ which captures how a marginal change in public output impacts local public goods. For example, when $G_j (G_j, N_j) = \frac{G_j}{N_j^\kappa}$ with κ the congestion parameter, an extra unit of public good output is discounted by N_j^κ before being equally enjoyed by all residents, and the Samuelson rule becomes $\frac{p_j^G}{p} \frac{\partial v_j}{\partial c_j} = N_j^{1-\kappa} \frac{\partial v_j}{\partial G_j}$. When $\kappa = 0$, it collapses to the familiar Samuelson rule $\frac{p_j^G}{p} \frac{\partial v_j}{\partial c_j} = N_j \frac{\partial v_j}{\partial G_j}$ stating that when public goods are fully shared, the marginal cost for a worker of providing an extra unit of public good should equate the sum of marginal benefits to all workers in the jurisdiction.

For completeness, we also report the first-order condition for the property tax τ_j^p

$$\Pi_j \left(\frac{1}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial G_j} - \frac{\partial v_j}{\partial c_j} \right) \left(1 + \frac{\partial \ln v_j}{\partial \ln N_j} \Big|_{\tau} \times B_j \right) + C_j \sum_{k \neq j} \Pi_k N_k \frac{v_j}{v_k} \frac{\partial v_k}{\partial c_k} = 0 \quad (2.22)$$

where B_j and C_j are defined in Appendix B.1.1. Appendix B.1.1 shows that a myopic jurisdiction would violate the Samuelson rule when allowed to levy both head taxes and profit taxes. Taxation would then be socially inefficient because myopic jurisdictions would fund part of their public spending through profits accruing to landowners nationwide without internalizing the cost to non-residents (Starrett 1980). This externality disappears when local governments correctly anticipate migration responses since the prospect of additional congestion from new residents deters excessive taxation of non-residents (Boadway 1982). Assuming that jurisdictions anticipate migration responses hence allows us to evacuate the profit taxation externality and to limit the scope of the efficiency discussion to population distribution and migration externalities only.

2.4.6 Equilibrium

An equilibrium given central policies $\{\mathcal{O}_j, T_j\}_j$ is defined by quantities $\{N_j, c_j, h_j, Y_j, H_j, G_j, L_j, \Pi_j\}_j$, utility levels $\{v_j\}_j$, local policies $\{\tau_j^h, \tau_j^p\}_j$ and prices $\{r_j, w_j, p_j^G\}_j$ and p such that population distribution satisfies the free mobility condition (2.9) with local utilities defined by (2.8); demand for the traded good and housing is set by (2.10) and (2.11) with profits defined by (2.16); supply of the traded good, housing and local public goods as well as labour demand in these three sectors are given by (2.12), (2.13) and (2.14); local public good demand and local taxes are given by (2.20), (2.21) and (2.22); and all markets clear according to (2.17), (2.18) and (2.19). The set of feasible $\{\mathcal{O}_j, T_j\}_j$ is determined by the central government budget constraint (2.5).

Given the existence of agglomeration forces in our model, the equilibrium may in not be unique. A sufficient condition for existence and uniqueness of a laissez-faire ($T_j = 0$) equilibrium in parameterized applications of our framework it that dispersion forces – location preference heterogeneity and diminishing returns to scale in production technologies – be

stronger than public good scales economies (Redding 2016). As shown by Fajgelbaum and Gaubert (2018), such conditions also ensure the existence and uniqueness of the equilibrium at the optimal spatial policy.

2.5 Optimal Policies

2.5.1 Intuition in a Two-Region Example

We illustrate the mechanism through which heterogeneity in location preferences, by slowing down migration responses, increases the social cost of migration incentives (spatial taxes and transfers) relatively to their social benefits (agglomeration gains) such that improving welfare in a Pareto sense over the laissez-faire may be impossible. We also highlight the role of diminishing returns, for instance in housing supply, as a necessary channel for Pareto improvements in the presence of agglomeration externalities and Pigovian transfers. To this end, we work with a simple application of our framework with two regions and Cobb-Douglas preferences. Detailed steps are given in Appendix B.1.2.

We assume that technology for traded and local public goods exhibits constant returns to scale. Geography only enters the model through exogenous local productivity $z_j^Y = z_j^G = z_j$ that is constant in both sectors but varies across space with $z_1 > z_2$. Labour demand yields $w_1 = z_1 > w_2 = z_2$. Technology for housing is uniform across space and exhibits diminishing returns with constant housing supply elasticity η . Agents have utility $v_{ij} = (c_j^{1-\alpha} h_j^\alpha)^{1-\phi} (G_j)^\phi \mu_{ij}$ where $\{\alpha, \phi\}$ are taste parameters in $]0, 1[$. For simplicity, we abstract from the national public good and assume that local public goods are financed by the residence tax only i.e. $G_j = \tau_j^h N_j^{1-\kappa}$. Public good benefits hence increase with population with constant elasticity $1 - \kappa > 0$. Combining local demand and supply equations, one shows that

$$v_j = (z_j + T_j + \Pi)^{1-\epsilon_H} (N_j)^{\epsilon_G - \epsilon_H} \quad \text{with} \quad \epsilon_H = \frac{\alpha(1-\phi)}{1+\eta}, \quad \epsilon_G = (1-\kappa)\phi \quad (2.23)$$

where $0 < \epsilon_H < 1$ and $0 \leq \epsilon_G < 1$ are the land congestion elasticity and the public good agglomeration elasticity respectively. Utility increases with disposable income, but less than one for one as more income means higher housing prices. Holding profits constant, utility increases or decreases with region population depending on the relative strength of public good agglomeration and land congestion forces. We assume that dispersion forces overall are stronger than agglomeration forces i.e.

$$\sigma + \epsilon_H > \epsilon_G \quad (2.24)$$

to ensure that the equilibrium is unique in the laissez-faire and that the planner's objective

is concave. Note that heterogeneity in location preferences $\sigma > 0$ implies that one may have $\epsilon_G > \epsilon_H$ i.e. public good agglomeration forces may be stronger than land congestion forces.

Small reform approach Central policies $\{T_1, T_2\}$ must balance the budget i.e. $N_1 T_1 + N_2 T_2 = 0$. Let us introduce a small transfer $dT_1 > 0$ starting from the laissez-faire ($T_1 = T_2 = 0$) while T_2 adjusts with $dT_2 < 0$. Only households that are initially marginally indifferent between 1 and 2 migrate. Using an envelope argument, welfare of these marginal households is not affected to a first order. Utility of infra-marginal residents in each region changes as follows

$$\begin{aligned}\frac{d \ln v_1}{dT_1} &\propto \frac{1}{z_1 + \Pi} + \frac{1}{z_1 + \Pi} \frac{d\Pi}{dT_1} + \frac{\epsilon_G - \epsilon_H}{1 - \epsilon_H} \frac{1}{N_1} \frac{dN_1}{dT_1} \\ \frac{d \ln v_2}{dT_1} &\propto -\frac{1}{z_2 + \Pi} \frac{N_1}{N_2} + \frac{1}{z_2 + \Pi} \frac{d\Pi}{dT_1} - \frac{\epsilon_G - \epsilon_H}{1 - \epsilon_H} \frac{1}{N_2} \frac{dN_1}{dT_1}\end{aligned}\tag{2.25}$$

In each equation, the first term is the direct impact of dT_1 on infra-marginal households' budget, positive in region 1 and negative in region 2. The second term is the change in profits²², positive because households are enticed to locate in the more populated region 1 where house prices increase faster than they decrease in 2. The third term is the gain from agglomeration net of extra land congestion, negative or positive depending on $\epsilon_G - \epsilon_H$ but with opposite signs in region 1 and region 2. To know the sign of welfare changes in each region, we substitute the expressions for $d\Pi$ and dN_1 in (2.25).

Proposition 2. *The sign of welfare change in each region at $T_1 = T_2 = 0$ is*

$$\begin{aligned}\text{sign} \left\{ \frac{dv_1}{dT_1} \right\} &= \text{sign} \left\{ N_1 \frac{z_1 - z_2}{z_2 + \Pi} \epsilon_G + \sigma \right\} \\ \text{sign} \left\{ \frac{dv_2}{dT_1} \right\} &= \text{sign} \left\{ N_2 \frac{z_1 - z_2}{z_1 + \Pi} \epsilon_G - \sigma \right\}\end{aligned}\tag{2.26}$$

Benchmark with no externality or no geography Absent public good agglomeration gains i.e. $\epsilon_G = 0$, welfare changes have opposite signs (that of σ and $-\sigma$), consequently no Pareto improvement is feasible. As expected, the laissez-faire is efficient in the absence of externality. When dispersion in location preferences vanishes i.e. $\sigma \rightarrow 0$, the spatial equilibrium equalizes utilities between 1 and 2. The small tax has zero impact on welfare since taxes and transfers are exactly compensated for by changes in local house prices and profits through migration responses. When $\sigma > 0$, dT_1 has a negative effect on region 2 since out-migration is too small to compensate it through decreased house prices and increased profits, and conversely a positive effect on region 1.

²²From an optimal policy viewpoint, accounting for housing profits is necessary as land congestion is not an externality.

Absent geography i.e. $z_1 = z_2$, welfare changes have the sign of σ and $-\sigma$ so that no Pareto improvement is feasible either. In this case $N_1 = N_2$ so $dT_1 = -dT_2$, agglomeration gains in 1 equal agglomeration losses in 2, changes in house prices in 1 equal changes in house prices in 2 and $d\Pi = 0$ so that there are no aggregate gains. When $\sigma \rightarrow 0$, utility must be equalized between 1 and 2 hence stays constant in the absence of aggregate gains. When $\sigma > 0$, the net effect is positive for region 1 and negative for region 2 since migration responses are smaller²³.

Thus, when agglomeration externalities have constant elasticity, it is the interaction between agglomeration gains and differences in geographic fundamentals that calls for policies correcting population distribution.

Cases with geography and agglomeration \leq congestion In this case $0 < \epsilon_G \leq \epsilon_H$. One can have $\sigma \rightarrow 0$ while satisfying (2.24). When $\sigma \rightarrow 0$, welfare changes are positive at the limit in both cities since $z_1 > z_2$ and there are now aggregate gains to giving incentives to migrate to 1. It is Pareto-improving to introduce a small subsidy $dT_1 > 0$ and the small tax $dT_2 < 0$ that balances the budget. This is the usual setup examined in the literature. By continuity, Pareto improvements are feasible at least for small $\sigma > 0$. Since welfare change in region 1 is always strictly positive, the only Pareto improving candidate policy is $dT_1 > 0$. One can find a sufficient condition for welfare change in region 2 to always be strictly negative i.e. a condition under which no Pareto improving reform exists, featuring only structural parameters and the model's geography.

Proposition 3. *When $0 < \epsilon_G \leq \epsilon_H$, there is a non-empty region for $\sigma > 0$ in which Pareto improving transfers exist. However, when heterogeneity in location preferences is high enough, no policy can achieve Pareto gains. A sufficient condition for this is*

$$\sigma > \epsilon_G \frac{z_1 - z_2}{z_1} \quad (2.27)$$

When location preferences are sufficiently heterogeneous, migration pressures are too weak to ensure that house prices and profits adjust to have direct payers indirectly benefit from the transfer scheme.

Cases with geography and agglomeration $>$ congestion In this case $\epsilon_G > \epsilon_H$ and one can allow a minimum limit of $\sigma \rightarrow \epsilon_G - \epsilon_H$ to satisfy (2.24). From Proposition 3 we know that there is a small region where $\epsilon_G > \epsilon_H$ for which Pareto improvements are feasible when $\sigma \rightarrow \epsilon_G - \epsilon_H$. This is because although net migration gains in region 2 are strictly negative, region 2 is still compensated through the increase in profits Π . When σ increases too much

²³Here we assumed $\epsilon_G \leq \epsilon_H$ such that net gains from density are negative, to allow for the possibility that $\sigma \rightarrow 0$.

no Pareto improving reform is feasible as stated by Proposition 3. Finally, one can show that no welfare gains are feasible when agglomeration forces are too large compared to land congestion forces.

Proposition 4. *A sufficient condition for the impossibility of any Pareto improving reform whatever the value of $\sigma > \epsilon_G - \epsilon_H$ is that the agglomeration force is too strong relative to the land congestion force*

$$\epsilon_G > \frac{z_1}{z_2} \epsilon_H \quad (2.28)$$

Proposition 4 highlights the central role of the housing market as the channel by which the taxed region 2 gets compensated by lower house prices and higher profits in this example. For example, with perfectly elastic housing supply ($\eta \rightarrow \infty$ so $\epsilon_H \rightarrow 0$) no Pareto improving reform exists in this example.

Armed with these intuitions, we now characterize the efficiency frontier in the general case using sufficient statistics that are robust to the model's primitives.

2.5.2 Efficient Allocations

We come back to the general model of section 2.4. A standard method to find all Pareto efficient allocations is to maximize the social welfare function

$$W = \mathbb{E} [\omega_i \ln u_i] \quad (2.29)$$

for all combinations of individual Pareto weights $\{\omega_i\}_i$ where $\omega_i > 0$, subject to resource and market clearing constraints²⁴. Each vector of Pareto weights $\{\omega_i\}_i$ (and its multiples) is associated with a Pareto efficient allocation and pins down a particular equity objective on the efficiency frontier.

Reaching first-best efficiency would require the planner to be able to freely displace populations and offer ij -specific consumption bundles. We impose additional constraints which will make efficiency only second-best. First, we assume that the planner does not observe types i and has to give the same c_j and h_j to all individuals living in j . Together with the assumption that G_j is locally non-excludable, it implies that the same v_j has to be granted to all residents of j . Thus, the planner is bound to optimize over $\{v_j, N_j, c_j, h_j, G_j, H_j, L_j, \mathcal{O}_j\}_j$. Second, the planner is constrained by agents' free location decisions

$$u_i = \max \{v_j (c_j, h_j, G_j(G_j, N_j), \mathcal{G}) \mu_{ij}\}_j$$

²⁴That is, if the planner's problem is convex. We make the assumption that underlying dispersion forces – e.g. the housing market and location preferences – are strong enough to ensure convexity of the planner's problem.

Choice of Pareto Weights As in most optimal taxation settings, the planner may choose Pareto weights *in abstracto* i.e. based only on the knowledge of the distribution of the μ_{ij} 's even though individual realisations are unobserved. This would require the planner to know where each type will locate in equilibrium even though type is unobserved (and should stay unobserved after the equilibrium is realised since several types will end up in the same location). Alternatively, the planner may choose Pareto weights as a function of individuals' observed situation in the status-quo in the spirit of Saez and Stantcheva (2016)²⁵. In this case, Pareto weights would realistically be constrained to be homogeneous across households that live in the same city in the status-quo. The assumption about how weights are chosen does not affect the efficiency discussion below.

Proposition 5. (Envelope Theorem) *Given Pareto weights $\{\omega_i\}_i$, any small deviation from the status-quo has the following effect on social welfare*

$$dW = \sum_j N_j \Omega_j \frac{dv_j}{v_j} \quad (2.30)$$

where

$$\Omega_j \equiv \frac{1}{N_j} \mathbb{E} \left[\omega_i \mathbb{1}_{[v_{ij} = \max\{v_{ik}\}_k]} \right] \quad (2.31)$$

is the average Pareto weight across households living in city j in the status-quo.

Proof. We give intuition for this discrete choice version of the envelope theorem. Inframarginal residents, weighted Ω_j on average, benefit from the first-order change in local conditions v_j 's. Only marginal residents migrate in response to a small change in the v_j 's. Because they are initially indifferent between two or more locations, migration does not have a first order effect on their own welfare holding constant the v_j 's. However, migrants will also benefit from small changes in the v_j 's. Because both these changes and the size of migrants are marginal, the compound effect on W is only of second order. \square

The status-quo $\{v_j, N_j, c_j, h_j, G_j, H_j, L_j, \mathcal{O}_j\}_j$ is efficient if and only if it is a critical point for social welfare W for some profile of positive weights $\{\omega_i\}_i$. We report below two salient conditions.

Proposition 6. (Efficient Allocation) *The optimal population allocation satisfies*

$$\frac{dF_j^Y}{dL_j^Y} + N_j \frac{\partial v_j / \partial G_j}{\partial v_j / \partial c_j} \frac{\partial G_j}{\partial N_j} = c_j + h_j \frac{\partial v_j / \partial h_j}{\partial v_j / \partial c_j} + E + (E_j - E) \quad \text{for all } j \quad (2.32)$$

²⁵However, weights are kept exogenous in the maximization procedure, a necessary condition for non-violation of the Pareto Principle.

where $E = \sum_j N_j E_j$. Local output should be produced in each location such that

$$\sum_k N_k \frac{\partial v_k / \partial \mathcal{G}}{\partial v_k / \partial c_k} \frac{\partial \mathcal{G}}{\partial \mathcal{O}_j} = \frac{\partial F_j^Y / \partial L_j^Y}{\partial F_j^O / \partial L_j^O} \quad \text{for all } j \quad (2.33)$$

Proof. See Appendix B.1.3. □

Equation (2.33) simply states that national public goods should be produced according to Samuelson rules with no consideration for equity nor migration externalities. This notably evacuates indirect redistribution through central public demand stimulating local labor markets. Equation (2.32) characterizes the efficient population distribution. The first term of the left hand-side is the benefit of moving a worker to location j through increased production. The second term is the congestion of local public goods brought by an extra worker expressed in money terms. The first term of the right hand-side is the cost of moving one worker to location j as this worker now needs to consume c_j and h_j . The second term E captures the cost of an additional worker in the economy.

The novelty in (2.32) is the third term $E_j - E$ which is the social opportunity cost of having one more worker located in j and not elsewhere. This cost is increasing in the average welfare weight of all workers relative to workers of city j . It reflects the fact that moving one worker to j implies taxing residents of all other cities in order to create the migration incentive that must hold in a decentralized equilibrium.

2.5.3 Optimal Transfers

We characterize the central government's tax and transfer system that decentralizes the planner's efficient allocation, expressed in terms of estimable sufficient statistics (Chetty 2009). All endogenous variables below are given at the optimal policy so this characterization is implicit.

Proposition 7. (Optimal Transfers) *The optimal per capita transfer T_j is implicitly defined by*

$$T_j = T + T_j^G + T_j^\Pi + T_j^\Omega \quad (2.34)$$

where

$$\begin{aligned}
T &= \sum_j N_j T_j = \sum_j L_j^O w_j \\
T_j^G &= x_j^G \left(1 + \epsilon_{G_j, N_j}\right) - \sum_k N_k x_k^G \left(1 + \epsilon_{G_k, N_k}\right) \\
T_j^\Pi &= - \left[x_j^G (1 - \tau_j) - \sum_k N_k x_k^G (1 - \tau_k) \right] \\
T^\Omega &= \sigma (\Omega_j - \lambda_j v_j)
\end{aligned} \tag{2.35}$$

Proof. Substitute in equilibrium equations in (2.32) and the planner's first-order condition for v_j . \square

Proposition 7 characterizes the transfers achieving the government's efficiency and equity objectives. The first term T in (2.34) funds the national public good in a lump-sum i.e. geography-neutral fashion.

The second term T_j^G is the corrective tax and transfer scheme that tackles public good agglomeration externalities, with $x_j^G = \frac{p_j^G G_j}{N_j}$ the per capita spending on local public goods and $\epsilon_{G_j, N_j} = \frac{\partial G_j}{\partial N_j} \frac{N_j}{G_j}$ the congestion elasticity of local public goods. With the efficient public good provision result of Proposition 1, agglomeration elasticities $\{1 + \epsilon_{G_j, N_j}\}_j$, per capita public spending $\{x_j^G\}_j$ and population distribution $\{N_j\}_j$ are the sufficient statistics characterizing the efficient tax²⁶. Assuming constant agglomeration elasticity $1 + \epsilon_{G, N} = 1 - \kappa$ for example, the corrective tax becomes $T_j^G = (1 - \kappa)(x_j^G - \bar{x}^G)$ and is zero only if all locations spend the same amount per capita on local public goods. The pigovian net transfer should be higher in municipalities where per capita public spending is higher. *Ceteris paribus*, this typically means transferring resources towards high-productivity and low-density places.

The third term T_j^Π tackles rent-sharing externalities, with $\tau_j = \frac{\tau_j^h N_j}{p_j^G G_j}$ the share of local spending paid for by residents and $1 - \tau_j = \frac{\tau_j^p \Pi_j}{p_j^G G_j}$ the share paid for by local profit taxation. When an individual migrates to location j , she automatically gets a fraction of $\tau_j^p \Pi_j$ – the share of local profits captured by residents of j through the property tax – which was previously allocated to current residents (see Boadway and Flatters 1982). This creates a negative migration externality that vanishes when property taxation disappears. The sufficient statistics characterizing the efficient tax are per capita public spending $\{x_j^G\}_j$, residents' tax share $\{\tau_j\}_j$ and population distribution $\{N_j\}_j$. Transfers correcting rent-sharing externalities should tax away all profits captured by local governments.

The fourth term T_j^Ω achieves equity goals by redistributing between locations, with Ω_j the average Pareto weight in j and λ_j a multiplier. Under homogeneous preferences ($\sigma \rightarrow 0$),

²⁶Without loss of generality, we assumed $\frac{\partial G_j}{\partial G_j} \frac{G_j}{G_j} = 1$ to ease exposition.

because the term in brackets is typically bounded, the redistributive tax goes to zero. Indeed, the spatial equilibrium guarantees that utilities are everywhere equal when $\sigma \rightarrow 0$ so that equity concerns vanish. As mentioned, the introduction of observed skill groups would only generalize the model leaving the above argument intact. Unobserved location preferences – when not fully correlated with skill – open the door to geographic equity concerns orthogonal to what skill-based transfers can compensate.

Finally, note that corrective and redistributive tax and transfer schemes are self-financed at the optimal policy i.e.

$$\sum_j N_j T_j^G = \sum_j N_j T_j^\Pi = \sum_j N_j T_j^\Omega = 0$$

Proposition 7 implies that the second welfare theorem breaks down. Unsurprisingly, the first two Pigovian taxes T_j^G and T_j^Π dealing with migration externalities are place-based policies. Importantly and unlike in Flatters et al. (1974), Albouy (2012) or Fajgelbaum and Gaubert (2018), the third tax T_j^Ω related to equity goals is not people-based but place-based, because individual types – here idiosyncratic location preferences – are unobserved. Because redistribution can only be achieved by targeting locations, compensating losers of a reform targeting population efficiency cannot be done in a non-distorting way.

2.5.4 An Efficiency Test

The above sections characterized the efficient transfers given a set of Pareto weights $\{\omega_i\}_i$. In this section, we invert that logic and derive a simple efficiency test for observed allocations. Given any allocation, we reverse-engineer the weights that rationalize it as one maximizing social welfare (2.29). Assuming homogeneity of degree 1 for v_j , one easily shows that $\lambda_j v_j = x_j$ where x_j is total per capita spending (public and private) in j .

Proposition 8. (Implied City Weights) *The profile of city weights implied by policy $\{T_j, \mathcal{O}_j\}_j$ is*

$$\begin{aligned} \tilde{\Omega}_j &= x_j \\ &+ \frac{1}{\sigma} \left(T_j - \sum_k N_k T_k \right) \\ &- \frac{1}{\sigma} \left(x_j^G (1 + \epsilon_{G_j, N_j}) - \sum_k N_k x_k^G (1 + \epsilon_{G_k, N_k}) \right) \\ &+ \frac{1}{\sigma} \left(x_j^G (1 - \tau_j) - \sum_k N_k x_k^G (1 - \tau_k) \right) \end{aligned} \tag{2.36}$$

This follows directly by reversing Proposition 7. The assumption of homogeneity of degree 1 makes the implied weights fully computable given a value for σ . Proposition 8 char-

acterizes the set of weights that the government must assign to households in the status-quo to justify the absence of further policy intervention according to objective (2.29). It is stated in terms of average city weights in the status quo. In coherence with the fact the government may in practice only condition weights on observed city of residence, a feasible set of individual weights is when all agents living in a same city j in the status-quo equilibrium are given the same weight $\tilde{\Omega}_j$.

One can use Proposition 8 to diagnose the inefficiency of various situations and relate to the existing literature. Indeed, when the planner's problem is convex, transfers are efficient if and only if they maximize (2.29) for a given set of Pareto – that is strictly positive – weights. This means that observed central policies are efficient only if they imply city weights that are Pareto weights i.e. only if $\tilde{\Omega}_j > 0$ for all j . We use proposition 8 to revisit two recent results in the optimal spatial policies literature.

Proposition 9. (Albouy (2009) With Location Preferences) *When workers have heterogeneous location preferences, efficient spatial transfers need not compensate the “unequal geographic burden” of national taxes funding national public goods.*

In a seminal paper, Albouy (2009) shows that national income taxes, although place-independent, are made de facto place-dependent because wages are partly determined by location. Under homogeneous preferences, this geographic tax gap creates a dead-weight loss. To see how this result changes with heterogeneous preferences, call the spatial laissez-faire the situation in which the central government only supplies the national public good according to (2.33), financed through a geography-neutral head tax T . For simplicity, let's assume away agglomeration and rent-sharing externalities. In this case, implied average city weights in the laissez-faire are $\tilde{\Omega}_j = x_j > 0$ where x_j is total per capita spending in j in the equilibrium arising under the national lump-sum policy T . Unsurprisingly, the spatial laissez-faire can be related to a set of Pareto weights – since implied average city weights are strictly positive – so it is efficient. It may however not be considered equitable. The government may deviate from the head tax and carry out spatial redistribution while keeping the economy on the efficiency frontier as long as both (2.33) and $x_j + \frac{1}{\sigma} (T_j - T) > 0$ hold for all j . By continuity and since $x_j > 0$ in the laissez-faire, introducing some geographic redistribution from $T_j = T$ will not break efficiency. Hence, unlike in Albouy (2009) or Albouy (2012), efficient policies here need not compensate the “unequal geographic burden” of national income taxes funding national public goods. Unobserved location preferences introduce spatial equity concerns and the (second-best) efficient funding of national public goods may feature spatially differentiated contributions.

Proposition 10. (Fajgelbaum and Gaubert (2018) With Location Preferences) *Under homogeneous location preferences, the laissez-faire is generally inefficient. When heterogeneity in location preferences is high enough, the laissez-faire is efficient.*

In the presence of agglomeration gains and rent-sharing externalities, inefficiency of the spatial laissez-faire depends on location preference heterogeneity. Under homogeneous preferences ($\sigma \rightarrow 0$), efficiency requires $x_j^G (\epsilon_{G_j, N_j} + \tau_j) - \sum_k N_k x_k^G (\epsilon_{G_k, N_k} + \tau_k) = 0$ for all j , which is impossible unless the term $x_j^G (\epsilon_{G_j, N_j} + \tau_j)$ is identical across space. Barring knife-edge cases (e.g. constant agglomeration elasticity and no differences in geographic fundamentals), the spatial laissez-faire is never efficient under homogeneous location preferences. This nests the results in Flatters et al. (1974), Albouy (2012) or Fajgelbaum and Gaubert (2018) for instance.

However, with large enough preference heterogeneity, Pareto-improving spatial policies become unfeasible. When $\sigma \rightarrow \infty$, the last two terms of Proposition 8 will typically go to zero²⁷. The spatial laissez-faire will correspond to a set of Pareto weights and be efficient. Put differently, the government cannot improve everyone's welfare through place-based transfers when preference heterogeneity is too high, even in the presence of migration externalities, because spatial policies are bound to hurt infra-marginal residents somewhere. Higher preference heterogeneity dampens migration responses, which may make the social redistribution cost of migration incentives larger than the social benefits of agglomeration gains.

2.5.5 Model Calibration

Proposition 8 can be taken to the data and be used to diagnose the inefficiency of observed spatial transfers in France. As mentioned, the existence of some negative implied weights are a sufficient condition for the observed allocation to be inefficient. Under our assumption that the preference draws are i.i.d across cities and workers and distributed Type-1 Extreme Value, these weights also give the direction of Pareto-improving marginal reforms.

Proposition 11. (Pareto Improving Marginal Reform) *Given a status-quo equilibrium with transfers, Pareto-improving marginal transfers should be positive in locations having negative implied weights, and negative in locations having positive implied weights.*

Proof. See Appendix. □

Construction of variables Using our rich administrative data, we are able to construct the variables of Proposition 8. Per capita spending on private and public goods $x_j = w_j + \Pi + T_j - \tau^h + x_j^G$ is computed as the sum of gross wages, pensions, capital income and net transfers T_j plus the sum of extracted local profits i.e. local property, land and business taxes. The term w_j is computed from income tax data IRCOM and national accounts as the sum of

²⁷In the last two terms in brackets, x^G , N and τ are bounded due to physical constraints. In most applications, agglomeration elasticity $1 + \epsilon_{G_k, N_k}$ will be bounded as well, and per capita expenditure x_j will be bounded from below by a strictly positive number.

labour and pension income. Capital income Π is computed from national accounts as the sum of dividends, mixed income and rental income (including implicit rental income) net of total local household property tax computed from local tax data REI and accounts BCC. It already accounts for national and local business taxes²⁸ and is distributed lump-sum in coherence with our hypothesis of geography-neutral ownership in section 2.3.2 and the construction of composition-neutral variables.

Per capita net transfers from the central government T_j are computed from IRCOM and BCC data and include (i) taxes on wages, pensions and capital income (including means-tested negative income taxes), (ii) various annual operating subsidies to municipalities and municipal federations and (iii) the current *stock* of investment subsidies to municipalities and their federations discounted by $\frac{R}{1+R}$, the interest rate $R = 3\%$ hence transforming the current subsidy liability in a stream of yearly subsidies.

Municipal financial accounts allow us to construct x_j^G as the sum of operating expenditure and public assets, the latter being discounted by a factor accounting for depreciation and the fact that it is financed by debt repaid over time (see Jannin and Sotura 2019). We compute resident's tax share τ_j from REI local tax data and BCC financial account data as the sum of all taxes paid by residents – residence tax and resident user fees – divided by total municipal tax revenues – from residence, land, property, business and various resident and business user fees –.

Calibration for scale economies To illustrate our main argument, we need an estimate for the agglomeration elasticity $1 + \epsilon_{G_j, N_j}$. For this empirical application, we assume that it is constant and equal to $1 - \kappa$ where κ is the congestion parameter. In their review, Ahlfeldt and Pietrostefani (2019b) compute a public good density elasticity of 0.17 based on original estimates in Carruthers and Ulfarsson (2003). However, it is unclear whether this elasticity is comparable to what $1 - \kappa$ captures in our framework, which is the influence of city size on public good provision, holding constant urban land area. In appendix B.2.1, we calibrate our public good demand equation (2.21) in the spirit of the seminal work of Borchering and Deacon (1972) and Bergstrom and Goodman (1973) and report a value of $\kappa = 0.44$. We emphasize that this value is more reflective of association in the data rather than causal relationship, and use it to illustrate our main argument below.

2.5.6 Efficiency of Observed Transfers

Exploration of preference heterogeneity space We compute implied weights pooling years 2010 and 2012 for different values of σ . Importantly, the set of Pareto-improving marginal reforms the economist would advocate strongly depends on the amount of heterogeneity in

²⁸We make the admittedly strong assumption that VAT and other sales taxes are equivalent to a lump-sum tax on firms' profits and are already accounted for in our capital income term Π .

location preferences $\tilde{\sigma}$ that she believes lead to the observed allocation²⁹. Panel (a) of Figure 2-5 maps the direction of marginal spatial transfers that a government who is blind to the existence of heterogeneity in location preferences would favor³⁰. Regions in red would get less net transfers than in the current allocation, whereas regions in green would receive larger net transfers. Strikingly, under this homogeneous-preference hypothesis, marginal transfers should encourage migration to already dense and productive areas such as those surrounding Paris, Lyon, Toulouse, Strasbourg or Nice, as well regional sub-centers such as Tours, Grenoble or Rennes. However as $\tilde{\sigma}$ increases, the range of marginal reforms that the government thinks are efficient narrows until it becomes empty, as exhibited in the other panels of Figure 2-5. Hence, under-estimating preference heterogeneity may lead to advocating marginal reforms that would favour the most productive areas and would at best achieve redistribution, and at worse lead to efficiency losses.

Assessment of efficiency To assess the efficiency of current transfers, one needs an educated guess for preference dispersion parameter σ . We take a central estimate from Janin and Sotura (2019) who find σ around 0.08 on similar data and at the municipal level. However, this estimate is valid only when locations are municipalities and not municipal federations. We show that under mild assumptions, we may still use it to carry out a back-of-the-envelope efficiency diagnosis³¹. Looking at Panel (f) in Figure 2-5, it is likely that the French current transfer system is close to being spatially efficient.

2.6 Equity and Density

We now turn to equity considerations and to the joint role of public good agglomeration economies and location preferences in defining redistribution. In a context where high preference heterogeneity dampens migration responses, the set of transfers chosen by the government is more likely to reflect redistribution preferences than efficiency concerns. The intensity of observed transfers thus likely mirrors French preferences for spatial equity.

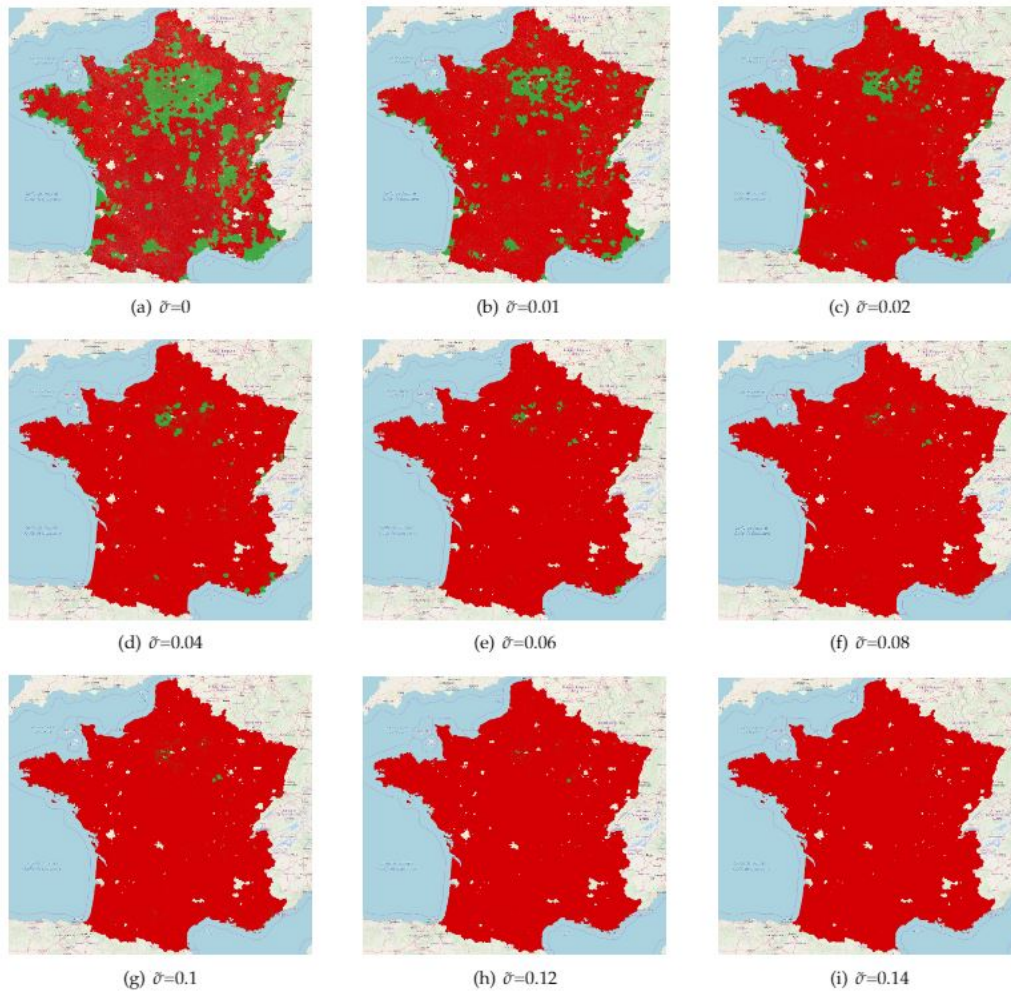
To provide intuition about how the interplay between public good agglomeration economies and location preferences may shape redistribution motives, consider the following two-city

²⁹Note that for endogenous variables to stay at their observed level when σ changes, other deep fundamentals need to vary as well. However, the sufficient statistics approach precisely allows to characterize optimal policies independent of the underlying parameters, so that what parameters exactly are behind the observed equilibrium is irrelevant.

³⁰This is obtained by letting $\tilde{\sigma} = 0$ which yields the efficiency condition $T_j - \sum_k N_k T_k = (1 - \kappa) \left(x_j^G - \sum_k N_k x_k^G \right) + x_j^G (1 - \tau_j) - \sum_k N_k x_k^G (1 - \tau_k)$.

³¹Under the hypothesis that utilities are constant within the municipal federation, the parameter at municipal federation level σ_{MF} is close to the municipal level one σ_M if the geometric average difference of the number of municipalities in the federation \mathcal{N}_{MF} is small enough before population N geometric average difference, so that $:1 - \frac{\sigma_{MF}}{\sigma_M} = \ln \left(\frac{\mathcal{N}_{MF}}{N} \right) / \ln \left(\frac{N}{\mathcal{N}_{MF}} \right)$ a condition that seems reasonable.

Figure 2-5: Direction of Pareto-improving transfers ($\kappa = 0.44$)



Note: These maps show the sign of Pareto-improving marginal reforms of the current transfer system an economist would recommend conditional on different beliefs $\tilde{\sigma}$. Green areas should receive positive marginal transfers, while red areas should be marginally taxed.

example. Natural amenities in city 1 are exogenously better than in city 2, and it is also less costly to build housing there. Productivity is fixed, equal in both cities and production exhibits constant returns to scale so that wages are fixed and equal. Attractive and cheap city 1 will be more populated in equilibrium, and will offer more endogenous public good benefits because of positive agglomeration externalities. We can carefully engineer the fundamentals of the model – in particular the housing supply elasticity in 1 and 2 – such that wages, rents, taxes and per capita consumption of housing and of the traded good will be exactly equal in equilibrium³². The only difference between households will be the exogenous pure amenities and the endogenous public goods of the city they live in. In this context, one may want to compensate residents of 2 for benefiting from less public goods (and maybe for living in an unattractive place) because of horizontal equity concerns. Achieving this goal will require a tax and transfer scheme that compensates low density beyond income redistribution.

2.6.1 Compensation and Responsibility

Whether society wants to redistribute to low-income and low-density places will depend on the interpretation of idiosyncratic draws μ_{ij} determining agents' location in equilibrium. Are they spatial draws that should be compensated for – it may be costly to leave the environment one was socialized in – or pure preferences – one may really appreciate amenities in places destined to be low-density e.g. remote steep mountains – that society deems the responsibility of individuals? The discussion here is reminiscent of “skill vs laziness” type arguments found in the optimal taxation literature (e.g. Saez and Stantcheva 2016) and more generally of the compensation vs responsibility principle discussion (see Fleurbaey and Maniquet 2011).

Even if a burning issue for policymakers, the question whether preference draws pertain to the compensation or the responsibility principle is beyond the scope of this chapter. What we propose to do however is to investigate what principle seems to empirically prevail as revealed by the current geographic tax and transfer scheme.

2.6.2 Revealed Social Preferences

We use Proposition 8 to reveal collective preferences and investigate which underlying social welfare function is supported by the implied weights. However, when transfers achieve both efficiency and equity objectives, one can only analyze the structure of implied weights *at an efficient allocation*. Indeed, since negative weights are a symptom of the government not accounting for all sources of inefficiencies when maximizing the social welfare function

³²E.g. by making the extra assumption that amenities and public goods do not influence the marginal utility for consumption goods.

(2.29), they do not reflect actual social preferences³³. As such, any discussion on equity and revealed social social preferences should start by investigating the planner's beliefs about sources of inefficiency, which must be such that the current situation is efficient from the point of view of a mistaken planner i.e. is rationalized by positive implied weights.

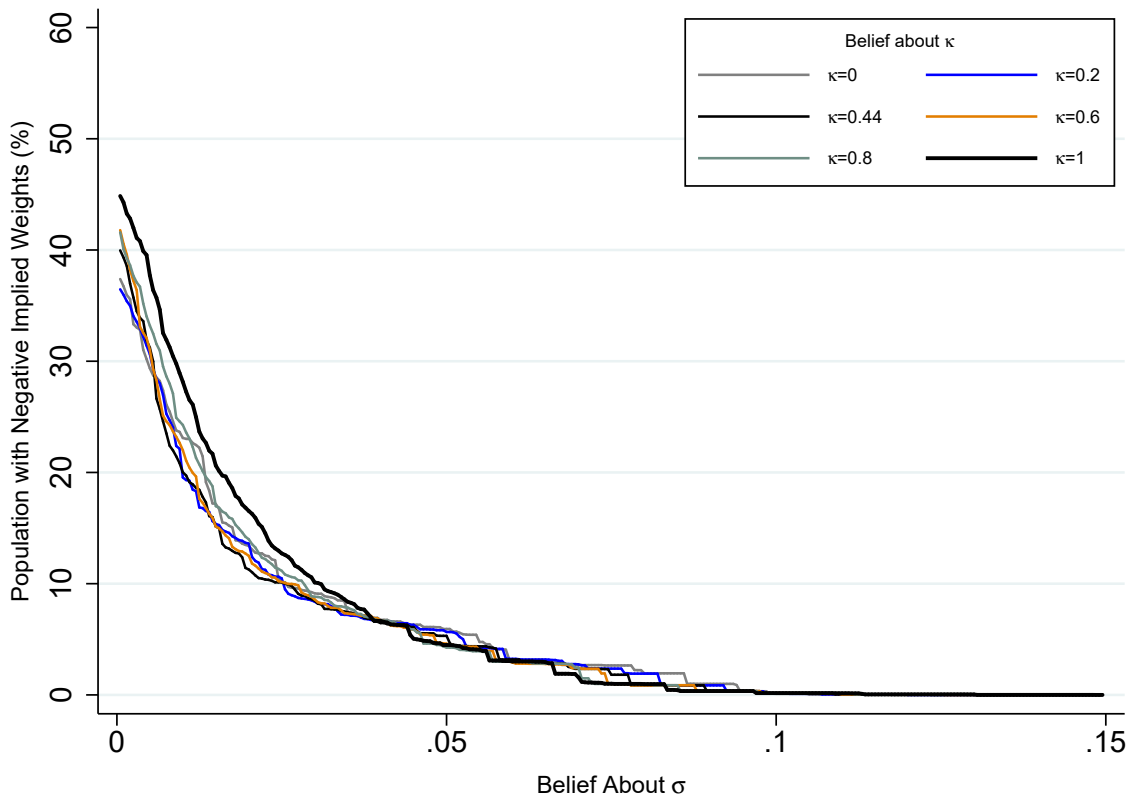
Figure 2-6 reports the fraction of the population receiving negative weights as implied by the observed allocation, for different planner's beliefs about preference dispersion $\tilde{\sigma}$ and congestion parameter $\tilde{\kappa}$. We report this relationship pooling years 2010 and 2012. Any combinations of $\tilde{\sigma}$ and of $\tilde{\kappa}$ such that implied weights are all positive may be what the government actually had in mind when designing "optimal" transfers leading to the observed situation. The only definitive conclusion we can draw from Figure 2-6 is that the government likely overstates preference dispersion compared to our best guess $\hat{\sigma} = 0.08$, as only values for $\tilde{\sigma}$ above 0.13 rationalize all possible planner's optimizations.

We make the conservative assumption that the planner is as close as possible to our best guess $\hat{\sigma} = 0.08$ while being rational i.e. we assume that the planner has belief $\tilde{\sigma} = 0.13$. It seems reasonable to assume that the democratic process of preference aggregation leads to the government having beliefs about σ not too far from the "true" value since location preferences are a common feature of all individuals. For $\tilde{\sigma} = 0.13$ we cannot reject any belief $\tilde{\kappa}$ since they all lead to positive implied weights. We then have to examine their structure for each situation. Figure 2-7 reports the distribution of individual Pareto weights for various beliefs about the true parameter κ . Strikingly, for most beliefs the median of the weight distribution is almost exactly equal to one, i.e. to the utilitarian weight, and the weight distribution is quite symmetric. For all beliefs, the dispersion around the median is quite limited with 90% of the population being weighted within 30% of the unitary weight. It thus appears the the French government is roughly utilitarian and that it carries out some limited redistribution beyond what a strictly utilitarian objective would command.

We investigate the structure of this deviation from utilitarianism. We test two simple hypothesis: whether the government compensates low resources beyond utilitarianism – which already seeks to compensate high marginal utility of consumption – and whether it compensates low density which we believe captures limited access to local public goods. Pooling years 2010-2012, Table 2.1 reports results of the corresponding regressions. We cannot conclude that the planner compensates low resources beyond the utilitarian objective. However, whatever the governments' true belief about the congestion parameter we estimate that it compensates lower densities i.e. lower population sizes holding constant urban

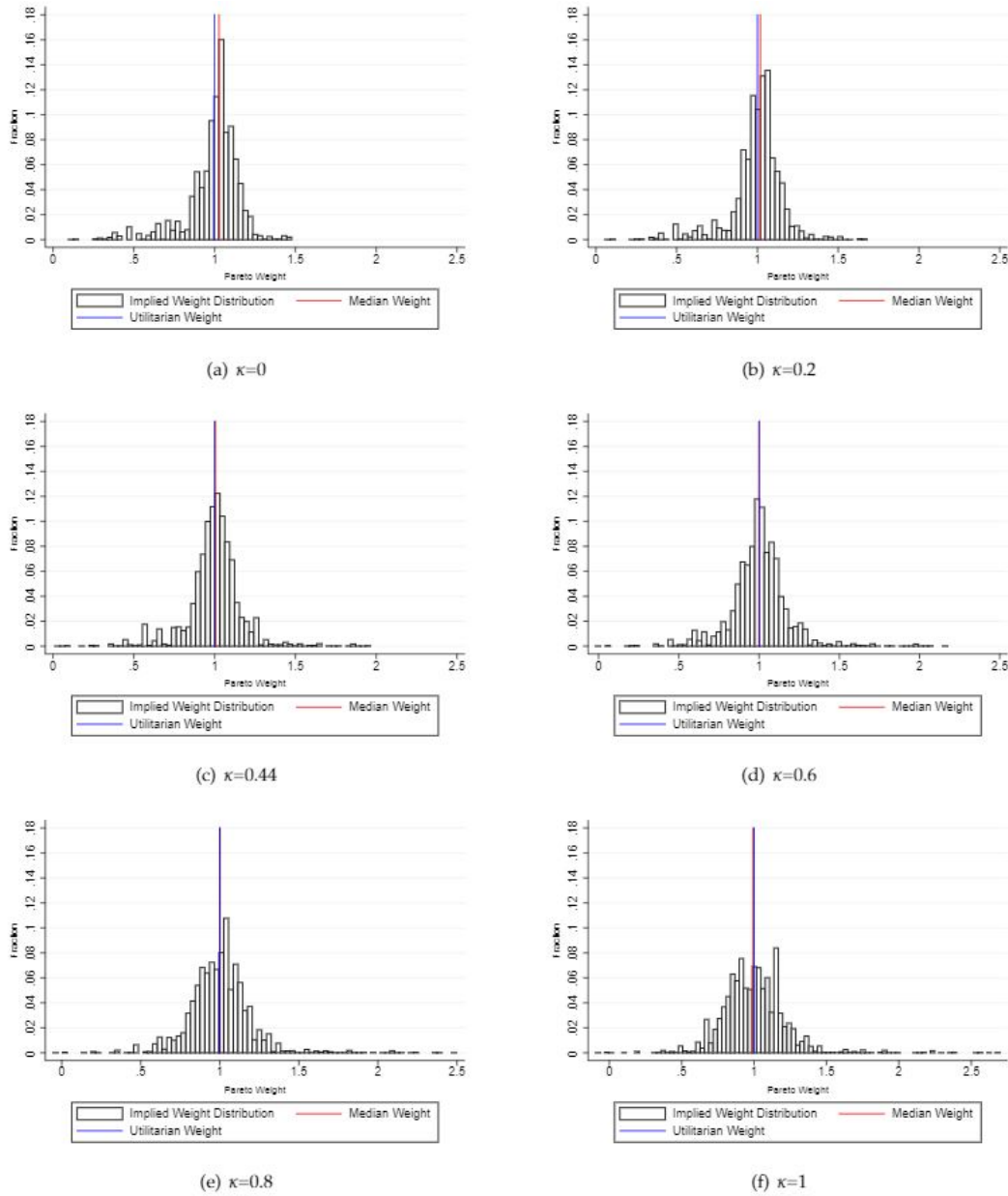
³³That is, if one accepts that the planner acts in accordance with the Pareto principle. Here we do not model how collective preferences emerge from the political process, however, assigning negative weights to a municipal federation would mean that the government wishes the welfare of individuals living in this jurisdiction to be less than what it could be – all others households' welfare being held constant –. Deliberate economic degradation of some locations does not seem to be consistent with any political process of preference aggregation, at least in a democratic system where there are no "second class citizens" nor spatial discrimination.

Figure 2-6: Government's Beliefs



Note: This graph shows which government's beliefs about σ and about κ are consistent with the observed transfers. We reject beliefs for which some implied weights are negative, as they would suggest that the planner is not acting rationally conditional on these beliefs.

Figure 2-7: Distribution of Implied Weights for Various Planner's Beliefs



Note: These graphs show the distribution of the planner's individual Pareto weights implied by the observed 2010-2012 allocation under different planner's belief for congestion parameter κ at $\bar{\sigma} = 0.13$. The distribution of individual weights is obtained by weighting MF Pareto weights by MF population.

Table 2.1: Structure of Pareto Weights

	$\tilde{\kappa} = 0$	$\tilde{\kappa} = 0.2$	$\tilde{\kappa} = 0.44$
Log Resources	-0.235 (0.288)	-0.146 (0.261)	-0.110 (0.273)
Log Population	-0.027** (0.014)	-0.042** (0.016)	-0.055** (0.023)
Log Urbanized Land	0.012 (0.015)	0.034** (0.016)	0.057*** (0.022)
R-squared	0.055	0.057	0.053
Observations	4134	4133	4133
	$\tilde{\kappa} = 0.6$	$\tilde{\kappa} = 0.8$	$\tilde{\kappa} = 1$
Log Resources	-0.092 (0.283)	-0.072 (0.297)	-0.051 (0.317)
Log Population	-0.062** (0.028)	-0.071** (0.033)	-0.080** (0.040)
Log Urbanized Land	0.071*** (0.026)	0.089*** (0.032)	0.109*** (0.038)
R-squared	0.050	0.046	0.041
Observations	4133	4133	4133

Note: This table explores the structure of Pareto weights for different hypothesis about the planner's belief for congestion parameter κ . Per capita resources are constructed as in section 2.3.

sprawl, and larger sprawl holding constant population size. Holding constant resources and urban sprawl, a doubling of status-quo population size increases Pareto weights by 2% to 8%. This last piece of evidence supports some kind of horizontal equity concerns for the consumption of local public goods. We argue that public good agglomeration economies likely explain the horizontal inequities that the government seems to compensate here.

2.7 Conclusion

In this chapter, we study the implications of heterogeneous location preferences for the design of efficient and equitable spatial transfers when local public goods are the leading cause of migration externalities.

Using a unique combination of French local administrative panel datasets, notably comprehensive local financial accounts, we first document new stylized facts suggesting the existence of large public good scale economies.

We then build a spatial equilibrium model that incorporates the most salient features of the local tax system in France. We characterize the transfers that implement efficient population distributions by the way of estimable sufficient statistics. We show that with homogeneous preferences, the laissez-faire is generally inefficient and there is room for welfare-enhancing spatial transfers. However, Pareto-improving transfers may not exist when location preferences are heterogeneous, because heterogeneity increases the equity cost of migration (transfers) relatively to its efficiency benefits (agglomeration gains). This has important consequences for the design of spatial policies aiming at harnessing agglomeration forces for the benefits of all. We then apply our framework to the current French transfer system. We empirically show the importance of accounting for location preferences as ignoring them may lead to severely mistaken recommendations that overstate the feasibility of marginally efficient reforms and to anti-redistributive policies. Finally, we explore whether the coexistence of location preferences and public good agglomeration economies creates horizontal equity concerns about public good consumption and find that the French system indeed compensates low-density areas beyond a utilitarian objective. This is a particularly striking result when we think that this does only include monetary redistribution, and not the central state spatial redistribution through public services (schools, etc.) which is very important in France and yet clearly oriented by horizontal equity criteria. Indeed, the theoretical framework used in the chapter has been largely developed for a US context, which strongly differs from the French one by the absence of such redistribution through public services funded at the national level.

Overall, our research suggests the need for more work on the estimation of public good scale economies – and more broadly on the impact of density on consumption amenities – and on the determinants of location preferences, as their interaction bears important consequences for the design of efficient and equitable spatial policies.

Chapter 3

The Carbon ‘Carprint’ of Urbanization: New Evidence from French Cities

“We should build cities in the countryside, because the air is cleaner there”.¹

Quotation credited to Alphonse Allais.

3.1 Introduction

As concerns about global warming rise, the reduction of greenhouse-gas (GHG hereafter) emissions has moved gradually to the central agenda of policymakers. The European Union adopted in december 2020 a commitment to reach carbon neutrality by 2050 and a 55% reduction of its GHG emissions in 2030 with respect to 1990 levels. Among all sectors in France, transportation represent the largest emitter as well as the sector whose emissions are the most difficult to curb down. Actually, transport-related GHG emissions rose by 11.4% over 1990-2015, while industrial and residential emissions fell by 30% and 15% respectively (Commissariat Général au Développement Durable, 2017). The road sector accounts for the lion’s share (94%) of these emissions. Private vehicles themselves represent almost 60% of this total (Commissariat Général au Développement Durable, 2020), and presumably more within urbanized areas, as suggested by Coulombel et al. (2018), who show that private cars account for more than 80% of the GHG emitted by road traffic in the Paris Metropolitan Area. A reduction in car-related emissions is thus necessary to the attainment of carbon neutrality. To that end, nation-wide policies such as carbon pricing have been put in place in France as well as in 44 other countries². However, these policies have faced considerable opposition

¹This chapter is based on a joint work with Miren Lafourcade and Camille de Thé.

²See an up-to-date survey on <https://carbonpricingdashboard.worldbank.org/>

from civil society, both in the peripheries of urbanized areas and in medium cities. Notably, in 2018, the French government plan to increase gasoline taxes to account for the true social cost of fuel combustion led to massive social unrest in both medium size cities and peripheries of large cities - the 'Yellow Vests' (*Gilets Jaunes*) movement. Its political aftermath seems to have sounded the death knell for carbon taxes on fuel in France. It poignantly underlined that inhabitants of some areas where public transport is scarce and urban morphology is designed for cars may experience a high car usage that could be described as a "car dependency". A fuel-levied carbon tax would impose a disproportionate tax burden on residents of such areas, leading to an acceptability issue, which may have been reinforced in the French case by the fact that peripheral areas often rank among the poorest in France³.

In the wake of the first two chapters, this acceptability issue may be interpreted as claims for vertical equity -within cities- or horizontal equity -between cities- in transportation cost. Indeed, if the carbon taxes on fuel were to rise, the transportation costs, after a long decline, would rise, but in a very uneven way across transport modes. For the same distance, the difference in transportation cost between car and public transport ridership would become more salient. This may not only increase the demand for public transport, especially from the less fortunate areas, but also could raise equity claims from urbanites that once chose to live in remote peripheries deprived of public transit to enjoy larger dwellings, and did not anticipate the rise in fuel prices. As shown in the first chapter, answering such a claim for vertical equity in access to public transport infrastructure is no easy task and may require a coordination between social housing and public transport developments. Moreover, larger equity issues may arise between cities, if the demand for public transport rises in car dependent ones. Indeed, the development of a public transport system faces large fixed costs that made it one of the better examples of the "zoo effect" exposed in the second chapter. The rise in carbon taxes on fuel may thus reinforce claims for horizontal equity on public transportation equipment arising from cities and territories less densely equipped with it. In our second chapter, we showed that such claims can be justified, if the public planner accounts for location preferences. The ecological transition may thus increase the tension identified in this late chapter between an utilitarian approach that would concentrate the population in the most (climatically) efficient cities, for instance through an installation tax proportional to the mean household local emissions – as proposed by Glaeser and Kahn (2010) – and horizontal equity approach that would transfer to each jurisdiction the financial means to build a public transport network.

In this context, the precise identification of the causes and factors of car use, both at city and infra-city level, appears as a priority task, to identify and reduce potential equity issues associated with a carbon tax, in order to increase its acceptability. Indeed, a better

³There is a strong core-periphery pattern of income segregation in France, where affluent households tend to live close to city-centres, and low-income households in remote neighborhoods (Brueckner et al., 1999)

understanding of the roots of car dependency may allow not only to anticipate acceptability issues but also to reduce them at the lower possible cost. As such, urban policies likely to reduce the dependence of cities to private vehicles deserve particular attention.

3.1.1 Theoretical framework

In this chapter, we assess the impact of city size and structure on car usage within and between French Metropolitan Areas. To do so, we model location choice and car use as follows :

- In the beginning of the period, an household chooses to live in a city. This choice may potentially be biased by unobserved preferences for some transportation modes or for car usage itself.
- Then, the household chooses, in this city, a residence, following the mononcentric model (Alonso, 1964) where workplace is located in the city center; or a residence-workplace pair, following the framework proposed by Ahlfeldt et al. (2015b), where workplace can be located elsewhere. This choices may also be biased by unobserved preferences.
- Then, from the chosen neighborhood, the household's car trips are decided with respect to : (i) the available transportation modes to workplace; (ii) the availability of recreational amenities (parks, historical amenities, cultural places, etc. - that may be largely fixed on the medium term) and the transportation modes to reach them; (iii) the availability of shopping places (that may be more endogenous to the previous choices) and the transportation modes to reach them.

Thus, we can describe car use as a function of :

- the length of trips from residence to workplace
- the length and frequency of trips from residence to amenities and shopping places

These length and frequency themselves would depend on city-wide and local characteristics. The pertinent characteristics and the functional form of this link, nonetheless, would depend on the underlying model of the urban economy. Basically, two polar options can be explored.

- Following the monocentric model, one can describe daily commuting to work as a function of the city's radius - or, more operationally, its surface-. Trips to amenities would be a function of their density (or equivalently, population, since surface is taken into account). The density of roads and public transport in the city may complement theses metrics to globally describe modal options available for the urbanites;

- Following Ahlfeldt et al. (2015b) structure-agnostic model, in which households choose an residence workplace pair depending on local amenities, local productivity and availability of public transport, one can raise doubts on the pertinence of a city-wide description of car usage that rely too much on the hypothesis that the city structure is simple. By contrast, in such a model that allows the emergence of polycentricity, daily commuting may be more efficiently modelled as a function of both neighborhood characteristics and access to the rest of the city by road or public transport, following Cervero and Kockelman (1997) “3 D’s” modelling. In this model, Density and Diversity of residence neighborhood influence the frequency of the trips, and Design, both at the local (walkability of the neighborhood) and city (access to the rest of the city through different modes) levels influence modal choice.

Actually, French cities can be adequately described by each of the two models, depending on their size and polycentricity. As far as small and medium MAs are concerned, the monocentric model provides a powerful and simple description of the city’s structure. However, the 10 largest MAs exhibit more than 700,000 inhabitants and 3,000 km^2 and may hardly be defined as monocentric structures. We will thus combine the two approaches to provide the most simple and meaningful description.

In a first time, we will thus analyse the impact of city-wide descriptors, and then show that the local description of urban form through the “3 D’s”, at the municipality level, is a necessary complement to this macro-approach.

3.1.2 Main contributions

Since the seminal analysis of Newman and Kenworthy (1989), Density has been by far the most extensively studied dimension of the urban form, as it is a good describer of how close destinations may be within the city. Glaeser and Kahn (2010) and Zheng et al. (2011) have notably shown that households living in denser cities have lower carbon footprints in the US and China.⁴ It has been studied as a descriptor both at the city and the neighborhood level, as such or through the inclusion of city population and surface. Design and Diversity, as neighborhood level descriptors, have been less systematically explored, though they received stronger interest in the interdisciplinary urban planning literature.⁵ The pioneer study in this field, Cervero and Kockelman (1997), finds that land-use Diversity and pedestrian-oriented Designs encourage non-auto travel in statistically significant ways, though their influence is fairly marginal compared to density in the San Francisco Bay Area. At city-level, only one dimension of cdesign, the density of transport stops, has been studied by Bento et al. (2005),

⁴See Ahlfeldt and Pietrostefani (2019a) for an extensive review of the economic effects of density.

⁵See the surveys and meta-analyses proposed by Ewing and Cervero (2001), Handy (2005), Ewing and Cervero (2010), Ewing et al. (2015), Stevens (2017) or Ahlfeldt and Pietrostefani (2017).

who estimate that a 10% increase in rail and bus miles supplied lowers the chance that a typical US worker drives to work by 0.5 percentage point. Moving such worker from a city like Atlanta to a city like Boston would reduce annual vehicle-miles-traveled by 25% and the average probability of driving to work from 0.87 to 0.73.

Our first main contribution is to estimate the effect on car usage of an extensive set of descriptors of inner urban structure metrics beyond density and city size. We analyze in particular: (i) the impact of access to urban transit supply, which has been shown to condition the probability of driving to work and (ii) the influence of a novel indicator of city-Design, the fractal dimension of the built environment, that enables us to capture differences in urban morphology likely to nurture or alleviate car dependence in France. French cities have indeed two peculiarities of which most of their American analogues do lack: (i) extended public transit networks offering households credible alternatives to car use, even in suburbs that are far from city-centers, and (ii) considerable variations in building morphology and geometry, due to differences in historical legacy and urban planning among cities. While some French neighborhoods are shaped in a pedestrian-friendly form barely favorable to car use, others are explicitly shaped for extensive driving, due to either war destruction⁶ or the ‘modernist’ architectural revolution of the 1960/70’s.⁷ In particular, many French suburbs display large housing compounds built along parking lots and highways, locally known as *Grands Ensembles*, a building structure much more common in France than anywhere else (Newsome, 2004).⁸

Our second key contribution is to highlight the existence of a bell-shaped relationship between city size and car emissions, which is unprecedented in the literature. We show that Design, and to a less extent Diversity, are the key drivers of such non-linearity, pointing toward new levers for curbing car-emissions down in French cities. Such concavity is an important insight over linear downsizing effects prevailing in previous empirical research, such as the notable contribution of Glaeser and Kahn (2010). First, it is perfectly consistent with theoretical frameworks showing that urban development generates conflicting environmental effects (Larson and Yezer, 2015; Legras and Cavailhès, 2016; Borck and Tabuchi, 2019; Borck, 2019; Borck and Pflüger, 2019), and that compacting cities is not always desirable when the general equilibrium effects of the urban structure and polycentricity are taken into account (Gaigné et al., 2012).⁹ Second, it is consistent with the observed geography of social unrest linked to the carbon tax : medium cities and peripheries, that lack Diversity and have a car-oriented Design, appear to experience larger claims for equity than rural spaces

⁶Le Havre or Brest harbours are two emblematic examples.

⁷Iconic examples include the financial district of Paris-la-Défense and its nearby residential districts, as well as the French ‘New Towns’ studied for instance by Garcia-López et al. (2017).

⁸Only former eastern block countries exhibit such concentration of high rise housing compounds.

⁹Actually, this chapter suggests that margins other than compaction can be used to reduce car dependence and the equity issues arising from it. In particular, potentially large gains can be expected from reshaping cities, developing public transit and, to a less extent, from changing their land-use mix.

and small towns (L'Obsoco, 2019). Third, such non-linearity may change the terms of the optimal city size debate evoked in chapter 2 : the overall benefits of living in large cities are confirmed, but it also appears that living in small cities could also be collectively beneficial, on the ecological point of view. In that context, policies that would encourage medium city inhabitants who face a disproportionate carbon tax to move to large metropolis could be misfounded. Encouraging the development of small cities could also be envisioned. Such an option could be more respectful of location preferences as exposed in chapter 2, in particular one's desire to stay in one's region of origin.

Alternatively to such spatial policies, our estimates of the impact of urban structure on fuel consumption and CO₂ emissions may help policy makers calibrate spatial transfers that could compensate for a rise in carbon taxes as proposed by Bureau et al. (2019) to tackle acceptability issues for a carbon tax. Though, estimating the welfare effects of improving each of the '3 D's' is far beyond the scope of this thesis.

Besides these contributions, this chapter improves on the extensive literature examining the effects of urban form on driving patterns. First, it uses a rich French households' survey combined with a Heckman strategy to address the issue that households with particular preferences for driving may sort into areas of particular D's, which has been overlooked in Europe.¹⁰ Indeed, if the relationship between urban form and fuel consumption is blurred by households intrinsic preferences for driving, there are few benefits to expect from, say, compacting cities, since people may not behave differently in denser or smaller conurbations.

We also use instrumental variables to tackle the problem of unobserved local determinants of car usage correlated with urban density as well as the reverse causality stemming from feedback loops between air pollutants, car ownership and residential choices (Hebllich et al., 2018; Koster et al., 2020). Though the possibility that households may live in locations consonant to their travel predispositions is widely recognized and generally addressed,¹¹ few papers have identified quasi-random sources of variations in urban settlements to address such endogeneity issues. In this paper, we draw inspiration from Duranton and Turner (2018), Carozzi and Roth (2020) and Borck and Schrauth (2021), and use geology to predict urban settlements. We concur in pointing to a statistically significant elasticity of car usage and emissions with respect to urban size. However, our results suggest that such elasticity is not constant. In large, yet potentially sprawling conurbations, we find that households emit few car emissions (about 2 tons of CO₂ per household per year in Paris), thanks to the intensive use of public transit, the walkability of the urban fabric and the functional diversity of jobs. In small cities, low densities are offset by shorter daily trips and greater job-housing centralization. Design can therefore counteract driving incentives stemming from low den-

¹⁰Noticeable exceptions are Gill and Moeller (2018) for Germany, and Kleinpeter and Lemaître (2009) or Bleuze et al. (2009) for France.

¹¹See Cao et al. (2009) for a survey of empirical strategies used to overcome this problem.

sity. In medium cities, where neither of the 3D's can substantially reduce car use, household carbon 'carprints' are much heavier. As population growth is particularly strong in these cities in France, specific policies targeting such conurbations are undoubtedly necessary.

Finally, this chapter also relates to the burgeoning literature on the environmental benefits of urban transit, in particular subway systems, that have been shown to reduce air pollutants in big cities (Chen and Whalley, 2012; Gendron-Carrier et al., 2020; Li et al., 2019). We depart from these papers by enlarging the focus on the whole urban transit system, as we take into account metro, bus, tram and rail networks, which are all credible car substitutes affecting city-Design in a more environmental-friendly way.

3.2 Data on fuel consumption and urban form

To analyze the interplay between driving and urban structure in France, we use confidential geo-coded micro-data and a comprehensive set of urban-form indicators, combining elements of residential density, urban-fabric design and sector diversity.

3.2.1 Fuel consumption: a household measure

We measure fuel consumption using the French 'Family Budget' household survey (*Budget des Familles*, hereafter BdF). This survey has been conducted every five years since 1972 by the French National Statistical Office (hereafter INSEE), and aims to assemble the expenditures and resources of a representative sample of households living in French Municipalities.¹² We restrict our empirical analysis to the 2001 and 2006 survey waves for two reasons. First, historical topographic data in vectorized format dates back to 1999 in France, and we cannot accurately characterize the urban environment of French households prior to this date. Moreover, since 2011, budgetary restrictions led the INSEE to drastically reduce the time coverage of the BdF survey, resulting in considerable censoring for a number of episodic expenditures such as fuel. By way of contrast, the 2001 and 2006 BdF surveys were conducted in six waves of eight weeks each, respectively from May 2000 to May 2001 and from March 2005 to March 2006, covering over 7,800 urban households (or almost 20,000 individuals) per year. The BdF surveys comprise two key data-collection tools:

Questionnaire A computer-assisted questionnaire (over three visits) records all household resources over the last twelve months, including regular resources (wages, independent earned income etc.), extraordinary revenues (gifts, lottery winnings, inheritance etc.) and

¹²Note that this is not panel data however, as households are not followed over time. Mainland France counts around 36,000 Municipalities, that are significantly smaller than their American counterparts, as the typical US municipal population is around 16,800 inhabitants, whereas it is around 1,660 inhabitants for French Municipalities.

other incomes (such as transfers from relatives). It also includes a rich set of household characteristics: municipality of residence,¹³ family composition (number of children, workers, job seekers and retired) and the educational attainment,¹⁴ occupation,¹⁵ age and gender of all household members.

Self-completion diary All household members aged over 14 are asked to fill out a self-completion diary of their detailed expenditure over two weeks. They can write in the amounts in by hand or attach cash-register receipts. All current expenditure is covered and broken down into 900 budgetary items, among which fuel expenditure broken down into gasoline, diesel and Liquefied Petroleum Gas (hereafter LPG) expenditure. We use the French average price of each type of fuel in 2001 and 2006 to convert these expenditures into volumes. As there is little spatial variation in fuel prices compared to that across gas stations of different brands in France, using national instead of local prices to calculate car emissions entails only little measurement error.¹⁶

Table 3.1 shows the descriptive statistics of the main BdF variables for households living in the Metropolitan Areas of mainland France.¹⁷ We measure household income by summing all the resources (apart from extraordinary revenues) of each individual in the household, divided by the number of Consumption Units (hereafter CU).¹⁸ In the original BdF surveys, fuel consumption is measured in litres, but for comparison purposes with North America, we convert these figures into US gallons.¹⁹ With one tank of fuel typically being 50 litres in France (approximately 13 gallons), annual average fuel consumption is about 20 tanks in France (265 gallons). We also measure the number of vehicles, whose variance is quite large. Actually, if 18% of our sample does not have any car (this figure is 10% in the US), some households may possess up to six vehicles.

¹³This information is subject to statistical disclosure.

¹⁴Classified as follows: 1. Doctorate, post-graduate or *Grande Ecole*, 2. University degree (Bachelors or Masters Degree), 3. University two-year degree (*DEUG*), 4. University professional degree, 5. Nursing and social training courses, 6. General Baccalaureat, 7. Technological Baccalaureat, 8. Professional Baccalaureat, 9. High-school technical qualification, 10. High-school professional and apprenticeship qualifications, 11. High-school general qualification (non Baccalaureat), 12. Primary school, 13. Without diploma.

¹⁵Classified as follows: 1. Individual farmers, 2. Businessmen, craftsmen, shopkeepers, 3. Executives and professionals, 4. Intermediate professions, administrative workers, technicians, 5. White-collars, 6. Blue-collars, 7. Unemployed, 8. Retired and non-workers who were never employed.

¹⁶The French administration publishes official statistics on daily fuel prices in gas stations only since 2007 (see <https://www.prix-carburants.gouv.fr/rubrique/opendata/>). In 2007, the French average price was 1.28 € per litre of gasoline, and 1.09 € per litre of diesel. The standard deviations of station prices are 7 euro cents per litre of gasoline and 8 cents per litre of diesel, i.e. 5 to 7% of the national average. Therefore, using national prices entails a measurement error that is presumably much smaller than the distortion that could be generated by back-casting local prices.

¹⁷Corsica and overseas territories are excluded from the analysis, as they are too specific.

¹⁸The INSEE calculates consumption units as follows: the first adult counts for 1, other members above the age of 14 years count for 0.5 and children under 14 for 0.3.

¹⁹One US gallon is equivalent to 3.8 litres.

Table 3.1: Descriptive statistics on fuel consumption and households' characteristics

Year	2001		2006	
	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
Household variables				
Fuel consumption (gallons)	295 (341)	8,180	234 (277)	2,890
No. of working adults	1.04 (0.88)	5	1.03 (0.87)	5
No. of non-working adults	0.84 (0.83)	6	0.82 (0.84)	6
No. of young children (< 16 y.o.)	0.55 (0.93)	7	0.55 (0.93)	6
No. of vehicles	1.20 (0.80)	5	1.27 (0.83)	6
Age (head of household)	50 (16.6)	99	49 (16.8)	99
Income (€ ₂₀₀₆)	33,182 (24,826)	510,952	33,665 (26,328)	688,617
Income per CU (€ ₂₀₀₆)	20,244 (14,850)	510,952	20,782 (14,768)	459,078
Number of urban households	7,812		7,797	

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006). A few outliers with very large incomes (the top 0.02% percentile of household income) were dropped from the raw data.

3.2.2 A set of quantitative measures of urban form

We supplement the BdF database with a number of metrics of urban form at the Municipality and Metropolitan Area levels. In France, the statistical definition of Metropolitan Areas (MAs hereafter) hinges on three underlying criteria: morphology (the continuity of the built-up environment, which draws the line between the predominantly urban and rural spaces), demography (a minimum threshold of inhabitants),²⁰ and functioning (a minimum number of jobs and commuters).²¹ As French MAs group together Municipalities with similar commuting patterns and rely on morphological and functioning criteria, they form a particularly relevant scale for investigating the impact of urban form on fuel consumption and car usage. To do so, we build a set of metrics of urban form at two levels: the MA -or city- scale, and the municipal -or neighborhood- one.

Descriptors of urban form computed at the MA level are the **number of inhabitants** in the household's MA (from 1999 and 2006 censuses), its **surface** (from Corine-Land-Cover database) and density of transportation infrastructure (from French National Geographical Institute (NGI) spatial database: BD-TOPO®). Mean population reported in Table 3.2 is 2.75M€, due to the presence of very large MAs (Paris, more than 11 million inhabitants) while there exist some very small ones (Volmerange les Mines, 9320 inhabitants). Their surface also exhibits large variations, from 21 km^2 to 14,508 km^2 for Paris. Density of public

²⁰An "Urban" Municipality is defined as a single unbroken spread of the built environment (with no distance between habitations of over 200 meters) with more than 2,000 inhabitants.

²¹From 1999 to 2010, the INSEE used to define a Metropolitan Area as a cluster of urban Municipalities hosting at least 5,000 jobs (called the "urban pole" of the MA) surrounded by a group of Municipalities socially and economically well integrated with this pole (i.e., according to the INSEE, at least 40% of the MA workforce is employed in the pole). Over our studied period, there were 352 MAs spread out over 50% of mainland France, and covering approximately 85% of the French population and employment (see the map provided in Appendix C.1.1).

transport stops (in km^{-2}) also exhibits large variations : some MA have no rail stations and only few bus services, but some large MAs exhibit 10 times the mean density. Road infrastructure are much more evenly distributed.

To build descriptors of urban form at the municipality level, we follow the classification first proposed by Cervero and Kockelman (1997), who define three broad dimensions of the built environment: Density, Diversity and Design (the “3 D’s”). Although Municipalities are our spatial unit of observation for Density and Diversity, the Design of the entire Metropolitan Area affects car usage through modal choices and travel flows, including commuting. We thereby compute our Design metrics at the two geographical levels.

Density Most observers agree that density is the first essential feature of urban development, which explains why it has been the most-explored dimension of land-use. As cities spread, their compactness falls, which is the most evident characterisation of urban sprawl. However, the effect of greater density gradients on driving is not entirely straightforward, making it difficult to determine the net impact of dense cities on fuel consumption. Compact cities make trips shorter, but this benefit may be - at least partly - canceled out by more-frequent trips, as the destinations are closer. In this paper, density is calculated as the number of inhabitants per km^2 of acreage in the household’s residential Municipality (Source: 1999 and 2006 censuses).²² Table 3.2, which lists summary statistics on the urban form of French Municipalities within MAs, shows that the average urban population density is around 3,200 inhabitants per km^2 , but may reach up 25,971 inhabitants per km^2 for central Paris in 2006.

Design Urban Design complements the quasi-mechanical effect of Density on fuel consumption. However, it has a greater scope of influence than the Municipality of residence as it determines modal choices and travel flows within MAs. The Design metrics we compute and study are the following:

Home-Business distance The existence of business centers may have potentially-adverse effects on commuting patterns, especially if they are located far from dense residential areas. A greater distance between jobs and housing is a typical consequence of urban sprawl. Unfortunately, the BdF surveys do not provide workplace information. Nevertheless, we use the great-circle distance between the home Municipality and the ‘Central Business District’ (CBD) of the home MA²³ to measure the household’s centrality or remoteness.²⁴ The Home-

²²This measure might not necessarily capture ‘true’ density, as some Municipalities have large areas of undeveloped land, while others are almost totally built-up. We can improve on this standard measure by using as the denominator the surface of developed-land drawn from the Corine-Land-Cover database, instead of the total surface area. Both measures producing similar results, we use standard density hereafter.

²³The CBD is the Municipality with the largest number of jobs in the MA.

²⁴Alternate metric is the average distance from residence to jobs, calculated by weighting great-circle distances between the Municipalities of each MA by the share of bilateral commuting flows reported in the 2006 census.

Table 3.2: Descriptive statistics on the urban form

YEAR	2001		2006	
	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
Urban-Form Variables				
CITY SIZE				
City population	2.75 M (4.44 M)	11.2 M	3.21 M (4.86 M)	11.8 M
City surface (km^2)	4,163 (5,501)	14,508	4,528 (5,726)	14,508
TRANSPORTATION MODES				
City rail stops density ($/km^2$)	0.018 (0.020)	0.14	0.018 (0.020)	0.14
City tram/bus stops density ($/km^2$)	0.42 (0.57)	3.90	0.42 (0.57)	3.90
Density of roads ($/km^2$)	0.474 (0.138)	1.607	0.474 (0.138)	1.607
DENSITY				
Population Density (<i>inhabitants</i> / km^2)	2,959 (4,519)	23,396	3,410 (5,282)	25,971
DESIGN				
Distance from residence to CBD (km)	8.55 (11.27)	71.20	9.02 (10.75)	58.37
Average commuting dist. in MA (km)	12.5 (4.25)	44.37	12.76 (4.63)	45.52
Dens. of pub. trans. in res. (<i>stops</i> / km^2)	4.85 (7.68)	34.13	5.20 (8.04)	34.24
Fractal dimension in residence	1.50 (0.18)	1.82	1.50 (0.19)	1.84
Road potential in the rest of the MA	14.46 (20.22)	69.01	16.06 (21.52)	69.01
Rail potential in the rest of the MA	1.26 (2.19)	8.46	1.44 (2.35)	8.46
DIVERSITY				
Herfindahl index of leisure activities	0.11 (0.17)	1	0.13 (0.20)	1
No. of MAs	156		181	
No. of Municipalities in MAs	1,379		1,674	

Note: Urban Municipalities sampled in the BdF surveys (INSEE, 2001 and 2006).

Sources: Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), and authors' own calculations.

Business distance is around 9 km on average, but can be over 70 km in large MAs such as Paris (see Table 3.2).

Transport accessibility The effect of distance to CBD can be mitigated by the design of transport infrastructure. The spatial extension of road and public-transit networks determines the households' ability to travel within the MA without a car.²⁵ To measure the connection of the household to the MA, we construct 'Transport Potential' indicators²⁶ based on the 2001 and 2006 versions of the BD-TOPO® topographical database developed by the French National Geographical Institute (NGI). The BD-TOPO® summarizes all the landscape elements of the French territory, to an accuracy of one meter, and in particular road and rail-transport networks. The 'Transport Potential' indicators are calculated as follows:

$$TP_{k,t}(x) = \sum_{k' \in MA, k' \neq k} \frac{dens_{k',t}(x)}{dist_{kk'}}, \quad (3.1)$$

This results in slightly longer trips on average (almost 13km). Our key findings continue to hold with this measure, as will be shown in section 3.3.3.

²⁵See among others Ewing and Cervero (2001).

²⁶In the same spirit as the 'Market Potential' indicator first proposed by Harris (1954).

where k is the Municipality of residence, $k' = 1, \dots, K$ are the other Municipalities in the MA and $dist_{kk'}$ the great-circle distance between the centroids of Municipalities k and k' .²⁷ The variable x is a measure of the transport supply in Municipality k' . This is alternatively the number of rail stations (including subway and tram stations) in the Municipality, or the length of its road network. The variable $dens_{k',t}(x)$ is thus the density of x per km² of acreage in municipality k' at time t .

However, transport is not only important for movement within a MA. For shorter trips, modal shift depends strongly on local transit systems (bus, tram and light rail) that are accessible close to the household residence. Unfortunately, the BD-TOPO® does not provide information on bus lines. We therefore add a comprehensive review of bus stops through OpenStreetMap in 2017 to our dataset, which we retropolate to 2001 and 2006 using the dates of line openings published either in French Official Journals or by local transport authorities. We then calculate the density of all public transport stops (railways, subways, trams and buses) in the Municipality of residence.²⁸

Fractal geometry and walkability Due to the contrasted history of French urban planning, very different urban morphologies coexist in France, as illustrated by Figure 3-1. Municipalities with historical legacy such as Roubaix (in the MA of Lille), have a highly connected fabric of small ancient streets lined with buildings of mixed land-use, that are relatively safe for pedestrians, unwelcoming to rapid driving, and favorable to social interactions²⁹. By contrast, other French Municipalities like Créteil (in the Paris MA) exhibit highly regular so-called 'modernist' morphologies reminiscent of the post-war car-friendly designs, with large fragmented housing and commercial compounds arranged geometrically on the edge of parking lots or big road arteries.

Previous works have measured the walkability of the local urban fabric via indicators such as street width, the number of roads that cross at junctions, number of building blocks, block length, car parks or dead-ends per acre.³⁰ We here consider a synthetic morphological index widely-used by quantitative geographers over the past two decades, but disregarded so far by economists: the fractal dimension of the local built-up area. This index, which is common to characterize irregular geometries in natural sciences, has been used since Frankhauser (1998) and Batty and Xie (1996) to classify urban morphologies.

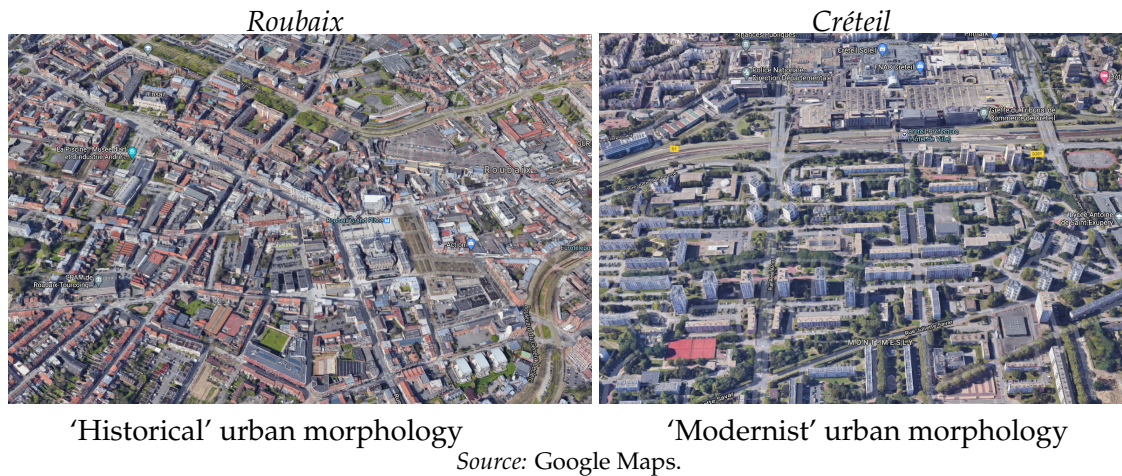
²⁷If the Municipality is a CBD, we calculate an 'internal' distance equal to two thirds of the equivalent radius of the Municipality (square-root of its surface area divided by π), which is the average distance to the CBD were the population spread uniformly and the Municipality a disk.

²⁸In the BD-TOPO®, rail and subway stations are weighted by the number of lines. For example, the 'Denfert-Rochereau' station in Paris counts as three stations, as three different rail lines connect there. The public-transit supply of a Municipality therefore increases with the number of connections, up to sometimes very large numbers, such as in Paris (over 34 public-transport stops per km²).

²⁹As noted by Jane Jacobs (1961), "...frequent streets and short blocks are valuable because of the fabric of intricate cross-use that they permit among the users of a city neighbourhood."

³⁰See the seminal paper of Cervero and Kockelman (1997), and also Ewing et al. (2015) for an extensive review.

Figure 3-1: Walkability and urban morphology of two Municipalities similar in all other respects



Mandelbrot (1982) coined the term ‘fractal’ to qualify intrinsically irregular objects whose mass is not evenly distributed, but scattered across space, and proposed a new metric to classify these objects: the ‘fractal dimension’, which is the ‘degree of inhomogeneity’ of a geometric object. The most common and robust way to calculate this dimension, which is also known as the Minkowski-Bouligand definition,³¹ is the following:

- Denote $(a_n)_{n \in \mathbb{N}}$ a series converging to zero, and cover the fractal object with a lattice of squares of size a_n ;
- Count the number $N(a_n)$ of squares in the lattice that intersect the fractal object;
- The fractal dimension is given by the limit $D = \lim_{a_n \rightarrow 0} \frac{\log(N(a_n))}{\log(1/a_n)}$.

This value connects to the classical geometric notion of dimension in the case of simple objects, and may be computed practically with a box-counting algorithm proposed by Liebovitch and Toth (1989) (see Appendix C.2).

A high fractal dimension then typically describes a set of heterogeneous clustered buildings whose sizes would follow a power law, typical of historical centers developed through a quasi-random demolition and reconstruction process. By contrast, a low fractal dimension corresponds to homogeneous suburbs composed of regular housing compounds, exemplary of contemporary developments.³² As emphasized by Salingaros (2003), “*historical cities are fractal, whereas the twentieth-century city is not*”.

This index is particularly well suited to measure walkability and pedestrian mobility. For instance, Osmond (2005) explains that a high fractal dimension favours walkability by

³¹See the comprehensive review of Schroeder (1991).

³²A near-zero power law corresponds to perfect homogeneity.

providing better connectivity and visual diversity. Based on a network-theoretical analysis corroborated by empirical examples, Yamu and van Nes (2019) also find that Dutch cities with higher fractal dimensions are associated with more walking and cycling. Moreover, De Keersmaecker et al. (2003) emphasize that car-dependent suburban areas display low fractal dimensions in Belgium.

We use the building footprint from BD-TOPO® to characterize the fractal geometry of the French urban fabric.³³ Our fractal index ranges from 0 to 2, the highest values being associated to Municipalities having the highest number of interlocked buildings of different scales. The average fractal dimension of French Municipalities is 1.5 (see Table 3.2). Typically, rural Municipalities have a much lower fractal dimension (below 1), while urban Municipalities usually range between 1 and 2. Fractal dimensions from 1 to 1.3 are typical of outer suburbs with leapfrogging or detached-housing developments. Medium dimensions (1.3 to 1.6) refer to large multi-family housing complexes. Larger figures (1.7 to 2) embody the more-complex built environments exemplary of old city centers, where buildings blocks of different sizes are arranged around a complex fabric of squares, avenues or narrow streets.

Figure 3-2: Differences in the fractal dimension of two Municipalities similar in all other respects



This fractal metric is obviously correlated with density. However, it captures the way buildings are distributed in space rather than density *per se*. Two municipalities with similar densities can have very different urban morphologies and hence, fractalities. For example, sparse tower blocks separated by large car parks can be as dense as low-rise terraced housing connected by narrow roads. However, these two morphologies produce very different driving behaviours. To illustrate, consider again Créteil and Roubaix. Both Municipalities have similar densities (7,939 inhab./km² and 7,262 inhab./km² respectively in 2006), similar distances to the CBD and similar transport accessibility.³⁴ However, they differ strongly

³³More details on this calculation are provided in Appendix C.2.
³⁴For instance, they both have a subway line that takes less than 30 minutes to go downtown.

in terms of fractal dimension, as illustrated in Figure 3-2. Créteil exhibits regular blocks of flats crossed by a grid of motorways, built from the mid 1950's to the early 1970's, whereas Roubaix is made of low-rise attached dwellings organized along a grid of narrow streets and large squares dating back to the 19th century. These different urban morphologies produce a fractal dimension of 1.65 for Créteil and 1.81 for Roubaix, the latter being close to the maximum value (that corresponds to Paris central districts).

Diversity The Diversity of local amenities constitutes our last 'D'. If households value local amenities, transport demand will depend strongly on the range of commercial and leisure activities available in the residence Municipality. The relationship between Diversity and fuel consumption is not straightforward, however. The more diverse the recreational and shopping opportunities, the shorter the distances needed to take advantage of these amenities. Nevertheless, the frequency of recreational trips may also increase with the number of entertainment and commercial activities available.

We measure Diversity via a Herfindahl index of retail and leisure activities in the home Municipality, using the matched employer-employee data from DADS (*Déclaration Annuelles de Données Sociales*) constructed by the INSEE from compulsory declarations made annually by all legal employers in France. These declarations provide longitudinal information about each employer (identifier, sector and location) and each employee (start and end date of each job spell, earnings, occupation, part-time/full time, permanent/temporary contract, occupation and working time).³⁵ We use the three-digit level of the 'Economic Nomenclature Synthesis' (NES) to calculate the market shares of the following activities in the home Municipality: restaurants (NES 553), bars and nightclubs (NES 554), cinemas (NES 991), museums, theaters and sport facilities (NES 923 to 927) and shops (NES 521 to 527). The Herfindahl index is then calculated as follows:

$$H_{k,t} = \sum_{s=1,\dots,S} \left(\frac{L_{k,t}^s}{L_{k,t}} \right)^2, \quad (3.2)$$

where $L_{k,t}^s$ is the number of jobs in sector s and Municipality k at time t , and S the total number of commercial and leisure activities taken into account.³⁶ This index ranges from $\frac{1}{S}$, the maximum level of Diversity, to 1, the minimum level of Diversity. There are some small Municipalities for which the Herfindahl cannot be calculated, as they are deprived of the leisure and commercial sectors, which censors the sample to Municipalities with more than one employee in these sectors. As we lose over 800 observations (5% of the total) when

³⁵The INSEE transforms the raw DADS data into files available to researchers under restricted access.

³⁶We focus exclusively on each employee's most remunerative activity, and do not count multiple times employees who work in different companies. To smooth out seasonal variations, we also restrict our calculation to *non-annexed posts*, i.e. job spells with working time greater than 30 days (or equivalently 120 hours), or a ratio of number of hours to total work duration of over 1.5.

Diversity is included in the regression, we provide two sets of estimates below (with and without this urban metric).

3.3 Empirical strategy and results

In this section, we detail the empirical strategy used to identify a ‘naive’ correlation and then a causal relationship between urban structure and fuel consumption.

3.3.1 Urban form and fuel consumption: Baseline estimations

Are city size descriptors sufficient to adequately describe the variety of driving behaviours, or would it be necessary to include explanatory variables at the neighborhood level ? To answer this question, we run a ‘naive’ OLS estimation restricted to city-size metrics, to which we may add a metric of the MA density of public transport (bus, tram, metro, train stops). The baseline OLS estimation is the following:

$$Fuel_{i(k,t)} = \alpha + \beta Population_{MA(k),t} + \delta Surface_{MA(k),t} + \gamma Transport_{MA(k),t}, \quad (3.3)$$

where $Fuel_{i(k,t)}$ is the fuel consumption (in gallons) of household i living in Municipality k at time t , and $X_{i(t)}$ a vector of the household characteristics including income per CU (in log), the number of working and non-working adults, the number of children under 16,³⁷ and the age, age-squared, sex, education and occupation of the household head. As city size variables are concerned, $Population_{MA(k),t}$ is the population of the MA of residence, $Surface_{MA(k),t}$ its surface and $Transport_{MA(k),t}$ its public transport and roads stock.

The coefficients β , δ and γ measure the impact of each dimension on fuel consumption, holding the other dimensions constant.

Table 3.3 shows the results of this ‘naive’ OLS estimation. Column (1) displays the point estimates with MA population and surface as sole geographic characteristics, and column (2) adds some descriptors of the density of public transport

Fuel consumption and household characteristics Unsurprisingly, income is positively associated with fuel consumption: richer households drive more, because they can afford it, and may prefer driving to other travel modes. As income per CU is multiplied by 2.7 annual fuel consumption rises by 70.1 gallons (column 1), around 25% of average French annual household fuel consumption. Family composition also matters: an additional working adult

³⁷We consider this threshold as the legal age for driving in France is 16, as long as an adult is also in the car. We thereby measure the impact on fuel of having children under 16, but not the extra consumption associated with their first vehicle.

Table 3.3: Household fuel consumption : OLS estimations

Dependent Variable: Fuel consumption (gallons)	(1)	(2)	(3)
HOUSEHOLD CHARACTERISTICS			
Log(Total income/CU)	70.1*** (4.14)	70.4*** (4.11)	70.4*** (4.11)
No. of working adults	124.7*** (12.40)	124.8*** (12.41)	124.8*** (12.41)
No. of non-working adults	73.4*** (7.49)	73.4*** (7.49)	73.4*** (7.49)
No. of young children (< 16 y.o.)	13.1*** (3.62)	13.2*** (3.62)	13.2*** (3.63)
Age (Head of household)	5.1*** (0.73)	5.1*** (0.73)	5.1*** (0.73)
Age-squared (Head of household) ÷ 100	6.7*** (0.55)	6.7*** (0.55)	6.7*** (0.55)
Female (Head of household)	-46.2*** (9.23)	-46.2*** (9.20)	-46.2*** (9.20)
CITY SIZE			
Log(Pop. in MA)	-14.2** (4.33)	-4.9 (6.60)	-3.5 (8.49)
Log(MA Surface)	-4.0 (5.88)	-13.6* (7.71)	-15.2+ (9.85)
TRANSPORTATION MODES			
Log(rail stops density in the MA)		-467.2** (198.57)	-462.4** (196.32)
Log(bus/tram stops density in the MA)		10.4 (11.31)	10.3 (11.32)
Log(density of roads in the MA)			-4.3 (15.56)
Year dummies	✓	✓	✓
Education dummies (Head of household)	✓	✓	✓
Occupation dummies (Head of household)	✓	✓	✓
Observations	15,609	15,609	15,609
R-squared	0.207	0.208	0.208

Notes: (i) OLS estimates drawn from equation (3.3); (ii) Robust standard errors in brackets (MA level); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; (iii) For the sake of clarity, the constant and coefficients associated with year, education and occupation dummies are not reported.

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

in the household is associated with higher annual fuel consumption of 124.7 gallons. This is to be compared to the 73.4 additional gallons associated with an additional non-working adult, and the 13.1 gallons from having one young child. The effect of a working adult is then around two times that of a non-working adult, and about ten times that of a child. Households headed by the elderly consume less fuel, as the elderly have fewer occasions to drive. The impact of age is not linear: the estimated coefficient on the linear term is significantly positive and that on the quadratic term significantly negative. Female-headed households use 46.2 gallons less than male-headed households.³⁸ Interestingly, when the sample is restricted to car owners only, the number of young children no longer significantly affects fuel consumption. This suggests that having young children requires vehicle purchase and therefore car ownership, without significantly changing the household travel demand.

Controlling for socioeconomic characteristics of the households is motivated by the existence of spatial sorting across neighborhoods that may blur the relationship we want to identify between urban form and fuel consumption. If low-income individuals live more often in areas that exhibit, for instance, low public transport connectivity, one may mistakenly identify the effect of income and the effect of the absence of public transport. However, if such association between a neighborhood's morphology and the socioeconomic characteristics of its inhabitants were to be systematic, it may not be meaningful to correct for the interaction between socioeconomics and geography. Appendix C.5 contains alternative specifications following such an hypothesis.

Fuel consumption and urban form As expected, the effect of city population on fuel consumption is negative. This effect, however, does not hold when we include the density of public transport in the MA among the regressors, which suggests that part of the reduction of fuel consumption with population is actually driven by the presence of heavy public transport (rail, including metro stops) in the largest cities. Moreover, the effect of city surface is either not statistically significant or exhibit a non-intuitive direction. Eventually, the densities of transport infrastructures are not significant, except for heavy rail that exhibit a highly significant effect. The specification directly drawn from the monocentric model thus appears misfounded.

From these results, we can make the hypothesis that the monocentric vision, where distance to city-center and density of transport modes would explain most of the variation in car use between cities, is not adequate. Notably, the absence of any effect of the city surface questions the hypothesis that city size explains the length of daily commuting. Moreover, the absence of any effect of the city road stock on car use is contradictory with the literature

³⁸Although their coefficients are not shown for clarity reasons, the occupation and diploma dummies are generally also very significant.

about the role of radial roads for suburbanisation (Baum-Snow, 2007). The absence of any effect of the density of light public transport is also puzzling, since they supposedly play a crucial role at the local level. However, as they are partly local, the effect of these variables may become significant if introduced at the neighborhood-level.

Indeed, the information provided by city-wide variables appears too scarce to adequately describe the diversity of individual situations faced by the households in our sample. Notably, even the evidence that heavy public transport drive the reduction of fuel consumption in large cities actually questions the pertinence of using city-wide public transport density as a predictor of car use. Indeed, heavy transportation infrastructure is usually very unevenly distributed across a city: eventually, local access to rail transport for urban peripheries could be more important *in se* than the overall stock of public transport in the city to determine car use. City-wide descriptors should thus at least be complemented by a neighborhood based set of urban form descriptors, notably to better describe access to the transportation network, modal choice or the frequency of trips, for which Cervero and Kockelman (1997) Density/Design/Diversity framework (hereafter 3D) appears as an ideal candidate.

A mixed-scales specification ? Is it possible to combine city-level variables inspired by the monocentric model with the 3D neighborhood-level variables inspired by a more local description of the causes of car trips ? Difficulties may emerge from the fact that some neighborhood characteristics are obviously correlated to city size. For instance, as noted above, Density at the neighborhood level is obviously correlated to city-wide population and surface. Similarly, availability of public transport, an element of urban form Design, may depend on a city's population, since such investments present important fixed costs. Diversity of local amenities may also depend on city size, since large cities may be more specialized at the local level. An adequate set of descriptors of the urban form is thus minimum set of non-redundant variables. Thus, we must determine is the neighborhood-level variables only explain part of the overall effect of city size, or if they provide a better description of the causes of car use.

To determine the possibility to combine the two approaches, we add successively the 3Ds to the previously used equation 3.3 specification. This specification is described by equation 3.4.

$$\begin{aligned}
 Fuel_{i(k,t)} = & \alpha + \beta Population_{MA(k),t} + \delta Surface_{MA(k),t} \\
 & + \gamma Density_{k,t} + Design_{k,t} \zeta + \eta Diversity_{k,t} + u_t + \varepsilon_{i(k,t)},
 \end{aligned}
 \tag{3.4}$$

where $Density_{k,t}^*$ is the log of population density in the residence Municipality, $Design_{k,t}^*$, the vector of log-variables capturing the design of the residential environment (road/rail transport potentials in the MA, home-work distance, density of public-transport stops and

fractality in the residence Municipality) and $Diversity_{k,t}^*$, the Herfindahl index capturing the diversity of residential amenities. We do not include city-wide transport since Table 3.3 showed their low significance.

The coefficients β , δ , γ , ζ and η measure the impact of each dimension on fuel consumption, holding the other dimensions constant. These are our main parameters of interest. With a semi-log specification, the size of these coefficients should be interpreted as follows. As residential density rises by 1%, annual fuel consumption is expected to change by $\zeta \div 100$ gallons. If shorter commutes are not offset by more-frequent trips, this coefficient should be negative. The same types of interpretation hold for the other urban-form log-variables. Table 3.4 reports the results of this estimation.

Density and distance to the CBD -the first variable of Design- are the only neighborhood-level variables directly connected to city-level descriptors of equation 3.4. Their inclusion is thus expected to have an important effect on the coefficient and significance of city size metrics. The coefficient of neighborhood density, when included in column (2), is highly significant, which suggests that neighborhood density plays a role alongside city density in the reduction of fuel consumption. However, due to the interaction between city and neighborhood densities which are highly correlated, the coefficients cannot be easily interpreted. The same applies for the inclusion of distance to CBD in column (3) : the existence of a significant effect suggests that neighborhood distance to central places play a role alongside city-surface in determining fuel consumption.

Our other 3D variables are not directly linked to the city-level metrics : their inclusion could then either explain part of the effect of city size, or be complementary to it. Inclusion in columns (4) to (7) of Design variables associated with transportation and local morphology affect negatively the point estimate and the significance of the city-level variables, which suggests that they explain most of the effect of city-size on fuel consumption. By contrast, the inclusion of Diversity in column (8) does not significantly affect the effect the city-level variables : it appears that Diversity channel was not taken into account by city-size variables : it appears complementary to it.

The inclusion of all variables in column (9) shows that they are all simultaneously statistically significant. The signs of the effect also appears aligned with theoretical expectations for all neighborhood-level variables. Though, for city-level ones, the sign is contrary to what we would expect, which is due to the high correlation between those variables and some of the 3Ds. If we remove these variables whose effect is difficult to interpret, though, in a 3D-only specification in column (10), we do not observe statistically significant differences from column (9), if not for a slight reduction in explained variance : the omission of city-level characteristics do not degrade too much the performance of our fuel consumption modelling. It appears that the neighborhood-level, 3D variables thus provide an adequate and parsimonious description of the effects of urban form on fuel consumption, as proposed by Certero

Table 3.4: Household fuel consumption and city size : Adding the 3 D's

Dependent Variable: Fuel consumption (gallons)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Log(MA population)	-14.2*** (4.33)	13.4*** (4.69)	-26.5*** (5.37)	11.1 (10.02)	-2.0 (6.99)	-3.0 (6.21)	3.0 (4.95)	-11.0*** (4.22)	12.3** (5.20)	
Log(MA surface)	-4.0 (5.88)	-20.8*** (6.30)	-6.8 (6.19)	-9.1 (5.82)	-0.4 (6.52)	-4.2 (8.81)	-13.0* (6.85)	-6.8 (5.89)	-22.1*** (6.51)	
DENSITY										
Log(Density of pop. in residence)		-36.0*** (4.41)							-14.3*** (4.86)	-12.2*** (4.59)
DESIGN										
Log(Distance from residence to CBD)			58.1*** (9.11)						14.3** (5.73)	13.3*** (4.34)
Log(Rail potential in the rest of the MA)				-71.1*** (20.57)					-60.1*** (8.09)	-56.1*** (8.79)
Log(Road potential in the rest of the MA)					-24.7** (12.26)				21.7*** (6.22)	15.1*** (5.69)
Log(Density of pub. transit in residence)						-37.3*** (6.59)			-8.0*** (3.05)	-9.9*** (3.06)
Fractal dimension in residence							-280.5*** (47.71)		-79.4** (38.08)	-82.8** (37.76)
DIVERSITY										
Herfindahl index in residence								133.9*** (21.54)	26.2* (13.44)	29.1** (13.56)
Year dummies	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609
R-squared	0.207	0.230	0.228	0.214	0.209	0.220	0.227	0.213	0.235	0.234

Notes: (i) OLS estimates; (ii) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, as well as the age, age-squared, sex, education and occupation of the household head; For the sake of clarity, neither these coefficients nor the constant are shown.

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

and Kockelman (1997).

In this latter case, we find a negative impact of **Density**, with a significant semi-elasticity at -12.2 (column 10). Multiplying by 2.7 municipal density within the same city would thus produce annual fuel savings of at most 12.2 gallons for urban residents. Put differently, a typical driver in the municipality of Toulouse -the center of Toulouse MA- where density is around 4115 inhabitants/ km^2 consumes ten less gallons per year than an observationally-equivalent driver in the municipality of Saint-Alban (less central neighborhood in the same MA, where density is around 1400 inhabitants/ km^2) via the density channel. These effects are larger if we compare areas where density varies by greater magnitudes: the less dense municipality of Toulouse MA (Lapayère, with 11 inhabitants per km^2) consumes $\ln(4115/11) \times 10.3 \cong 60$ more gallons (approximately 4 tanks, or one third of the average household fuel consumption in France) per year than an observationally-equivalent household in Toulouse center, *ceteris paribus*. More generally, the impact of density is less marked in France than in other countries, as the estimated elasticity ($-\frac{10.3}{265} = -0.04$ at the sample-mean) is half the average figure in the meta-analysis of Stevens (2017). It is nonetheless in line with the mean elasticity reported by Ahlfeldt and Pietrostefani (2019a) for commuting distances (-0.06).

Design metrics have a variety of effects. Dividing by 2.7 the distance from residence to CBD would save 13.3 gallons (column 10) which represents a 0.06 elasticity at the mean of our sample. Improving railway access leads to a fall in fuel consumption of an order of magnitude larger than the distance effect: roughly doubling municipal rail potential in a neighborhood by regard to rest of the city helps residents save 56.1 gallons or around 4 tanks per year, which translates into a 0.22 elasticity at the sample-mean. Conversely, road improvements increase fuel consumption, but to a lesser extent since doubling road potential would increase annual consumption by a bit more than one fuel tank (a 0.07 elasticity at the sample-mean). As such, a rail network with wide urban coverage can be a very effective substitute for car use. Last, local public-transit systems yield further significant environmental gains (a 0.03 elasticity at the sample-mean).

Moreover, urban morphology has a strong and significant pro-environmental effect. A 10% difference in the fractal dimension, similar to the Roubaix-Créteil gap above, translates into a reduction of $\ln(1.1) \times 82.8 \cong 8$ gallons per year (column 1).³⁹

By way of comparison, Glaeser and Kahn (2010) find semi-elasticities of 117 and 64 gallons for respectively density and distance to CBD in the US. These figures are not directly comparable to ours, however. First, US cars consume around twice as much fuel per km as

³⁹This impact is robust to the inclusion of other simpler morphological variables, such as the share of the built-up area or the minimum/maximum elevation.

French cars.⁴⁰ Second, the average distance to CBD in the US is approximately 23 km, but only half that figure in France (so that doubling distance implies a far greater rise in number of kilometers). Once we account for this difference, the US density coefficient is around four times that in France, and the distance coefficient twice as large. Moreover, if we restrict the urban-form variables to those in Glaeser and Kahn (2010) (only density and distance to CBD), the density semi-elasticity is 21.3 gallons which leads to a magnitude in line with that in the US literature, after the two corrections mentioned above.⁴¹ The remainder of this gap may be explained by the inclusion of the other D's and the fact that we account for many more household characteristics than do Glaeser and Kahn (2010).

Diversity has also a positive but less significant impact on fuel consumption in French cities. Within the same city, changing commercial and leisure diversity from average homogeneity ($H = 1/7 = 0.14$) to perfect homogeneity ($H = 1/14 = 0.07$) produces $0.5 \times 29.1 \cong 15$ fewer gallons per year (column 10), comparable to the effect of the Density and Design channels. Accounting for Diversity also sharply reduces the Density effect.

Should we center neighborhood variables at the MA level ? The coexistence of neighborhood -municipality- and city -MA- variables in the same statistical model poses the question of the functional form of the specification. We have seen that the inclusion of density and distance variables at the neighborhood level, notably, render the interpretation of city-level population and surface coefficient difficult. Should we include these neighborhood variables in absolute level or should they be centered at the city level ? In that latter case, equation 3.4 should use the following variables :

$$\begin{aligned}
 Density_{k,t}^* &= Density_{k,t} - Density_{MA(k),t} \\
 Design_{k,t}^* &= Design_{k,t} - Design_{MA(k),t} \\
 Diversity_{k,t}^* &= Diversity_{k,t} - Diversity_{MA(k),t}
 \end{aligned} \tag{3.5}$$

Indeed, since city-level variables may be correlated with neighborhood-level variables, it could make sense to center neighborhood-level predictors at the city level, so that their inclusion does not disturb the estimation of city-level effects. In such a specification, city-level effects would describe -and be estimated on- between-city differences in fuel consumption, while neighborhood level effects would describe -and be estimated on- intra-urban variance of fuel consumption. Table 3.5 reports the results of such an estimation.

We observe that the coefficients of city-level variables are indeed not affected by the inclusion of centered neighborhood-level ones. However, in the most comprehensive specifi-

⁴⁰US cars produced in 2006 consumed 9.8 litres per 100km, as against 4.7 litres for French cars.

⁴¹The corresponding tables are available upon request.

Table 3.5: Household fuel consumption and city-size with 3 D's centered at MA level

Dependent Variable: Fuel consumption (gallons)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Log(MA population)	-14.2*** (4.33)	-14.4*** (4.31)	-14.3*** (4.31)	-14.3*** (4.33)	-14.4*** (4.34)	-14.2*** (4.30)	-14.3*** (4.30)	-14.2*** (4.31)	-14.3*** (4.30)	
Log(MA surface)	-4.0 (5.88)	-4.5 (5.85)	-4.9 (5.85)	-4.4 (5.89)	-4.4 (5.89)	-4.8 (5.86)	-4.5 (5.83)	-4.1 (5.86)	-4.8 (5.84)	
DENSITY										
Log(Density of pop. in residence)		-37.6*** (4.57)							-10.3* (5.35)	-10.3* (5.32)
DESIGN										
Log(Distance from residence to CBD)			62.4*** (9.43)						15.7*** (5.84)	14.2*** (5.70)
Log(Rail potential in the rest of the MA)				-210.2*** (5.78)					-99.5*** (21.74)	-100.5*** (22.16)
Log(Road potential in the rest of the MA)					-193.4*** (35.28)				45.6+ (30.49)	48.1 (31.02)
Log(Density of pub. transit in residence)						-52.5*** (3.46)			-9.7*** (4.15)	-9.1** (4.31)
Fractal dimension in residence							-316.5*** (50.69)		-102.9*** (46.43)	-107.2*** (48.88)
DIVERSITY										
Herfindahl index in residence								149.2*** (23.72)	36.4** (14.63)	37.7** (14.56)
Year dummies		✓	✓	✓	✓	✓	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609
R-squared	0.207	0.230	0.228	0.220	0.219	0.225	0.227	0.213	0.233	0.221

Notes: (i) OLS estimates; (ii) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, as well as the age, age-squared, sex, education and occupation of the household head; For the sake of clarity, neither these coefficients nor the constant are shown.

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

cations in columns (9) and (10), one can observe that some neighborhood variables (notably access to roads) are no more significant at the neighborhood level. However, one can doubt that this channel (well known in the literature, notably Baum-Snow (2007)) is now taken into account in city-level variables : the inclusion of road density had indeed no significant effect in Table 3.3.

Actually, elegant it may be, this approach heavily relies on the hypothesis that city-level variables would adequately account for the differences in car usage between cities. The results in Table 3.3 suggest that this is not the case, notably as far as the effects of transportation infrastructure are concerned. For instance, in equation 3.4, the presence of a public transportation network is not specified at the city level (since it blurs the effects of other city-wide variables in Table 3.3) : we thus rely, for between city comparisons, on the hypothesis that variations in fuel consumption between cities due to the presence of a metro would be explained by city size, that conditions the building of a metro network. However, this does not take into account that public transport also depends on geology⁴² and political factors⁴³ as much as on city population and surface. Using only city-size metrics to account for differences in public transport infrastructure across cities could thus be misleading. A similar issue appears with the fractal dimension of a city's neighborhoods, which may depend on their history, notably the presence of war destructions, more than depend on city size only. Centering these variables at the MA level would thus deprive our between-city analysis from many pertinent dimensions. We thus choose not to center neighborhood specific variables at the MA level.

However, appendix C.6.1 reports the results of the following sections of this chapter with 3D metrics centered at the MA level. Interestingly, the main estimation results are not affected by this operation. Further results in Appendix C.7 shed light on the limits of such approach when trying to reconstruct mean fuel consumption for each city : the choice of a monocentric paradigm and a linear model limits the capacity to account for observed non-linearities in relationship between fuel consumption and city size.

3.3.2 Urban form and fuel consumption: Causal estimations

For the rest of the chapter, for clarity reasons and since the coefficients of city-level variables are difficult to interpret in the presence of non-centered neighborhood-level variables, we will describe urban form with the sole neighborhood variables, which we have seen to be perfectly adequate to that effect. However, the results of the following steps including

⁴²Rennes and Toulouse's MAs have built a metro network due to the low cost of boring tunnels in local geology, while Bordeaux and Nantes, much larger cities, have been forced to develop only tramways, due to instability of alluvial subsoil in the bottom of the estuary of the Garonne and Loire rivers.

⁴³See Appendix A.1.1 for a description of the political roots of the unequal development of tramways in French cities

city population and surface are reported in Appendix C.6.2 and largely consistent with the results presented *infra*.

We face two main empirical challenges to draw causal estimates from equation (3.3): the sorting of households with specific preferences for car driving across Municipalities and the endogeneity arising from either omitted counfounders correlated with one of our 3D's, or from reverse causality between air pollution and households' location choices.

Sorting A first empirical challenge is that car ownership is not random across our sample but may be correlated with some unobserved factors of location choice. For instance, individuals who particularly enjoy driving are more likely to own a car and locate far from job centers, in low-density areas with remote public-transport services that they do not value anyway. Conversely, those who dislike driving and prefer walking, cycling or taking public transport may self-select into denser areas where these options are available and choose not to own a car. In such cases, the effect of density on fuel consumption will likely be overestimated, and any attempt to change the urban form may misfire, as individuals may not behave differently in more compact, better designed or more diverse residential areas (Brownstone and Golob, 2009; Grazi et al., 2008; Kahn and Walsh, 2015; Duranton and Turner, 2018). This can be seen as a omitted variable bias - we do not observe intrinsic preferences for driving that may influence location choices, as well as a selection bias - households with cars may thus differ in significant unmeasured ways from those without cars.⁴⁴

Such potential bias may be mitigated by the inclusion of many household controls. Nevertheless, as we likely do not include all of the variables influencing residential choice, the error term in equation (3.4) likely remains correlated with the explanatory variables, which may produce inconsistent estimates. It could also be mitigated using panel data through the inclusion of household fixed-effects. However, the BdF survey is not conducted on the same sample and does not allow to follow households across years.

We thus pursue two different strategies to take into account this potential bias. First we run OLS regressions on the subset of urban households with cars which allows to evaluate the intensity of the *selection* bias by focusing on the subgroup of car-owners. We obtain very similar results (see column 2 of Table 3.6) for geographical variables, the main difference being that the point estimates for Density and rail public transport drop respectively by 30% and 20%, and the point estimates for Diversity raises by 20% (though the differences are statistically insignificant). This is consistent with car ownership being negatively correlated

⁴⁴Note that there is also a censoring issue, as a number of households do own cars but do not report fuel purchases during the survey period when they self-completed their expenditure diary. The measure of fuel consumption therefore reflects classic storage behaviour: some households may start the survey period of diary completion with a full fuel tank, and so report zero fuel expenditure. We cannot do much about this issue, except to provide robustness checks on the restricted sample of car owners, who must at some point have spent money on fuel.

with the presence of urban transit. As for individual characteristics, we observe a significant drop in the impact of the household income, as car ownership obviously depends on wealth. Moreover, the effect of young children becomes insignificant: *ceteris paribus*, the presence of young children seems to be more a cause of car ownership than lower fuel consumption *per se*. Globally, it appears that the regression restricted to car-owners give largely similar results to the whole sample regression : the selection bias appears limited.

Second, to precise this result, we apply a Heckman (1979) two-step procedure with selection for car ownership, which takes into account the *omitted variable* bias due to the potential dependency of car ownership to unobserved factors of location choice, i.e. that car owners could have a car because they value some unmeasured individual variable captured in the error term of equation (3.3) : the possession of a garage for instance. In other words, these households will get into the sample of car owners not because they live in a particular place with specific D 's, but because they have large error terms.

To deal with this issue, the first step of the 'Heckit' consists of the following Probit equation that expliciteley models car ownership :

$$\text{Prob} \left(\text{car ownership}_{i(k,t)} \right) = f \left(\alpha_P + \text{Density}_{k,t} \beta_P + \text{Design}_{k,t} \delta_P + \text{Diversity}_{k,t} \gamma_P + X_{i(t)} \theta_P + u_t \right),$$

where $\text{Prob} \left(\text{car ownership}_{i(k,t)} \right)$ is the probability that household i living in Municipality k owns at least one car at time t , with $X_{i(t)}$ being the same vector of household characteristics determining participation (i.e. car ownership) as that in equation (3.3).

In a second step, we re-estimate equation (3.3) adding the inverse of the Mills ratio⁴⁵ from the Probit regression, and exclude the number of young-children from the vector $X_{i(t)}$. Note that, technically, the Heckman model is identified even when the same independent variables appear in both the selection and outcome equations. However, in this case, identification relies only on the distributional assumptions regarding the residuals, and not on the choice of explanatory variables. In other words, identification is based on non-linearities, with a risk of more-imprecise estimates. It is therefore preferable to have at least one independent variable in the selection equation that does not appear in the outcome equation. We have reported above that the number of children under 16 determines car ownership but not fuel consumption, which constitutes our estimation exclusion restriction.

However, the introduction of a correction for a selection bias does not solve every empirical issue.

Endogeneity issues A second empirical challenge comes from endogeneity issues that may arise from reverse causality and from potential other omitted variables. Indeed, correcting

⁴⁵Calculated as $\text{Mills}(x) = \frac{F(x)}{f(x)}$, where x is the probability of car ownership from the Probit step, and f and F are the density and cumulative distribution functions of the normal distribution.

Table 3.6: Household fuel consumption and urban form: OLS estimations

Dependent Variable: Fuel consumption (gallons)	All households (1)	Motorized households (2)
HOUSEHOLD CHARACTERISTICS		
Log(Total income/CU)	70.4*** (4.11)	61.9*** (5.14)
No. of working adults	113.1*** (13.38)	104.2*** (13.73)
No. of non-working adults	70.1*** (7.86)	69.8*** (8.64)
No. of young children (< 16 y.o.)	7.9*** (2.77)	3.4 (3.05)
Age (Head of household)	3.7*** (0.70)	4.3*** (0.92)
Age-squared (Head of household) ÷ 100	-5.5*** (0.54)	-6.7*** (0.85)
Female (Head of household)	-39.0*** (7.92)	-32.2*** (10.54)
DENSITY		
Log(Density of pop. in residence)	-12.2** (4.59)	-10.1** (4.81)
DESIGN		
Log(Distance from residence to CBD)	13.3*** (4.34)	11.4** (4.65)
Log(Density of pub. transit in residence)	-9.9*** (3.06)	-8.5** (3.38)
Fractal dimension in residence	-82.9** (37.76)	-83.8** (36.20)
Log(Road potential in the rest of the MA)	15.1** (5.69)	14.0** (5.92)
Log(Rail potential in the rest of the MA)	-56.1*** (8.79)	-47.0*** (9.86)
DIVERSITY		
Herfindahl index in residence	29.1* (13.57)	31.3** (14.27)
Education dummies (Head of household)	✓	✓
Occupation dummies (Head of household)	✓	✓
Year dummies	✓	✓
Observations	15,609	12,889
R-squared	0.234	0.157

Notes: (i) OLS estimates drawn from equation (3.3); (ii) Robust standard errors in brackets (MA level); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; (iii) For the sake of clarity, the constant and coefficients associated with education, occupation and year dummies are not reported.

Sources: *Budget des Familles* survey (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

the selection bias arising from car ownership does not take into account every omitted variable bias. Our 3D metrics could still be correlated with unobserved determinants of car use, such as historical amenities (for instance Garcia-López et al. (2018) showed that suburbanization is reduced in presence of historical amenities, which also constitute obvious unobserved determinants of car use in our specification). Moreover, our 3D may also be simultaneously determined by car use, for instance through the increase of air pollution.

Among our 3D metrics, Density is the most likely to correlate with unobserved local determinants of car usage (especially historical amenities), and also the most likely to be simultaneously determined by some effects of car use (notably air pollution), while Design and Diversity have more chance of being conditionally exogenous, once the spatial sorting of individuals has been accounted for.

To address endogeneity concerns associated with density, we require instrumental variables inducing exogenous variations in this variable without affecting fuel consumption directly. Long lagged densities are *a priori* good candidates as they can remove any endogeneity bias caused by contemporaneous local shocks to fuel consumption. A pertinent historical instrument is the number of inhabitants per km² of the municipality in 1901, which provides a local source of variation in Density through urban settlements path-dependency.⁴⁶

We supplement these historical instruments with geological categorical variables drawn from the European Soil Database, which reports a detailed local typology of the topsoil and subsoil mineralogy, available water capacity, hydrogeology, organic carbon content, erodibility and depth to rock.⁴⁷ Soil characteristics influence historical urban settlements through many dimensions. First, geology is arguably one important catalyst of land fertility, in particular topsoil mineralogy and water capacity, that we prioritize accordingly. Topsoil organic carbon content also conditions fertility, even though it is also arguably affected by land use. Moreover, soil water capacity presumably affects urban settlements through flood avoidance, while low erodibility and depth to rock were originally crucial to ensure building stability after construction. The validity of exclusion restrictions for such geological characteristics is justified by the limited influence of agricultural productivity on present residential choices, and by technological progress in the building industry which has freed urban developers from soil constraints.

One must note that, conditional to the validity of our exclusion restrictions, this IV approach may also eliminate part of the omitted variable bias due to the selection effect seen previously. It would thus constitute our preferred specification.

⁴⁶Our data source is the history of Municipal Populations masterized by INSEE in 2019: *Historique des populations communales: Recensements de la population 1876-2017*.

⁴⁷The ESDB is the most comprehensive database on European soil characteristics, available online at <https://esdac.jrc.ec.europa.eu/content/european-soil-database-v20-vector-and-attribute-data>. We rely on a set of vectorized maps similar to the raster data used by Combes et al. (2010) and Borck and Schrauth (2021). When geology is missing for a Municipality (typically, central Paris, where the soil is too artificialized), the reported features of the closest municipality are imputed, as in Combes et al. (2010).

The 2SLS specification we finally estimate is the following:

$$Fuel_{i(k,t)} = \alpha_2 + \widehat{Density}_{k,t}^* \beta_2 + Design_{k,t}^* \delta_2 + Diversity_{k,t}^* \gamma_2 + X_{i(t)} \theta_2 + u_t + \varepsilon_{i(k,t)}, \quad (3.6)$$

where $\widehat{Density}_{k,t}^*$ is drawn from the first-stage regression:

$$Density_{k(i,t),t}^* = Z_k \lambda_1 + Design_{k,t}^* \delta_1 + Diversity_{k,t}^* \gamma_1 + X_{i(t)} \theta_1 + \mu_t + \varepsilon_{i(k,t)}, \quad (3.7)$$

with Z_k the set of excluded historical and geological instruments, centered at the MA level similarly to the variable they instrument.

Results Table C.8 provides the results from both our IV (column 2) and Heckman (column 3) approach. The geological instruments used in column (2) are topsoil mineralogy and available water capacity, but Table 3.8 display the results from other sets of geological instruments as a further robustness check.

In all specifications, household characteristics attract similar estimated coefficients across OLS and 2SLS specifications. As such, we will not show or discuss these estimates below. Instrumentation of the density effect in Table C.8 column (2) shows no statistical difference with our baseline OLS estimates transcribed in column (1), though they are larger by a gross 20%. Therefore, endogeneity does not bias too largely OLS estimates. The point estimates associated with the fractal and Diversity variables exhibit smaller magnitude and significance. The other coefficients are little affected by instrumentation. The Shea partial R-squared statistic shows that our instruments explain a non-negligible share of density, once the potential inter-correlations between instruments are taken into account.⁴⁸ However, we should check that this does not come about at the expense of their strength. We carry out a more formal assessment via the weak-instrument tests in Stock and Yogo (2005). The instruments are not weak, as the Cragg-Donald F-statistic is far above the critical value reported for a 5% maximum IV relative bias (19.86). Equally, the null of instrument validity is not rejected if we run a Hansen J-Statistic test for overidentifying restrictions, as the p-value is above 5%.

The right-hand panel of Table C.8 lists the coefficients from our ‘Heckit’ (column 3) and Probit (column 4) regressions.⁴⁹ We observe a small positive selection bias for household characteristics and Density. By contrast, the selection bias is negative for distance, consistently with the existing literature (Stevens, 2017). The coefficients of the other urban-form variables rise slightly (in absolute value) from approximately 10% for road potential to approximately 20% for the fractal dimension and rail potential. However, none of these changes appear to be statistically significant. Selection does not entail a too large underestimation of the 3 D’s impact on fuel consumption, which is not surprising since numerous

⁴⁸The first column of Table C.12 in Appendix C.8 presents the first-stage regression.

⁴⁹Only the marginal effects are listed for the Probit.

household controls are already included in our model specification.

As shown in column (4), including the inverse of the Mills ratio produces a significant positive lambda term: the error terms in the selection and outcome equations are positively correlated. Unobserved factors that increase car ownership are then also associated with greater fuel consumption. Regarding the size of the marginal effects (column 4), doubling density (respectively distance to CBD and road potential) reduces (increases) car ownership by less than 2%, while the marginal effects of other variables are up to ten times larger. Increasing fractality from the value of a Municipality like Créteil to the value of a Municipality like Roubaix (which is equivalent to a 10% increase) reduces car ownership by 1.3%. Nonetheless, due to the low variability of the fractal index, its marginal effect must be interpreted with caution.

Table 3.8 reports the 2SLS point estimates drawn from further 2SLS regressions combining our historical instruments with different sets of geological instruments capturing exogenous variations in construction costs rather than in land fertility (i.e. erodibility, depth to rock or organic carbon content). We find very similar point estimates. In particular, the density coefficient is still highly significant and OLS still slightly biased downward, while the point estimates for the fractal and Herfindahl indices fall by 10 to 25%, but the differences are not statistically significant. The other 2SLS point estimates are of similar magnitude as the OLS point estimates. The Shea partial R-squared statistics show that these alternative instruments also explain a significant part of density.

3.3.3 Robustness checks

Before proceeding any further, this subsection checks whether our 3 D's bring valuable information over and beyond simpler urban metrics, and whether our results are robust to several further econometric robustness checks.

Comparison with a more standard monocentric framework First, our 3 D's approach can be contrasted with a simpler urban monocentric paradigm whereby cities would emerge as concentric rings of Municipalities ranging from city-centers to remote suburban outskirts under the influence of city-centers Fujita (1989). To do so, we estimate the following specification:

$$Fuel_{i(k,t)} = \alpha_0 + \alpha_1 PCC_k + \alpha_2 PIS_k + \alpha_3 IS_k + \alpha_4 OS_k + \beta M_k + X_{i(t)}\theta + u_t + \epsilon_{i(k,t)}, \quad (3.8)$$

where M_k is one of the 3 D's metrics exposed *supra*. Six dummies embody a standard monocentric classification that has been used in previous literature:⁵⁰ PCC_k , PIS_k , IS_k , OS_k indicate whether the Municipality of residence k is a Parisian City-Center, a Parisian Inner Suburb, a

⁵⁰See for instance Kleinpeter and Lemaître (2009) for France, or Borck and Schrauth (2021) for Germany.

Table 3.7: Household fuel consumption and urban form: Causal estimations

Dependent Variable: Fuel consumption (gallons)	OLS (1)	2SLS (2)	Heckit (3)	dx/dy Probit (4)
HOUSEHOLD CHARACTERISTICS				
Log(total income/CU)	70.4*** (4.11)	70.4*** (4.11)	83.3*** (7.20)	0.089*** (0.005)
Number of working adults	113.1*** (13.38)	112.9*** (13.43)	119.3*** (5.52)	0.086*** (0.005)
Number of non-working adults	70.1*** (7.86)	70.0*** (7.82)	82.0*** (4.93)	0.058*** (0.004)
Number of young children (16 year old)	7.9*** (2.77)	7.9*** (2.77)		0.014*** (0.003)
Age (Head of household)	3.7*** (0.69)	3.7*** (0.69)	7.5*** (1.27)	0.010*** (0.001)
Age square (Head of household) / 100	-5.5*** (0.54)	-5.5*** (0.54)	-10.5*** (1.34)	-0.012*** (0.001)
Female (Head of household)	-39.0*** (7.92)	-38.9*** (7.83)	-56.1*** (8.00)	-0.088*** (0.007)
DENSITY				
Log(residential population density)	-12.2*** (4.59)	-16.7** (6.90)	-11.7*** (4.19)	-0.015*** (0.004)
DESIGN				
Log(distance from residence to CBD)	13.3*** (4.34)	11.8*** (4.15)	15.6*** (4.46)	0.014*** (0.004)
Log(Density of pub. transit in residence)	-9.9*** (3.06)	-8.6** (3.37)	-12.1*** (3.63)	-0.011*** (0.003)
Fractal dimension in residence	-82.8** (37.76)	-62.6* (34.33)	-100.2*** (31.06)	-0.103*** (0.028)
Log(Road potential in the rest of the MA)	15.1*** (5.69)	15.8*** (6.01)	16.9*** (5.07)	0.016*** (0.005)
Log(Rail potential in the rest of the MA)	-56.1*** (8.79)	-54.4*** (8.58)	-65.0*** (9.44)	-0.072*** (0.007)
DIVERSITY				
Herfindahl index in residence	29.1** (13.56)	25.0* (14.72)	29.0* (15.79)	-0.001 (0.020)
Education dummies (Head of household)	✓	✓	✓	✓
Occupation dummies (Head of household)	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.165		
Cragg-Donald F-Stat		435.9		ρ : 0.459
C-Stat (p-value)		2.212 (0.137)		σ : 297.5
Hansen J-Stat (p-value)		14.53 (0.069)		λ : 136.5
Shea Partial R-squared (density)		0.201		

Notes: (i) Robust standard errors in parentheses (MA level); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, + $p < 0.15$; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) For the sake of clarity, the dummy coefficients and the constant are not reported; (iv) The instruments are population density in 1901 (in log), distance to the largest Municipality of the home MA in 1806 (in log), as well as topsoil mineralogy and available water capacity).

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

Table 3.8: Household fuel consumption : 2SLS with other sets of geological instruments

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	Mineralogy (top) Hydrogeology Density 1901	Water (top) Hydrogeology Density 1901	Organic content Hydrogeology Density 1901	Depth to Rock Hydrogeology Density 1901	Erodibility Hydrogeology Density 1901
DENSITY						
Log(Density of pop. in residence)	-12.2*** (4.59)	-16.7** (6.90)	-17.5*** (6.13)	-17.2*** (6.28)	-21.0*** (6.28)	-17.2** (6.77)
DESIGN						
Log(Distance from residence to CBD)	13.3*** (4.34)	11.8*** (4.15)	11.6*** (4.17)	11.7*** (4.20)	10.4** (4.12)	11.7*** (4.19)
Log(Density of pub. transit in residence)	-9.9*** (3.06)	-8.6** (3.37)	-8.4** (3.38)	-8.5*** (3.27)	-7.4** (3.33)	-8.5** (3.36)
Fractal dimension in residence	-82.8** (37.76)	-62.6* (34.33)	-59.0+ (38.81)	-60.6+ (38.51)	-43.4 (38.83)	-60.5+ (39.09)
Log(Road potential in the rest of the MA)	15.1*** (5.69)	15.8*** (6.01)	16.0*** (5.78)	15.9*** (5.80)	16.5*** (5.83)	15.9*** (5.87)
Log(Rail potential in the rest of the MA)	-56.1*** (8.79)	-54.4*** (8.58)	-54.0*** (8.85)	-54.2*** (8.86)	-52.7*** (8.84)	-54.2*** (8.79)
DIVERSITY						
Herfindahl index in residence	29.1** (13.56)	25.0* (14.72)	24.2* (14.01)	24.5* (13.76)	21.0+ (14.23)	24.5* (14.05)
Household characteristics	✓	✓	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609	15,609	15,609
R-squared	0.234	0.165	0.165	0.165	0.165	0.165
C-Stat (p-value)		2.212 (0.137)	2.810 (0.094)	2.357 (0.125)	4.675 (0.031)	2.324 (0.127)
Hansen J-Stat (p-value)		14.53 (0.069)	11.31 (0.126)	11.78 (0.161)	16.21 (0.039)	12.49 (0.187)
Cragg-Donald F-Stat		435.9	545.9	480.3	464.4	430.6
Shea Partial R-squared (density)		0.201	0.219	0.217	0.211	0.216

Notes: (i) Robust standard errors in parentheses (MA level); ** $p < 0.01$, * $p < 0.05$, $p < 0.10$, $^+ p < 0.15$; (ii) The household characteristics include income per CU (in log), the number of working and non-working adults, the number of children under 16, and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

non-Parisian Inner Suburb or an Outer Suburb of a particular MA.⁵¹ Last, u_t is a year dummy and $\varepsilon_{i(k,t)}$ the error term.

The $\alpha_{j=1,\dots,6}$ coefficients show the effect of residence-type j on fuel consumption relative to the omitted category of a non-Parisian city-center.

The results from this set of regressions appear in Table 3.9. Column (1) shows the effect of the residence type on fuel expenditure. Columns (2) to (8) add each of the three D's successively to see how they interact with a particular residence-type, as a first attempt at identifying the mechanisms behind the effect of urban form.

There are sharp differences in fuel consumption across residence types, depending on the position of Municipalities in urban space, as shown in the first column of Table 3.9. For example, a household in Paris city center uses approximately 147 gallons per year (column 1) less than an observationally-equivalent household in a non-Parisian city center, more than half the mean annual French fuel consumption (i.e. 10 fuel tanks).⁵² Living in a Parisian inner suburb produces a smaller drop of almost 44 gallons per year (3.5 fuel tanks), whereas living in a non-Parisian inner suburb increases consumption by approximately 43 gallons per year (3 fuel tanks). The diseconomy associated with the next rings of suburbs are even larger, at 86 annual gallons (6.5 fuel tanks) for an outer suburb. The large gap found between city-centers and suburbs suggests that those urban areas have very different spatial organizations that may reflect differences in their urban form.

The addition of the 3D's to the monocentric classification in columns (2) to (8) helps to understand the contribution of each dimension to the evolution of fuel consumption between Municipalities in different rings. This addition leads to statistically significant changes in the estimates commented above: including residential density alone with residence-type brings about a 45% drop in the effect of living in a Parisian city-center (column 2), the impact of which nevertheless remains significant, and a two-thirds drop in the impact of living in a Parisian inner suburb (which loses most of its significance), and a 50% drop in the effect of living in a non-Parisian inner suburb. High density thus only explains a large part, but not all by far, of the Parisian effect. By contrast, residential density washes out the effect of living in an inner suburb of Paris or in an outer suburb of any kind of city: the higher fuel consumption of households living at the urban fringe of French MAs is entirely explained by the lower residential density there, whereas density seems not be the only mechanism at play in more central Municipalities.

Design turns out to have contrasting effects. The inclusion of distance to CBD magnifies

⁵¹See Appendix C.1.2, that provides a more detailed description of this typology.

⁵²We conjecture that this impressive drop is the result of a highly subsidized public transit network and a dense fabric of small streets that reduce drastically the share of driving relative to urban transit, walking or cycling in the historical center of Paris. Actually, the *Enquête Nationale Transports et Déplacements* (the main national transport survey in France) shows that, in 2007, cars accounted for only 14% of transport trips within downtown Paris, against 29% for public transit and 57% for walking or cycling.

Table 3.9: Household fuel consumption and residence-type : Adding the 3 D's

Dependent Variable: Fuel consumption (gallons)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Non-Parisian city-centre				All households				
				Reference				
City-centre(s) of Paris	-147.0*** (5.96)	-80.9*** (14.26)	-152.7*** (6.63)	-19.7 (15.36)	-89.6*** (9.42)	-98.7*** (9.99)	-104.7*** (11.88)	-147.7*** (5.90)
Inner suburb of Paris	-44.2*** (5.87)	-15.7* (8.45)	-68.3*** (13.81)	70.4*** (14.03)	12.5 (9.35)	-30.5*** (6.17)	-34.7*** (6.64)	-45.6*** (5.77)
Inner suburb out of Paris	43.1*** (7.08)	22.4*** (6.91)	28.0** (11.58)	51.4*** (7.07)	52.6*** (6.97)	37.6*** (6.34)	20.5*** (7.65)	39.2*** (7.14)
Outer suburb	86.9*** (9.10)	16.4 (13.16)	61.6*** (22.78)	98.2*** (11.32)	96.5*** (8.82)	64.6*** (9.48)	31.5** (12.34)	73.0*** (10.98)
DENSITY								
Log(Density of pop. in residence)		-27.9*** (4.78)						
DESIGN								
Log(Distance from residence to CBD)			14.3* (8.29)					
Log(Rail potential in the rest of the MA)				-67.6*** (6.83)				
Log(Road potential in the rest of the MA)					-19.7*** (2.39)			
Log(Density of pub. transit in residence)						-23.7*** (3.44)		
Fractal dimension in residence							-202.6*** (40.38)	
DIVERSITY								63.9*** (18.47)
Herfindahl index in residence								
Household characteristics								
Year dummies	✓	✓	✓	✓	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609
R-squared	0.225	0.233	0.225	0.228	0.227	0.230	0.231	0.226

Notes: (i) OLS estimates; (ii) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, as well as the age, age-squared, sex, education and occupation of the household head. For the sake of clarity, neither these coefficients nor the constant are shown.

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

the fuel-saving effect of living in Paris (column 3). The extra consumption of non-Parisian households therefore partly reflects the remoteness of these non-Parisian suburbs. The effect of rail access to the rest of the MA is even more salient: this entirely explains the effect of living in downtown Paris (column 4). It in addition switches the sign on the Parisian inner suburb dummy, and renders it similar in size to its non-Parisian analogue. It therefore seems that the largest part of the pro-environmental effect of living in Paris comes from the rail-transit network, which is the most dense in France. Conversely, rail access has little impact on non-Parisian inner suburbs and outer suburbs in general: these municipalities benefit less from public-transport, as the latter are concentrated in large cities in France and is mostly radial. Road access has similar but smaller effects than rail access (column 5): it halves the downtown-Paris pro-environmental effect and brings the Paris inner-suburb effect closer to (but still smaller than) that of other inner suburbs. The surprising negative coefficient on road access reflects the strong multi-colinearity of this variable with the Parisian dummies. When the latter are left out of the regression, better road access does increase fuel consumption, as expected, with this positive impact being robust to the inclusion of all of the other D's. The density of public transit (column 6) and the walkability of the built environment (column 7) partly alleviate the impact of all residence types, without changing their significance, so that urban transit systems and morphology are important additional mediators of the effect of urban form on fuel consumption. The inclusion of the fractal dimension in particular reduces the coefficient on the outer-suburb dummy. Therefore, a substantial part of the effect of living at the urban fringe comes from the leapfrogging morphology of outer-suburbs.

Finally, Diversity is also pro-environmental, as fuel consumption rises with the Herfindahl, with most of its influence coming from the functional specialization of suburbs (column 8).

Excluding Diversity from our urban metrics Tables 3.10 and 3.11 show the results from less conservative OLS and 2SLS specifications than equations (3.3) and (3.6), from which we exclude Diversity. The point estimates on density and distance to CBD are larger (columns 1 and 3), due to the correlation between diversity of the local leisure activities (restaurants, bars, cinemas, museums, theatres) and both density and centrality. In particular, when diversity is left out the regression, the density coefficient increases by 25% while its statistical significance decreases. This reflects the fact that, as a municipality get denser, it becomes more likely to host different leisure activities due to the stronger local demand for such amenities. This effect reinforces the influence of density on fuel consumption, when diversity is not taken into account, but it also blurs it. By contrast, the 3D theoretical framework allows to distinguish it from the intrinsic contribution of density to the reduction of emissions which is the compaction of the city and the correlative reduction of trip length.

In columns (2) and (4), we also include MA fixed effects to control for unobserved time-invariant municipality confounding factors. Logically, in this highly demanding specification, certain design variables become insignificant, due to their low intra-MA variance. Nevertheless, most of the other urban metrics remain significant, despite the fewer degrees of freedom, which makes us more confident about the identification power of our first 2 D's.

Table 3.10: Fuel consumption and urban form (without Diversity) : OLS

Dependent Variable: Fuel consumption (gallons)	All urban households in surveys		Motorized urban households	
	(1)	(2)	(3)	(4)
HOUSEHOLD CHARACTERISTICS				
Log(total income/CU)	70.5*** (4.12)	71.7*** (4.33)	62.0*** (5.15)	64.2*** (5.21)
Number of working adults	113.1*** (13.43)	112.7*** (13.55)	104.2*** (13.77)	103.1*** (13.70)
Number of non-working adults	70.0*** (7.91)	70.0*** (8.09)	69.8*** (8.69)	69.3*** (8.80)
Number of young children (16 year old)	8.0*** (2.77)	7.5*** (2.85)	3.4 (3.05)	3.0 (3.15)
Age (Head of household)	3.7*** (0.69)	3.5*** (0.75)	4.4*** (0.92)	4.2*** (0.97)
Age square (Head of household) / 100	-5.5*** (0.54)	-5.4*** (0.57)	-6.7*** (0.84)	-6.5*** (0.87)
Female (Head of household)	-39.1*** (7.97)	-37.1*** (8.48)	-32.2*** (10.63)	-30.2*** (11.27)
DENSITY				
Log(Density of pop. in residence)	-14.0*** (4.32)	-12.8** (4.99)	-12.0*** (4.47)	-11.6** (5.63)
DESIGN				
Log(Distance from residence to CBD)	12.8*** (4.18)	15.2*** (5.72)	10.8** (4.49)	13.9** (7.00)
Log(Density of pub. transit in residence)	-9.6*** (3.04)	-9.3** (4.16)	-8.3** (3.37)	-5.9 (4.66)
Fractal dimension in residence	-86.5** (37.48)	-105.7** (46.59)	-88.1** (36.12)	-98.4** (48.62)
Log(Road potential in the rest of the MA)	16.2*** (5.58)	45.5+ (30.77)	15.3*** (5.82)	27.3 (31.02)
Log(Rail potential in the rest of the MA)	-56.0*** (8.71)	-98.3*** (21.89)	-47.0*** (9.80)	-86.1*** (22.43)
Education dummies (Head of household)	✓	✓	✓	✓
Occupation dummies (Head of household)	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
MA dummies		✓		✓
Observations	15,609	15,609	12,889	12,889
R-squared	0.234	0.250	0.156	0.177

Notes: (i) OLS estimates from equation (3.3); (ii) Robust standard errors in parentheses (MA level); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; (iii) For the sake of clarity, neither the constant nor the dummy coefficients are shown.

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

Causal estimations with another distance metric Table 3.12 checks whether the results change when we consider another measure of travel-to-work distance, computed as the av-

Table 3.11: Fuel consumption and urban form (without Diversity): Causal

Dependent Variable: Fuel consumption (gallons)	OLS (1)	2SLS (2)	Heckit (3)	dx/dy Probit (4)
HOUSEHOLD CHARACTERISTICS				
Log(Total income/CU)	70.5*** (4.12)	70.5*** (4.12)	83.6*** (7.20)	0.089*** (0.005)
No. of working adults	113.1*** (13.43)	113.0*** (13.39)	119.5*** (5.52)	0.086*** (0.005)
No. of non-working adults	70.0*** (7.91)	70.0*** (7.86)	82.1*** (4.93)	0.058*** (0.004)
No. of young children (16 year old)	8.0*** (2.77)	8.0*** (2.76)	- -	0.014*** (0.003)
Age (Head of household)	3.7*** (0.69)	3.7*** (0.69)	7.5*** (1.27)	0.010*** (0.001)
Age square (Head of household) / 100	-5.5*** (0.54)	-5.5*** (0.54)	-10.6*** (1.34)	-0.012*** (0.001)
Woman (Head of household)	-39.1*** (7.98)	-39.1*** (7.93)	-56.4*** (8.01)	-0.088*** (0.007)
DENSITY				
Log(Density of pop. in residence)	-14.0*** (4.32)	-17.8*** (6.11)	-13.5*** (4.08)	-0.015*** (0.004)
DESIGN				
Log(Distance from residence to CBD)	12.8*** (4.18)	11.5*** (4.18)	15.1*** (4.45)	0.014*** (0.004)
Log(Density of pub. transit in residence)	-9.6*** (3.04)	-8.5** (3.39)	-11.9*** (3.63)	-0.011*** (0.003)
Fractal dimension in residence	-86.5** (37.48)	-68.1* (39.63)	-104.4*** (30.99)	-0.103*** (0.028)
Log(Road potential in the rest of the MA)	16.2*** (5.58)	16.7*** (5.61)	18.1*** (5.03)	0.016*** (0.005)
Log(access to rail in the rest of the MA)	-56.0*** (8.71)	-54.4*** (8.91)	-65.1*** (9.44)	-0.072*** (0.007)
Household characteristics	✓	✓	✓	✓
No. of young children (< 16 y.o.)	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
Cragg-Donald F-Stat		526.8		ρ : 0.463
C-Stat (p-value)		2.454 (0.117)		σ : 297.6
Hansen J-Stat (p-value)		11.21 (0.130)		λ : 137.7
Shea Partial R-squared (density)		0.213		

Notes: (i) 2SLS estimates from equation (3.6); (ii) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (iii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iv) The household characteristics include income per CU (in log), the number of working and non-working adults and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither the dummy coefficients nor the constant are shown; (v) The instruments are population density in 1901 (in log), distance to the largest Municipality of the MA in 1806 (in log) and geological characteristics (topsoil water capacity and mineralogy).

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

erage commuting distance in the whole MA, rather than the distance to the MA CBD. The distance coefficients are magnified and the Herfindahl index turns insignificant, which is presumably due to the negative correlation between the two variables: a Municipality less diverse is more likely to lack daily services jobs which forces its inhabitants to commute more frequently.

It is worth stressing that this distance metric may actually be less appropriate for several reasons. First, it is time invariant, as old French censuses were produced every ten years (in a transition between two data collections). Moreover, it encapsulates travel-to-work trips only, whereas distance to CBD, a central place that usually hosts various amenities, is more representative of all possible trips beyond commuting. Finally, it could even yield a bias for denser Municipalities, where people use public transit for commuting and car for purposes other than work.

Causal estimations with a metric of housing prices Table 3.13 checks whether the results change if we include explicitly one of the mechanisms of spatial sorting : the housing prices. Rents and housing prices could indeed have an effect *per se*, even after correcting for socioeconomic characteristics, since they could be proxies of unobserved characteristics of our sample's households. Indeed, if housing prices sort urbanites across their income, it also sorts them across their preference for surface : a household having a high preference for surface would be more sensitive, *ceteris paribus*, to housing prices and choose a more remote location where it can afford a larger dwelling. Housing prices at residence could thus be seen, after the inclusion of every control for socioeconomic characteristics, as a proxy of preferences for surface. Such preferences could be arguably correlated with unobserved preference for car use, which motivate the inclusion of such a complementary control.

Actually, the BdF database contains a proxy of this variable : rents. Those are either asked to the household if he is a tenant, or imputed from the dwelling's characteristics by National Statistical Institute. The database also provides us with the dwelling's surface. We are thus able to supplement our specification with this additive control.

The inclusion of housing rent as a control is highly significant, but hardly changes the results from our preferred specification. Interestingly, the coefficient of housing rent is slightly higher after the Heckman correction, which confirms that it could be a factor of unobserved sorting.

Causal estimations instrumenting both density and distance to CBD Finally, Table C.13 in Appendix C.8 presents further 2SLS estimations in which we consider as endogenous regressors both the Density and the Distance to the MA CBD. Distance to the CBD could indeed be considered endogeneous due to reverse causality, notably from air pollution. If the city center traffic generates too high levels of emissions, certain households may move to

Table 3.12: Fuel consumption and urban form: 2SLS with another distance metric

Dependent Variable: Fuel consumption (gallons)	(1) OLS	(2) 2SLS	(3) Heckit	(4) dx/dy Probit
DENSITY				
Log(Density of pop. in residence)	-13.2*** (4.17)	-20.8*** (5.79)	-13.0*** (4.05)	-0.017*** (0.004)
DESIGN				
Log(Average commuting distance in the MA)	39.5*** (11.82)	35.9*** (10.09)	44.9*** (9.96)	0.026*** (0.010)
Log(Density of pub. transit in residence)	-9.7*** (2.98)	-7.4** (3.44)	-11.8*** (3.63)	-0.011*** (0.003)
Fractal dimension in residence	-90.0** (37.06)	-50.8+ (33.23)	-107.8*** (30.63)	-0.118*** (0.028)
Log(Road potential in the rest of the MA)	17.3*** (5.19)	17.8*** (5.28)	19.6*** (4.80)	0.019*** (0.004)
Log(Rail potential in the rest of the MA)	-47.1*** (7.58)	-45.2*** (7.43)	-54.4*** (9.26)	-0.064*** (0.007)
DIVERSITY				
Herfindahl index in residence	26.9* (13.75)	19.9 (14.91)	26.5* (15.75)	-0.005 (0.020)
Household characteristics	✓	✓	✓	✓
No. of young children (< 16 y.o.)	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.166	-	-
Cragg-Donald F-Stat		901.7		ρ : 0.452
C-Stat (p-value)		3.183 (0.074)		σ : 297.2
Hansen J-Stat (p-value)		14.48 (0.070)		λ : 134.4
Shea Partial R-squared (density)		0.249		

Notes: (i) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) The household characteristics include income per CU (in log), the number of working and non-working adults and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown; (iv) The instruments are population density in 1901 (in log), distance to the largest Municipality of the MA in 1806 (in log) and geological characteristics (topsoil water capacity and mineralogy).

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

Table 3.13: Fuel consumption and urban form: 2SLS with housing prices metric

Dependent Variable: Fuel consumption (gallons)	(1) OLS	(2) 2SLS	(3) Heckit	(4) dx/dy Probit
DENSITY				
Log(Density of pop. in residence)	-12.0*** (4.58)	-14.9** (5.96)	-11.2*** (4.20)	-0.014*** (0.004)
DESIGN				
Log(Distance to CBD)	13.3*** (4.27)	12.3*** (4.07)	15.7*** (4.46)	0.014*** (0.004)
Log(Density of pub. transit in residence)	-9.7*** (2.99)	-8.8*** (3.02)	-11.7*** (3.64)	-0.010*** (0.003)
Fractal dimension in residence	-82.9** (33.57)	-69.7** (33.65)	-100.6*** (31.08)	-0.104*** (0.028)
Log(Road potential in the rest of the MA)	14.8*** (5.60)	15.3*** (5.83)	16.5*** (5.07)	0.015*** (0.005)
Log(Rail potential in the rest of the MA)	-54.7*** (8.61)	-53.6*** (8.46)	-63.3*** (9.44)	-0.069*** (0.007)
DIVERSITY				
Herfindahl index in residence	29.1** (13.53)	26.4* (14.10)	28.6* (15.80)	-0.001 (0.020)
CONTROLS				
Housing rent (€/ m ²)	-1.3*** (0.40)	-1.3*** (0.39)	-2.7*** (1.04)	-0.002*** (0.001)
Household characteristics	✓	✓	✓	✓
No. of young children (< 16 y.o.)	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.166	-	-
Cragg-Donald F-Stat		901.7		ρ : 0.452
C-Stat (p-value)		3.183 (0.074)		σ : 297.2
Hansen J-Stat (p-value)		14.48 (0.070)		λ : 134.4
Shea Partial R-squared (density)		0.249		

Notes: (i) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) The household characteristics include income per CU (in log), the number of working and non-working adults and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown; (iv) The instruments are population density in 1901 (in log), distance to the largest Municipality of the MA in 1806 (in log) and geological characteristics (topsoil water capacity and mineralogy).

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

farther neighborhood to avoid it.

Column (1) displays the results associated with our preferred set of geological instruments (topsoil mineralogy and water capacity).⁵³ Columns (2) to (8) provide the coefficients from the other geological sets (as in Table 3.8). The results are virtually unchanged, and the low p-value associated with the C-Statistic suggests that distance to the CBD is not endogenous and thereby, instrumentation not needed for this variable.

All of these checks reinforce our conclusion that the 3 D's exert a robust influence on fuel consumption, beyond any selection effects or other endogeneity biases. Therefore, next section use our estimates to predict the carbon footprint of urban households in France, and analyze the nexus between metropolitan size and car emissions.

3.4 CO₂ car emissions and city-size: a bell-shaped curve

In the same spirit as Glaeser and Kahn (2010), we can use our causal estimates to predict the CO₂ car emissions produced by a standardized household in each French MA. We then identify the greenest and dirtiest cities according to this 'carprint', and ask how this is related to city size.

3.4.1 CO₂ car emissions of the sample-mean household across MAs

We calculate the 'carprint' of a representative household as follows. We first estimate how much fuel the sample-mean household j would consume in each urban municipality k , based on either the 2SLS (equation 3.9) or Heckman (equation 3.10) estimates in Table C.8:

$$\widehat{Fuel}_{j(k)} = \hat{\alpha} + Density_k \hat{\beta} + Design_k \hat{\delta} + Diversity_k \hat{\gamma} + \bar{X}_j \hat{\theta}, \forall k, \quad (3.9)$$

$$\widehat{Fuel}_{j(k)} = \hat{\alpha} + Density_k \hat{\beta} + Design_k \hat{\delta} + \hat{\gamma} Diversity_k + \widehat{Mills} \hat{\lambda} + \bar{Y}_j \hat{\mu}, \forall k, \quad (3.10)$$

where \bar{Y}_j is the vector of the sample-mean household characteristics except for the dummy for young children (as this represents our exclusion restriction).

As French Municipalities have widely different levels of wealth, we also calculate a second set of predictions, letting average Municipality income vary along with the geographical determinants of fuel. We estimate average income in each urban Municipality using exhaustive files on personal income tax and housing tax returns provided to INSEE by the General Tax Directorate. We first run an OLS regression of average Municipal income per CU drawn from the 2006 BdF survey on the average municipal income from tax sources.⁵⁴ We then use

⁵³The related first-stage regressions are displayed in Table C.12 (columns 2 and 3).

⁵⁴In detail, we run the following regression: $\log \left(Inc_{k,2006}^{BdF} \right) = \Phi_1 + \Phi_2 \log \left(Inc_{k,2006}^{tax} \right) + \zeta_{k,2006}$. We then use $\widehat{\Phi}_1$ and $\widehat{\Phi}_2$ to estimate the real average income of each French Municipality so as to calculate the CO₂ emissions.

these estimates to calculate car emissions as before, except that we measure the household income as the average income in the home Municipality, instead of the sample-mean income:

$$\widehat{Fuel}_{j(k)CI} = \widehat{\alpha} + Density_k \widehat{\beta} + Design_k \widehat{\delta} + Diversity_k \widehat{\gamma} + \overline{Z}_j \widehat{\eta}, \forall k, \quad (3.11)$$

where \overline{Z}_j is the vector of the mean-household characteristics in 2006, except for income per CU, which is replaced by the Corrected Income (CI) estimated above.

With these two different regressions for each urban Municipality, we predict the fuel consumption of a standardized household in each French MA as the sum of all Municipal predictions in the MA, weighted by the share of households with cars in each Municipality:

$$\widehat{Fuel}_{j(MA)} = \sum_{k \in MA} \left(\widehat{Fuel}_{j(k)} \times \text{Nb of motorized households}_k / \text{Nb of households}_{MA} \right). \quad (3.12)$$

Last, we retrieve carbon emissions from those volumes using the conversion factors provided by the French Ministry for an Ecological and Solidarity Transition. To account for the mix of fuels in French vehicles, we use a national conversion factor for each energy type: 10.8 kg of CO₂ per gallon of gasoline, 12.2 kg of CO₂ per gallon of diesel, and 7.1 kg of CO₂ per gallon of LPG.⁵⁵ Weighting each energy type by its share in total fuel consumption from the 2006 BdF survey, we obtain a global conversion factor of 11.96 kg of CO₂ per gallon of fuel.⁵⁶

Tables 3.14 and 3.15 show the mean household car emissions in the 25 ‘greenest’ and ‘dirtiest’ French MAs.⁵⁷ Each panel of the table presents the emissions calculated from either the OLS, 2SLS or Heckit estimates, and the rank of each MA with respect to these emissions. The last column lists the number of inhabitants per MA in 2006, to fix ideas.

The CO₂ ranking of French MAs is fairly stable across estimation methods.⁵⁸ Whatever the estimation method, car emissions vary sharply across French MAs, from approximately 2.2 tons of CO₂ per year in Paris up to 3.9 tons of CO₂ per year in MAs such as Bourg-Saint-Maurice, Annemasse and Chamonix, which are all located in the French Alps.⁵⁹ In other words, a French standardized household that decides to live in Bourg-Saint-Maurice (respectively Chamonix) generates a driving footprint almost 100% (resp. 80%) larger than an observationally-equivalent same household in Paris.

The car emissions of a standardized household are much lower in French MAs than those in American MSAs, however. In Glaeser and Kahn (2010), the US marginal household pro-

⁵⁵The fuel mix is remarkably stable across the urban space in France. Table C.1 in Appendix C.3 shows that there are no statistically significant differences in the average fuel mix across small, medium and big MAs.

⁵⁶Glaeser and Kahn (2010) use a slightly lower conversion factor of 19.564 lbs or 8.874 kg per gallon of fuel.

⁵⁷Appendix C.8 Tables C.14 and C.15 replicate this exercise with emissions calculated from equation (3.11).

⁵⁸Appendix C.9.1 Tables C.14 and C.15 show that while the rankings do not change much when we allow Municipal income to vary (as in equation 3.11), the predicted CO₂ car emissions in MAs are lower.

⁵⁹Note that, since we calculate the standard errors of these predictions, we can conclude that the differences between high and low emissions are very significant. We have moreover checked that the particularity of mountainous MAs is not due to their altitude by controlling for different measures of elevation.

Table 3.14: The Greenest French MAs: CO₂ ‘carprint’ of the sample-mean-household (kg/year)

City	MA pop.	OLS	Rank	2SLS	Rank	Heckit	Rank
Paris	1.180e+07	2140	1	2173	1	2070	1
Fourmies	16324	2458	2	2519	2	2396	3
Lille	1.165e+06	2477	3	2539	3	2379	2
Caudry	14322	2520	4	2609	4	2439	4
Menton	68826	2842	13	2693	5	2797	16
Saint-Étienne	318993	2733	5	2746	6	2654	5
Montereau-Fault-Yonne	26109	2757	7	2755	7	2686	7
Bolbec	15750	2756	6	2776	8	2686	8
Nice	991899	2936	31	2804	9	2891	33
Lyon	1.748e+06	2794	9	2818	10	2711	9
Sète	73674	2802	10	2838	11	2734	10
Hendaye	14993	2793	8	2841	12	2685	6
Marseille	1.601e+06	2910	25	2855	13	2881	31
Le Havre	290826	2875	16	2856	14	2836	23
Boulogne-sur-Mer	133195	2890	21	2887	15	2851	27
Douai	546721	2901	23	2895	16	2844	25
Yvetot	15432	2916	28	2902	17	2810	18
Grenoble	531439	2881	18	2909	18	2799	17
Calais	125525	2913	27	2916	19	2873	29
Nemours	18429	2870	15	2917	20	2788	14
Strasbourg	638672	2877	17	2918	21	2822	19
Tergnier	23383	2837	12	2918	22	2771	13
Nancy	415765	2828	11	2930	23	2756	12
Villerupt	19019	2882	19	2933	24	2795	15
Landerneau	14927	2924	29	2934	25	2827	20
Creil	101982	2959	34	2940	26	2904	35

duces between 18,000 lbs or 8.2 tons of CO₂ in New York to 32,000 lbs or 14.5 tons in (the inappropriately named) Greenville, South Carolina. A typical French driver thus produces around one fifth of the carbon emissions of a typical US driver. This is partially explained by the larger fuel consumption per kilometer for US vehicles, as well as the larger commuting distance.

3.4.2 Driving footprint and city-size: A bell-shaped curve

Figure 3-3 depicts the car emissions for a standardized household for all French MAs, using the Heckman estimates in Table C.8 (column 5).⁶⁰

⁶⁰The results are qualitatively very similar with 2SLS estimates, which are not shown here.

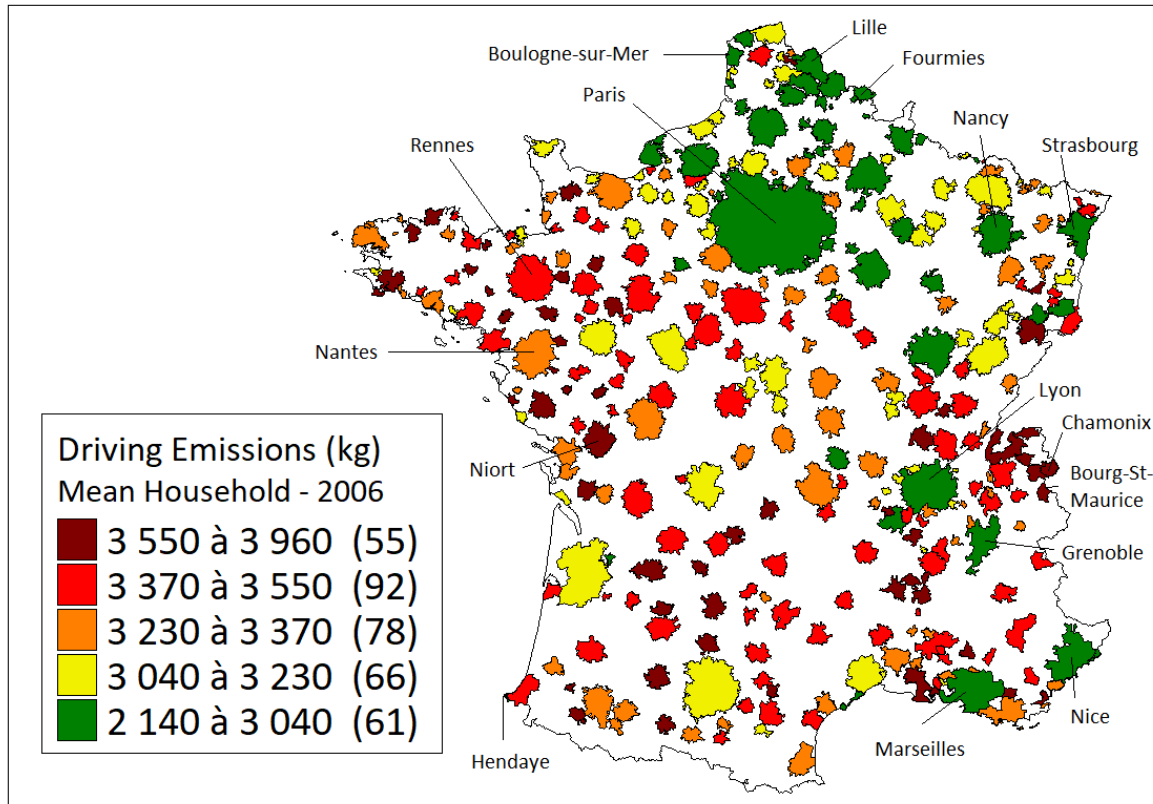
Table 3.15: The Dirtiest French MAs: CO₂ ‘carprint’ of the sample-mean household (kg/year)

City	MA pop.	OLS	Rank	2SLS	Rank	Heckit	Rank
Bourg-Saint-Maurice	10357	3761	351	3887	352	3767	352
Chamonix-Mont-Blanc	13127	3608	324	3867	351	3582	325
Saint-Gaudens	27175	3680	343	3833	350	3681	344
Sarlat-la-Canéda	18022	3775	352	3808	349	3764	351
Oloron-Sainte-Marie	22382	3665	340	3796	348	3656	340
Cahors	40175	3713	345	3795	347	3730	350
Belley	16547	3632	333	3783	346	3619	332
Saint-Lô	49761	3723	349	3782	345	3724	347
Sablé-sur-Sarthe	30193	3721	348	3777	344	3720	345
Ancenis	19308	3700	344	3775	343	3661	341
Avallon	15427	3539	302	3773	342	3532	310
Ussel	14074	3622	329	3773	341	3606	327
Auch	36934	3668	341	3764	340	3668	342
La Bresse	12851	3656	338	3755	339	3648	338
Les Herbiers	14833	3620	328	3750	338	3560	320
Lannion	63425	3719	346	3748	337	3723	346
Aubenas	44546	3720	347	3744	336	3729	349
Saint-Louis	89549	3638	334	3739	335	3617	331
Niort	134927	3592	320	3732	334	3570	323
Loudéac	14217	3607	323	3731	333	3579	324
Annemasse	244178	3736	350	3730	332	3725	348
Fontenay-le-Comte	26391	3553	308	3725	331	3514	301
Mayenne	26361	3648	336	3721	330	3617	330
Bressuire	18225	3581	318	3719	329	3547	315
Louhans	15598	3593	322	3717	328	3544	313
Castelnaudary	20942	3613	325	3716	327	3613	328

A salient geographic divide There is considerable spatial heterogeneity of household emissions across French MAs. Large MAs such as Paris, Lyon, Nice, Strasbourg and Lille exhibit low-carbon ‘carprints’ (under 3 tons of CO₂ per year per household), due to the combination of high population densities (up to 1,200 inhabitants per km² in the MA of Lille) and good public transport systems, allowing those in the suburbs to commute easily to city-centers. The MAs of Nantes and Rennes are noticeable exceptions, suggesting that they are more affected by urban sprawl than other large French cities. Small MAs such as Hendaye (at the South-Western tip of France), Boulogne-sur-Mer (at the North-Western border of France) and Fourmies (at the North-Eastern border of France) are also environmentally-friendly, due to a compact design partly driven by their border nature, which provides a natural limit to sprawl.

By way of contrast, small MAs located in the Alps (such as Bourg-Saint-Maurice and Chamonix), as well as medium-sized Western cities (such as Niort), have high-carbon ‘carprints’

Figure 3-3: Estimates of the CO₂ 'carprint' of the sample-mean household (kg/year)



due to the large dispersion of their population in a geographically-scattered urban fabric (valleys in the Alps), while medium-sized Eastern cities (such as Grenoble or Nancy) have lower car emissions due to the political decision to develop light-rail transit systems and a more compact urban form. A geographical East-West divide then emerges. It is worth noting that the differences between low-carbon cities are far from negligible: a standardized household driving in Paris consumes 25% less fuel than an observationally-equivalent driver in Lyon, a gap that is of the same order as moving a standardized US household from Atlanta to Boston (Bento et al., 2005).

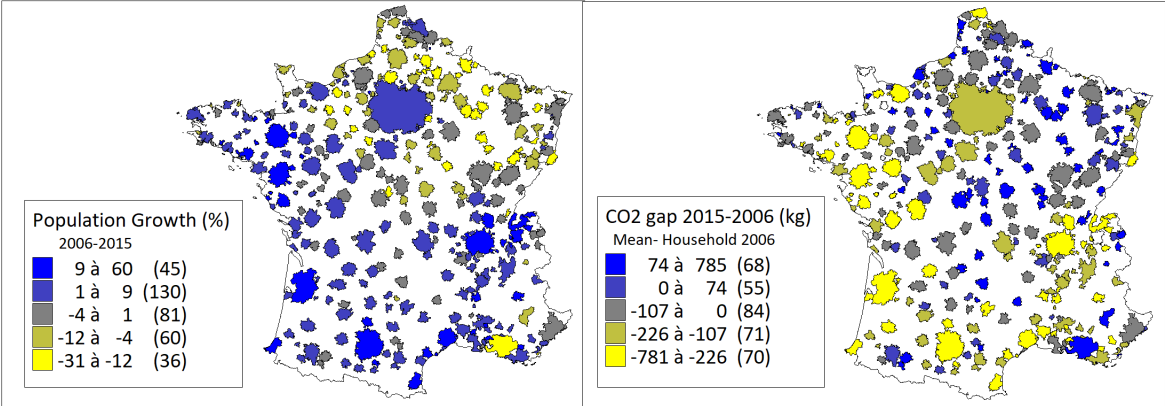
These figures may be important for policy makers willing to design optimal spatial policies to accompany the ecological transition. Indeed, Atlantic and Mediterranean cities have experienced strong urban growth over the past decade, however they do not host the most efficient cities. As such, Figure 3-4 depicts the 2006-2015 MA population growth (on the left) against the differences in predicted car emissions over the same period (on the right): the two patterns are mirror images, growth rates of population and CO₂ emissions have a correlation coefficient at -0.8. This is consistent with the annual 0.9% of built surface in continental

France⁶¹, near to twice the pace of population growth (0,5%). From our framework, one can only try to assess whether these changes have degraded or improved the French carbon footprint, since we do not model explicitly fuel consumption in the rural space, from where or to where population may move. However, adding a dummy variable for rural space in the previous specifications allows to describe its situation and compute tentative projections of national CO2 emissions in 2006 and 2015. Results in Table shows that the increase in the population of the high-emissions MAs induced a significant 17% increase of the mean household car-related emissions.

Table 3.16: Estimated mean ‘carprint’ of a French household (kg/household/year)

Year	2006	2015
	2,371.4	2,791.2

Figure 3-4: Population growth (left) and car emissions differences (right), 2006-2015



Note: The CO₂ gap is the difference between car emissions predicted in 2015 and 2006 for the sample-mean household in 2006. Car emissions in 2015 are estimated by imputing population in 2015 into equation (3.11), holding all the other variables at their 2006 value. Hence, the right-map depicts the partial equilibrium effects of population changes over 2006-2015.

A bell-shaped curve Our estimates therefore suggest that Density, Diversity and Design together significantly affect household car emissions in France. Densely-populated MAs have lower driving footprints, as do MAs with good public-transport networks. As it is easier for large cities to afford mass-transit infrastructure, Density and Design feed on each other to sustain the low-carbon ‘carprint’ of large metropolitan areas. Moreover, large cities save on carbon emissions as they are on average more diverse. On the contrary, job-housing centrality, the absence of leapfrogging suburbs and high walkability (a high fractal dimension) of the historical city center (when there is one) might provide a Design that compensates for low Density in small cities. This cannot be attained in medium cities, which are either

⁶¹Source : Corine Land Cover, 2015

sprawling (low-density suburbs), not big enough to sustain large public-transport networks, or endowed with extensive road networks and fragmented built environments (a low fractal dimension). The tipping point at which French cities can potentially achieve a low-carbon ‘carprint’ is between 50,000 and 100,000 inhabitants.

Figure 3-5 and Table 3.17 thus reveal an inverted U-shaped relationship between MA-size and mean household car emissions.⁶² It is important to notice that this bell shape is not driven by the two tails of the MA distribution, as it still holds when we exclude Paris and Volmerange-les-Mines from the sample, as shown by Figure C-6 and Table C.16 in Appendix C.9.2.

Figure 3-5: MA-size and the CO₂ ‘carprint’ of the sample-mean household (kg/year)

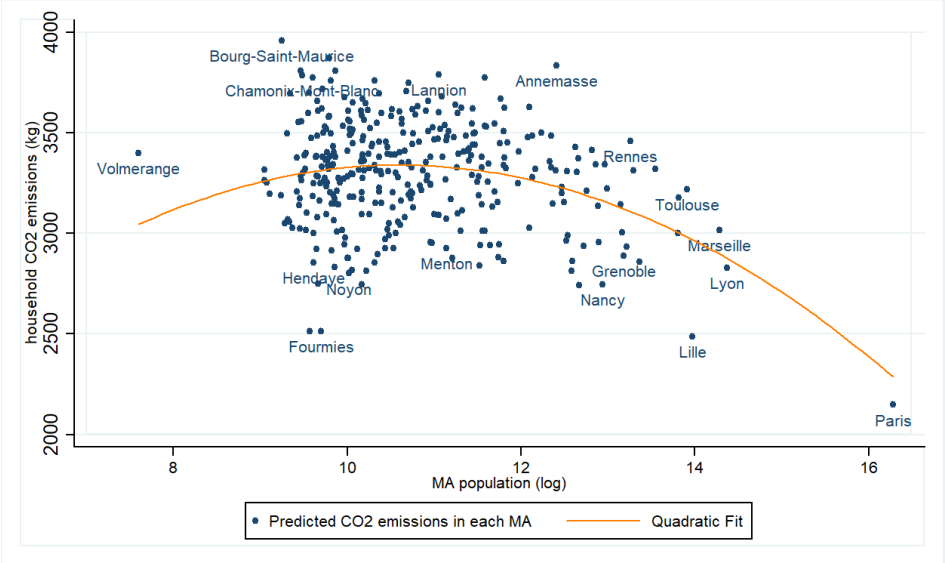


Table 3.17: MA-size and the CO₂ ‘carprint’ of the sample-mean household: estimations

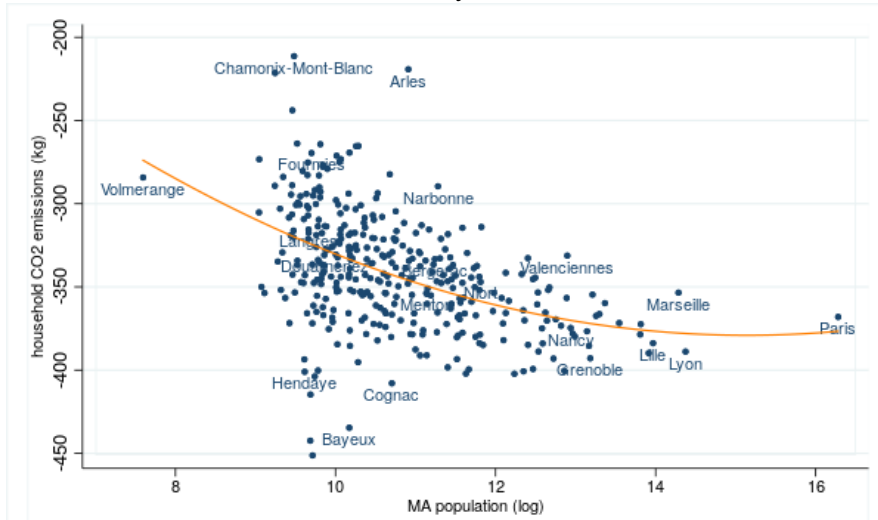
CO ₂ car emissions	OLS coefficients	(Std. Dev.)
Log(MA-size)	736.1***	(140.3)
Log(MA-size) ²	-35.7***	(6.1)
Constant	-367.3	(793.2)
Observations	352	
R-squared	0.188	

Notes: Standard errors in parentheses: ***p<0.01.

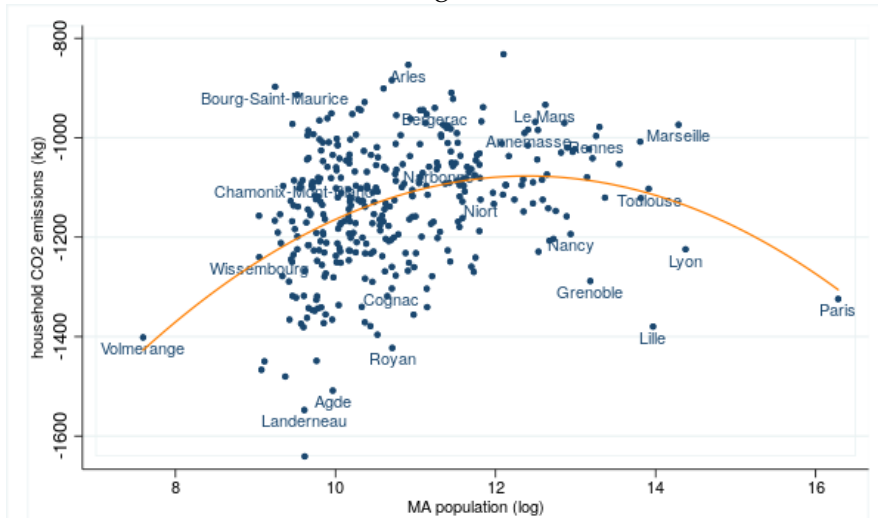
⁶²Calculated from the Heckman estimates in Table C.8. The results are qualitatively similar with 2SLS.

Figure 3-6: MA size and the CO₂ 'carprint' associated with the 3 D's

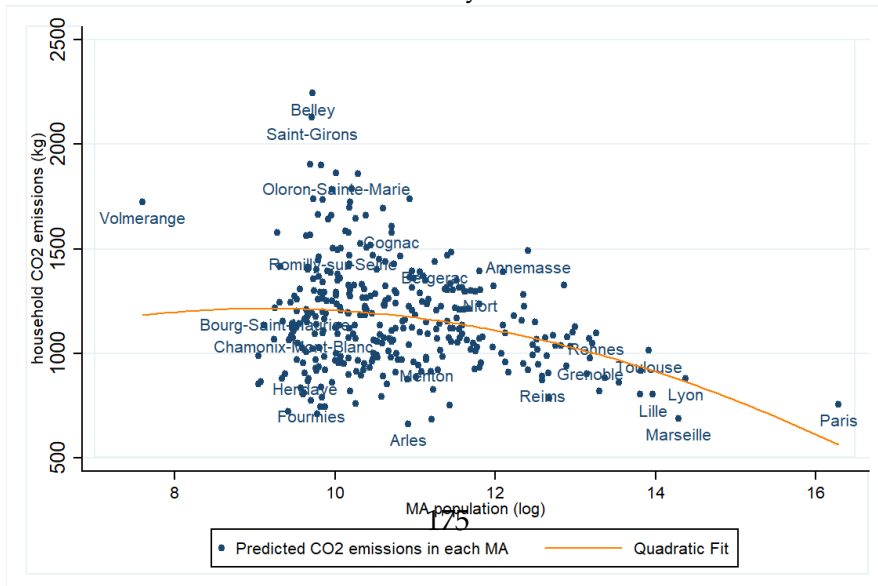
The Density channel



The Design channel



The Diversity channel



Since our fuel consumption model is linear, we can study independently the effect of each of the 3 D's by setting virtually all other variables to zero in the projection. Figure 3-6 shows the results of such partial projections against MA size, and helps to better understand the pathways driving this bell shape.

We find that Density has a strong negative linear effect on driving emissions, as commonly found in the literature: larger MA exhibit higher populations density and hence, larger car-emission savings.

The effect of Design is much more diverse. The smallest MAs are usually more pedestrian-friendly (they have a higher fractal dimension) and have a good job-housing balance and a scarce road network. However, as commuting distances and the road stock rise with MA size, driving first increases with city population. Above the 300,000 inhabitant threshold, the development of public transit compensates for the other effects and generates drastic savings in car emissions, while ultimately building a more walkable city through urban-planning strategies may lead to greater walkability. Design thus generates an inverted U-shaped relationship between car emissions and city-size that was not previously documented in the literature.

The impact of Diversity varies substantially in small MAs, depending on consumption amenities driven by the presence of commercial or recreational activities. Even if this is not systematic, small isolated MAs often have high sectoral diversity. Medium MAs are thus the least-diverse on this aspect. This reinforces the bell-shape fostered by Design. By contrast, large MAs have a fairly good job-mix that leads to lower driving emissions.

This confirms that, in small cities, households do not drive much either because of the good job-housing balance or the relatively good walkability. Design therefore compensates for the driving incentives stemming from low densities. As cities grow, trips become longer due to the expansion of road networks and longer commuting distances, until public transit becomes sufficiently widespread to curb car emissions. Overall, the maximum 'carprint' is reached for MA standing between 50,000 and 100,000 inhabitants.

From an urban-planning perspective, it should be emphasized that the existence of areas with what seems to be sub-optimal populations may require tailored policy interventions that address medium-sized MAs, so that they can develop in a more sustainable manner.

3.5 Conclusion

Transports are still excluded from the EU Emissions Trading System, the cornerstone of the European policy to reduce GHG emissions⁶³. Actually, they account for a rising share of GHG emissions in European countries such as France, and their reduction is made difficult

⁶³An extension of the ETS framework to include transportation has been recently discussed by the European Commission, however, it faces considerable opposition due to, notably, doubts on its acceptability

notably through car dependence that still hampers efforts towards the decarbonation of urban mobility.

The electrification of the car stock, especially in urban areas, may constitute a technological solution to the dilemma presented *supra*. However, technological improvements could not change the fact that the ecological transition will made energy less affordable than it was in the period when the geographic structures of contemporaneous cities have been built, and that this path dependency threatens the acceptability of the transition. In particular, one should recall that the transition from a fuel propelled, CO2 emitting car stock to a fully electric one will be costly⁶⁴, take time⁶⁵ and thus follow a very uneven rhythm across neighborhoods. Basically, low-income households living in car dependant neighborhoods could be expected to be the last to change for electric cars, since their are used to buy second-handed, low-cost cars that would remain fuel propelled. This equity issues that motivate the study of the causes of car dependence in this chapter would thus remain stringent, even in the scenario of a swift electrification of the car stock.

In this chapter, we posit three pathways through which urban form affects car usage within French metropolitan areas: Density, Design and Diversity. We in particular analyze the influence of a novel indicator of urban Design - the fractal dimension of the built-up environment - that captures spatial disparities in urban morphology likely to nurture or alleviate car dependence within cities.

To address the issue that households with particular preferences for driving may sort into areas of particular density, and the problem of unobserved local determinants of car usage correlated with urban form, we combine a rich longitudinal French household survey with a Heckman approach and IV strategies relying on historical settlements and soil geology.

We show that compaction decreases only slightly the driving footprint of urban households, since doubling residential density would reduce the fuel consumption of a representative urban driver by about one tank per year, 5% of the average household fuel consumption in France. Further environmental gains can yet be expected from shifting the urban structure toward stronger job-housing centralization, extensive rail/bus coverage, less road construction, more 'fractal' morphologies, and higher functional Diversity.

In this respect, this chapter provides quantitative evidence to back the "Smart City" ideals of integrated sustainable urban development. It also suggests that an urban-policy package combining Densification with better Design and greater Diversity could provide an excellent foundation for low-carbon cities in France. As estimating the cost of such policy package is far beyond the scope of this paper, we cannot yet conclude on the superiority of these 3 D's over policy tools such as greening the French vehicle fleet or implementing a fuel carbon

⁶⁴The overall cost of electrification, for all economic actors, from the deployment of recharge points to the cost of onerous electric vehicles, is expected to add up to a 10% increase of the cost of capital renewal in the sector

⁶⁵The French government plans the end of thermal vehicles sells in 2040. However, the reduction of emissions must start well before this date

tax, which could have strong impacts in the shorter term. However, the results of this study may help to better identify the areas where equity claims will likely come, and may help to design redistribution schemes that would contribute to the acceptability of the transition. Notably, for instance, the identification of car-dependant areas may allow to focus electric car purchase grant on households more likely to have few alternatives to individual driving, due to the geography of residence.

Finally, our study highlights a non-monotonous effect of metropolitan size on per capita driving emissions in France, that was not previously documented in the literature. In large conurbations, which can be nevertheless very spread out, households have a lower carbon 'carprint' (about 2 tons of CO₂ per household per year in Paris), thanks to the intensive use of public transport, the strategic infill of empty spaces and the functional diversity of jobs. Small cities can compensate for either low density or diversity by greater job-housing centralization and shorter travel distances. By contrast, in medium cities - from 50,000 to 100,000 inhabitants - where neither of these mechanisms can substantially reduce car use, household carbon footprints are much heavier. Such non-linearity in the urban size - car pollution nexus, which is mostly driven by urban Design, constitutes an interesting bifurcation between French and American cities in the optimal city-size debate. Beyond the slogan promoting the pro-environmental effect of big cities on the driving footprint of households, there is also sustainable advantages for small cities, which may spontaneously be as 'smart' as their large heavily-engineered analogues. Conversely, medium cities may require particular attention from policy-makers. The identification of this bell-shaped curve could thus contribute to the design of a spatial policy for the ecological transition that would favor population displacement to energy-efficient cities.

Conclusion

This dissertation presents an assessment of the possible use of public good distribution – especially public transport infrastructure – in order to answer vertical and horizontal equity concerns in the spatial economy, and an application to the case of equity concerns linked to the rise of the carbon tax of fuels.

In the first chapter, we found evidence that no short term effects in terms of labor market integration can be expected for segregate neighborhoods from better connection to a public transit network. By contrast, the housing market adjustment may lead to an improvement in social mixity that should prove beneficial in the long term. However, this improvement comes at the cost of the departure of the most deprived households from the newly connected neighborhood, and do not happen in neighborhoods where the share of social housing –that prevents the departure of the most deprived– is large. The expected local reduction in vertical spatial iniquities is therefore inhibited by the presence of social housing, but at the same time increases global vertical iniquities unless social housing is present. These results suggest, consistently with the literature, that public transit infrastructure targeting the most deprived areas is not an efficient tool for the reduction of vertical equity issues in a city. However, and contrary to the literature on US cases, a moderate development of social housing simultaneous to the opening of the new transit option may increase this efficiency.

In the second chapter, we prove that, in the presence of idiosyncratic location preferences of households, a spatial transfer scheme targeted at the smallest cities may be more efficient than a scheme inciting population to move to large centers. Given the estimated level of location preferences, these results suggest that between cities, spatial redistribution policies may be efficient tools to reduce horizontal equity issues. Thanks to a sufficient statistic approach, this result is consistent with many modelling choices. Furthermore, we find that French current redistribution pattern is indeed inspired by an horizontal equity agenda. Whether this applies to public transportation remains to be precised. These results remain heavily dependent on the importance of location preferences, a parameter that cannot be easily estimated.

In the third chapter, we show empirically that there exist dramatic vertical and horizontal spatial inequalities in terms of fuel consumption. Within cities, a standardized household living in the city center would consume less than half the average fuel consumption, while

he would consume $3/2$ of the mean consumption at the urban fringe. Between cities, a standardized household living in the greenest city would annually burn half the fuel consumption of an household living in the dirtiest. The existence of such drastic inequalities, that can adequately be described as "car dependence" for the most unlucky areas, may translate in large equity concerns in case of a fuel price shock. We show that these discrepancies are largely driven by the presence of public transit and by the existence of car-designed urban morphologies inherited from a period of low fuel prices. Moreover, it appears that the relationship between city-size and fuel consumption is bell shaped. Small cities exhibit efficient city structure, where every destination can be reached on foot. Large cities compensate their size and congestion by the presence of extensive public transportation networks. Medium sized cities are in the worst of two worlds.

On the theoretical point of view, this dissertation confirms that, consistently with the naive approach, deviating public good production decision from utilitarian criteria to equity-motivated place-based policies is largely inefficient, notably at the urban scale when it comes to the allocation of public transport infrastructure. Population mobility allows the wealthiest to capture most of the benefits from infrastructure, and one can only expect little equity improvement from general equilibrium. However, getting into more details on the results of the two first chapters, this dissertation also shows that the large frictions at play in spatial economics may actually restore, locally, the possibility of a cautious and well calibrated spatial intervention. Within cities, development of social housing (a radical friction on a subset of the housing market, since it is reserved to the urban poor) simultaneously to public transit may allow to efficiently reduce vertical inequities in some cases. Between cities, in case of large mobility frictions (location preferences), spatial redistribution towards small cities may even be more efficient than utilitarian transfers. These results represent an interesting illustration of a well-known general result : spatial market imperfections can justify place-based, equity-motivated policies.

On the policy point of view, this dissertation confirms that spatial equity is a crucial issue that has no easy spatial solution. Indeed, the reduction of global inequalities, that condition and structure spatial inequalities, is not in the hands of local governments, who are therefore bound to second best spatial policies. However, on the specific case of equity concerns linked to a rise in the fuel-levied carbon tax, that are largely spatial and do not only depend on initial inequalities, the results of the last chapter may even offer some leads for first best policies.

At the city level, the third chapter's empirical results show that an urban form improvement may significantly contribute to emission reduction. However, such urban reshaping policy suffer from severe drawbacks : first, the results of the first chapter show that population mobility may respond to such improvements so that their effect on spatial inequalities is minimized; second, due to this effect, the cost of such inequalities mitigation policies, whose estimation is anyway beyond the scope of this thesis, may exceed the capacities of local ju-

risdictions.

However, some low-cost urban policies can be carried out in growing cities. Since the development of new neighborhoods will be necessary anyway, urban regulation should organize this development in a highly fractal, dense urban fabric, since the cost of such constraints would be minimal –they are basically principles of urban planning more than improved equipment of infrastructure – and they nonetheless account for approximately one third of the overall effect of a full urban form reshaping.

Public transit investment constitute another lever, however, the cost of transportation infrastructure does not allow to develop such equipment in every city, whatever the budgetary effort of the central state would be. We thus fall into chapter two's framework where the central state decide the allocation of public good. Depending of the intensity of location preferences, we would recommend, on the basis of its results, to prioritize investment in small and medium size cities. The results of the third chapter would even modulate this recommendation to focus transfers on medium cities. Indeed, we shown that they are both the most fuel consuming cities and the places where most of current urban growth in France occurs.

In the light of urban geography trends, notably those exposed in Combes and Lafourcade (2005), who show in a Krugman (1991) framework that medium size regional cores are currently drawing populations from both the Parisian agglomeration and small regional cities, this recommendation to focus urban reshaping investments on medium size cities appears as the strong policy conclusion of this dissertation : since these cities, currently the largest fuel emitters per capita, are growing, and since redistribution towards them can be efficient in an optimal city size framework, the central state could actually get a double dividend from environmentally friendly public good distribution to these medium cities, both to develop a fully fledged public transit system and to adapt new neighborhoods at the urban fringe to the ecological transition.

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Appendix A

A Streetcar Named Opportunity

A.1 French Tramways

A.1.1 A brief history of Tramways

Electric tramways, alongside heavy suburban steam engine trains, played an important role of connecting poor workers to jobs in modern metropolis (Heblich et al., 2020b). This transportation mode have been indeed very popular in early 20th century France, where more than 130 cities were equipped, as well as in most Western countries. However, its development was severed in the late 30's by the competition of internal combustion vehicles and almost totally disappeared after World War II due to the combination of low fuel prices, rise of individual car and a correlated shift of public investment to road construction (Goddard, 1996). In the United States, streetcars totally disappeared from the urban landscape. In France, only 3 networks out of 130 remained operational in 1975. The exception of Germany and Northern Europe, where most networks remained in activity, is partly explained by the high densities in Rhine valley cities, low electricity price nearby coalmines and local institutional settings that favoured decentralized decision-making. Countries of the Eastern block also kept their pre-war networks, notably because of the low development of individual vehicles. The resulting disconnection between centers and peripheries was a growing concern for mayors in the end of the 20th century. France pioneered a new "glorious era" for LRT in the mid-1980's. Yet in 1975, a national scheme, the "Cavallé Plan" financially encouraged eight major cities to build a LRT to solve congestion issues induced by the rapid extension of peripheral neighborhoods. It was thought that LRT was the best compromise for medium size French cities, since it can carry 5 times the flow a bus system can, for a cost limited to 3 times the one of buses, and only one fifth of the cost of a metro line. After half a century of decline, French tramway renewal has pioneered a renewed popularity of tramways among urban planners during the last two decades both in developed and developing countries. In a context of growing metropolisation, LRT, cheaper, quicker to build and more versatile than

heavy rail infrastructure, is expected to facilitate commuting to jobs, temper spatial disparities and reduce carbon emissions in rapidly growing cities worldwide. In North Africa, 9 cities have been building a LRT network since 2000, alongside with 11 in the Middle East, 4 in China and many ongoing projects. However, none of these LRT construction programs have been larger and more consistent than the French one. Moreover, the French case often serves as an explicit reference case for these works.

A.1.2 Descriptive statistics

Figure A-1: Public transportation Monthly pricing

	Normal Monthly Fare	Lowest Social Monthly Fare
Angers	43,50 €	21,00 €
Besancon	43,50 €	2,00 €
Bordeaux	50,00 €	- €
Brest	38,50 €	6,20 €
Caen	41,00 €	- €
Clermont Ferrand	52,20 €	9,10 €
Dijon	42,00 €	- €
Grenoble	60,00 €	2,50 €
Le havre	43,00 €	12,50 €
Lemans	41,00 €	3,80 €
Lyon	65,00 €	10,00 €
Marseille	50,00 €	- €
Montpellier	53,50 €	3,00 €
Mulhouse	43,00 €	17,00 €
Nantes	69,00 €	- €
Nice	45,00 €	20,00 €
Orleans	43,60 €	10,10 €
Paris	75,00 €	18,00 €
Reims	38,55 €	unknown
StEtienne	47,00 €	3,73 €
Strasbourg	51,80 €	5,80 €
Toulouse	50,00 €	- €
Tours	45,00 €	10,00 €
Valenciennes	38,50 €	13,20 €
Average	48,96 €	6,68 €

Priced are as publicised on the internet website of the local transport agency in septembre 2019. Price includes access to the local public transport network for a month. Several social monthly fare exists and depend on the household revenue. A welfare recipient would be entitled to the lowest social fare.

Figure A-2: Number of tram stops by year in the last two decades in France

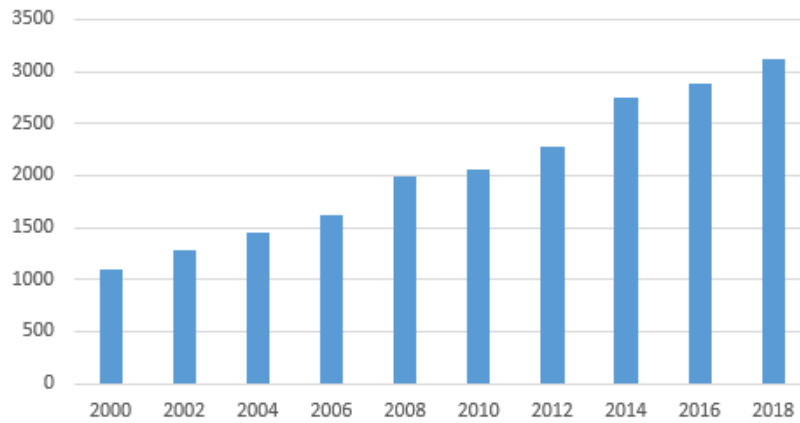
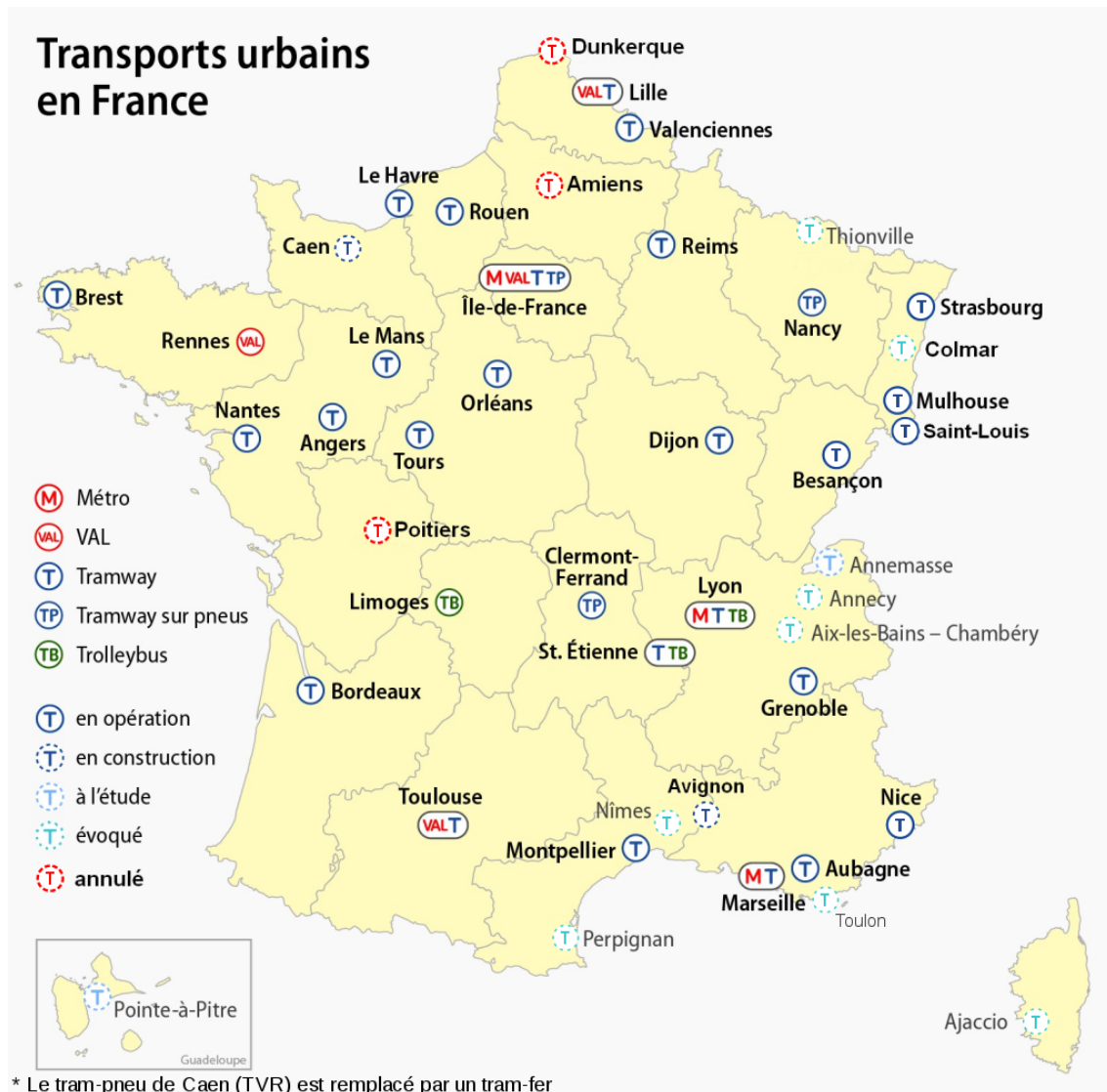


Figure A-3: Tram lines openings in the last two decades in France

	City	Opening Date	Length (km)	
	Saint-Étienne	04/12/1881	11,7	
	Lille - Roubaix - Tourcoing	04/12/1909	17,5	
	Nantes 1	07/01/1985	17,6	
	Grenoble A	05/09/1987	12,7	
	Grenoble B	26/11/1990	10,5	
	Paris 1	06/07/1992	17	
	Nantes 2	26/09/1992	11,7	
	Strasbourg A	25/11/1994	14,65	
	Strasbourg B	26/11/1994	14,8	
	Strasbourg C	27/11/1994	8,1	
	Rouen	17/12/1994	15,1	
	Strasbourg D	20/06/1995	12,5	
	Paris 2	01/01/1997	17,9	
	Nantes 3	27/09/1998	14,1	
	Montpellier 1	30/06/2000	15,7	
	Orléans A	24/11/2000	18	
	Orléans B	24/11/2000	11,3	
	Nancy	08/12/2000	11,1	
	Lyon T1	02/01/2001	11,7	
	Lyon T2	02/01/2001	14,9	
	Lyon T3	02/01/2001	14,6	
	Bordeaux A	21/12/2003	24,2	
	Bordeaux C	24/04/2004	20,8	
	Bordeaux B	15/05/2004	19,5	
	Paris 3	01/01/2006	26,7	
	Paris 4	01/01/2006	7,9	
	Mulhouse 1	20/05/2006	16,2	
	Mulhouse 2	20/05/2006	5,8	
	Grenoble C	21/06/2006	9,4	
	Valenciennes T1	03/07/2006	18,3	
	Clermont-Ferrand	16/12/2006	15,7	
	Montpellier 3	16/12/2006	17,5	
	Strasbourg E	01/01/2007	11,85	
	Marseille T1	30/06/2007	5,4	
	Marseille T2	30/06/2007	6,5	
	Grenoble D	06/10/2007	2,6	
	Le Mans T1	17/11/2007	9	
	Le Mans T2	17/11/2007	9	
	Nice	24/11/2007	16,2	
	Lyon T4	21/04/2009	16	
	Lyon T6	09/09/2010	22	
	Toulouse	11/12/2010	16,7	
	Mulhouse 3	12/12/2010	6,2	
	Reims 1	16/04/2011	9,05	
	Reims 2	16/04/2011	10	
	Angers	25/06/2011	12,3	
	Montpellier 3	07/04/2012	23	
	Montpellier 4	07/04/2012	9,2	
	Brest	23/06/2012	14,3	
	Dijon T1	01/09/2012	8,5	
	Lyon T5	17/11/2012	3,8	
	Paris 5	01/01/2013	6,6	
	Paris 7	01/01/2013	11,2	
	Paris 6	01/01/2014	14	
	Paris 8	01/01/2014	8,5	
	Dijon T2	01/12/2012	11,5	
	Le Havre A	12/12/2012	8,35	
	Le Havre B	12/12/2012	8,95	
	Tours	31/08/2013	15,5	
	Valenciennes T2	24/02/2014	15,5	
	Grenoble E	29/05/2014	11,5	
	Besançon T1	30/08/2014	13,4	
	Besançon T2	31/08/2014	9,6	
	Marseille T3	30/06/2015	3,6	
	Paris 9	01/01/2017	11	
	TOTAL		625,5	

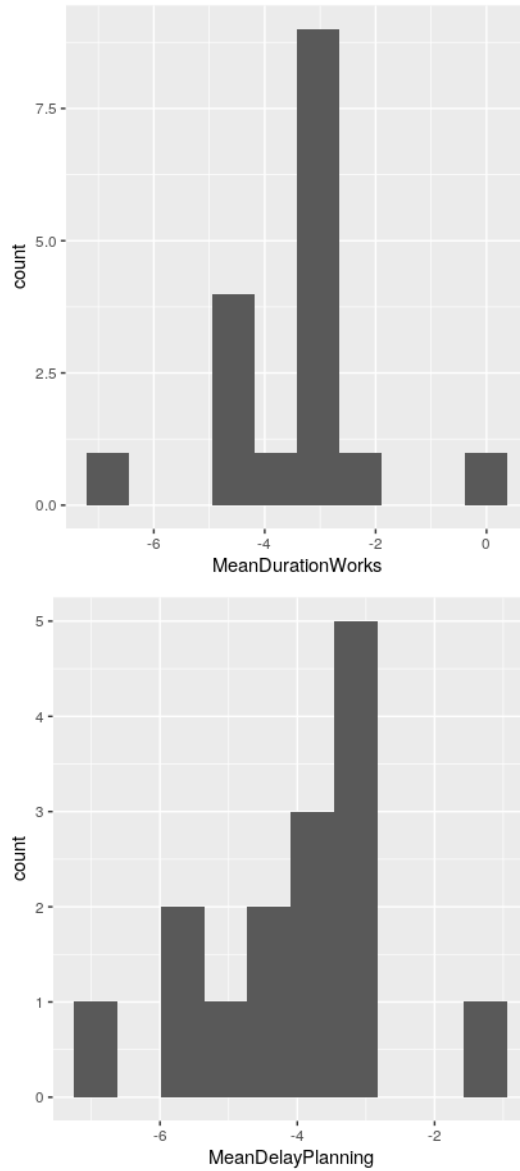
Figure A-4: Tramway and Light Rail Transit networks in France



A.1.3 The French public transport infrastructure decision process

The mean delay between the publication of the chosen route and the line opening is 3,48 years. The delay between public debate and line opening is more volatile, however the mean project being completed 4 years after public debate. Histograms A-5 show the distribution of these delays among projects.

Figure A-5: Mean duration of works and mean delay after public debate



A.2 Unemployment analysis

A.2.1 Geocoding procedure for unemployed's addresses

Using a phonetic fuzzy string matching algorithm and the French database of Postal Addresses BAN provided by French Postal Service, we are able to associate up to 85% of spells with the coordinates of the job seeker's residence, through the geocoding of 41,579,075 addresses.

Data and methods The *Base d'Adresses Nationale* (BAN)¹ is the French national postal service addresses database. It offers a set of spatial coordinates with a metric precision for each location in the French territory whose address is specified according to the rules of the postal service, which notably implies a correct spelling of name of the road, the municipality and its postal code. It contains 24.6 million addresses and 200 000 rural localities.

We resort to this database to geocode the job seekers addresses exerted from the *Fichier Historique* database. However, we face an important issue since information entered in the administrative forms by job seekers are usually not structured according to the rules of the postal service, and even often not correctly spelled. We thus need a phonetic correspondence matching algorithm to be able to geocode a significant fraction of our job seekers. Table A.1 exhibits some fuzzy matching challenges one has to deal with when locating job seekers from these addresses.

Table A.1: Random sample of *Fichier Historique* addresses and their correspondance in the BAN

Address entered by job seeker	Address structured by the rules of the Postal Service
N RTE REYRIEUX, 01600	N Route de Reyrieux, 01600 Trévoux
RESIDENCE LE FONTAINE, CHEM DES MAGNY, 01280	Nf Chemin de Magny, 01280 Prévessin-Moens
CHEZ MR Y, 01450	N/A
LA BOURDONNIERE, RTE DE BOURG EN BRESSE, 01320	N Route de Bourg, 01320 Chalamond
RUE BEL FERME, 01170	La Belle Ferme, 01170 Gex
HAM L AMICOLIERE 01270	Hameau La Nicolière 01270 Beaupont
N R MAL DELATTRE DE TAS 01100	N Rue du Maréchal de Lattre de Tassigny, 01100 Oyonnax
FONDATION ANTONIOZ, RTE DE GENEVE 01120	Avenue de Genève, 01120 Divonne les Bains
CHEZ MR X, N R ANTOINE DE SAINT EXUPERY 01160	N Rue Saint-Exupéry, 01160 Pont d'Ain
N RUE DU DR MONTREAL LA CLUZES	N Rue du Docteur Rossand, 01460 Montréal la Cluzes

Notes: Random sample of addresses from the *Ain* département and result from fuzzy matching with the BAN. Names of eventual hosts have been anonymized for privacy reasons.

Fuzzy string matching algorithm exist in currently used statistical programs, however, to the best of our knowledge, none of thee is able to compute a phonetic correspondence based on French language. This issue is particularly important since French phonetics may be particularly ambiguous. We thus turned to an open source matching engine named *Addok*, specifically designed to deal with french addresses, developed by the government Open Data Office (*Etalab*). An API is available on the government website, however, due to the heavy volume of data (41,579,075 addresses) we have to deal with, we preferred a local implementation of the algorithm, using the code available on GitHub². We then cross validated a sample of our results with the google maps API.

Practically, we run the Addok engine over the BAN on a 40 Go RAM local machine, while a Python routine interrogates both the Addok engine and the Google Maps API, if

¹Publicly available on the governmental website <https://adresse.data.gouv.fr/>

²See <https://github.com/cquest/geocodage-spd/>

necessary.³ The complete review of the 41 million addresses takes 4 days.

Considering that many job seekers do not correctly specify their addresses (typically, they may enter the name of the person that is hosting them, instead of their address), we are in the end able to we are able to associate up to 85% of spells with the coordinates of the job seeker's residence.

A.2.2 Descriptive statistics

Table A.2: Summary Statistics - Population Mean (std. dev.) before tramway arrival

group	Treated	Never Treated	General population
Disable worker	0.05 (0.22)	0.05 (0.22)	0.04 (0.2)
Indemnisation_Indemnisation	0.36 (0.48)	0.39 (0.49)	0.4 (0.49)
Single	0.61 (0.49)	0.6 (0.49)	0.63 (0.48)
Married	0.31 (0.46)	0.32 (0.47)	0.3 (0.46)
EmploiRech_CDD Temps Complet	0.03 (0.16)	0.02 (0.15)	0.03 (0.18)
EmploiRech_CDI Temps Complet	0.81 (0.39)	0.82 (0.38)	0.81 (0.39)
EmploiRech_Contrat Saisonier	0.05 (0.21)	0.04 (0.2)	0.05 (0.22)
Agriculture and Fishing	0.02 (0.14)	0.02 (0.15)	0.02 (0.13)
Art and Shaping Art works	0.01 (0.07)	0.01 (0.08)	0.01 (0.09)
Banking, Insurance, Real Estate	0 (0)	0 (0)	0 (0)
Trade Sale and Large distribution	0.16 (0.37)	0.16 (0.37)	0.16 (0.37)
Communication and media	0.01 (0.11)	0.01 (0.1)	0.02 (0.16)
Construction Building and Public Works	0.1 (0.3)	0.09 (0.29)	0.07 (0.26)
Restauration Tourism and Leisure	0.07 (0.26)	0.07 (0.25)	0.08 (0.26)
Industry	0.08 (0.27)	0.08 (0.26)	0.07 (0.25)
Installation and Maintenance	0.03 (0.18)	0.04 (0.2)	0.03 (0.17)
Health	0.02 (0.13)	0.02 (0.14)	0.02 (0.15)
Personal Community Services	0.21 (0.41)	0.22 (0.41)	0.21 (0.4)
Show	0.01 (0.1)	0.01 (0.09)	0.02 (0.14)
Support to the Company	0.09 (0.29)	0.1 (0.3)	0.14 (0.34)
Transport and Logistic	0.09 (0.29)	0.1 (0.3)	0.07 (0.25)
Unkown	0.08 (0.28)	0.08 (0.27)	0.09 (0.28)
Population	16176	7288	123161

Notes : Statistics from jobseekers registering in their local agency in the second quarter of 2005
Housing variables and Joblessness Survival are block level mean weighted by the number of unemployed living in the blocks in each group

³Code available upon request. Provided we do not have a paid key to access the Google Maps API, we are limited in terms of daily requests, and chose only to submit to the Google API the addresses whose score with the Addok engine was low. On subsample tests, we observe that the Google API is less precise than the Addok engine in the general case, but performs very well to localize isolated or rural localities that do not appear in the BAN.

A.2.3 Heterogeneity Analysis

Figure A-1: Heterogeneity results by cities

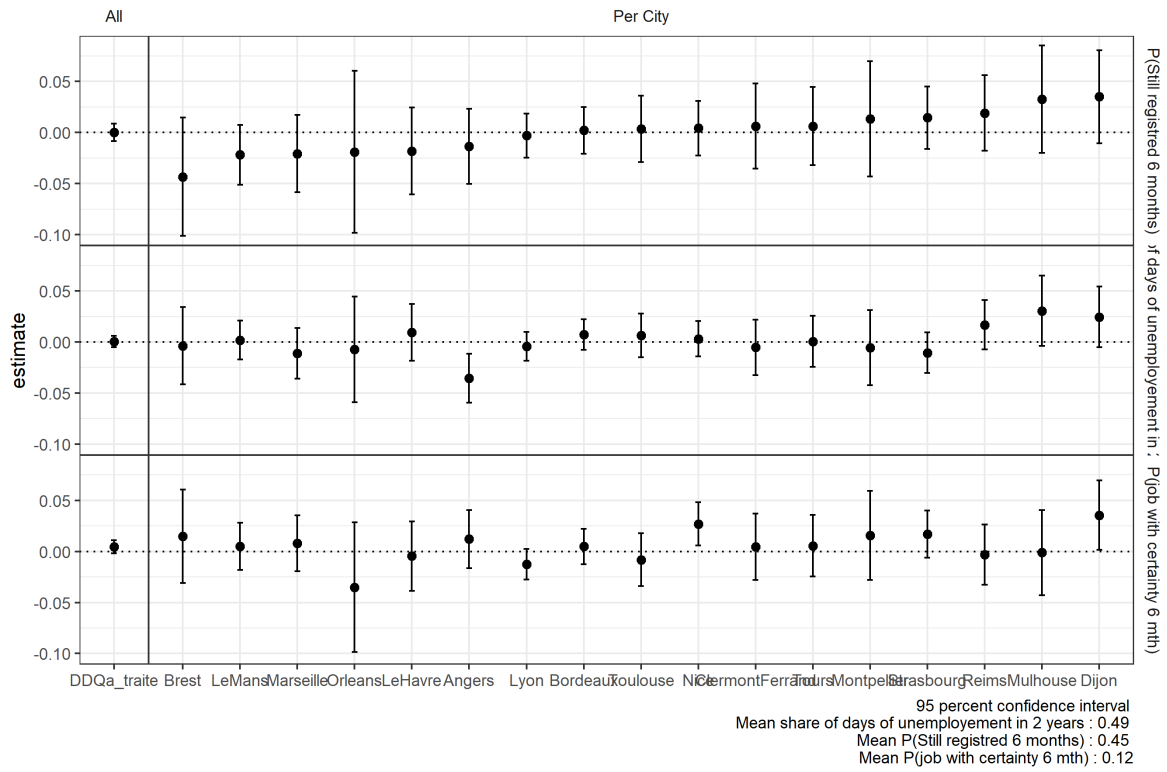
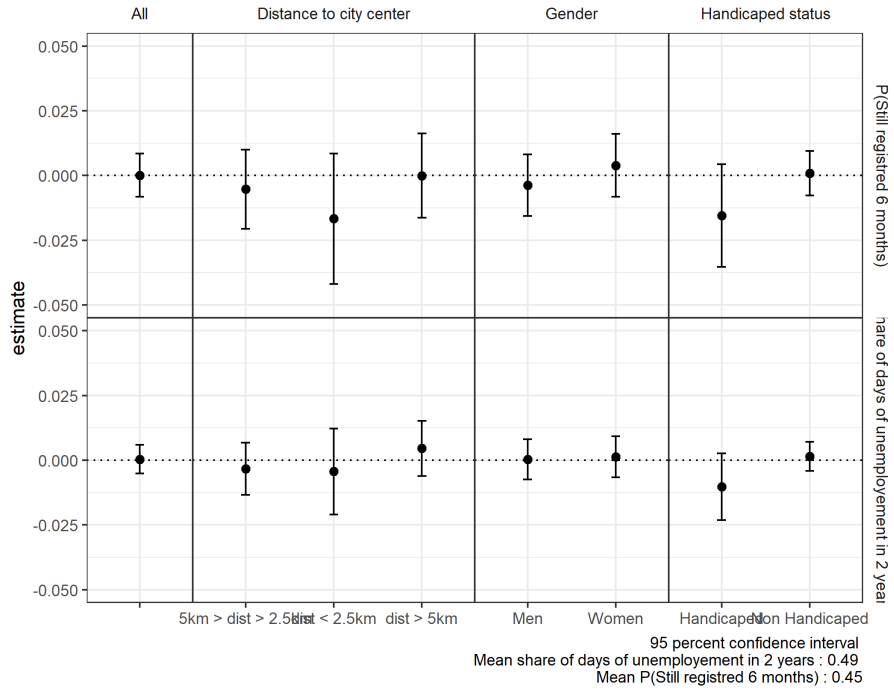


Figure A-2: Heterogeneity Analysis



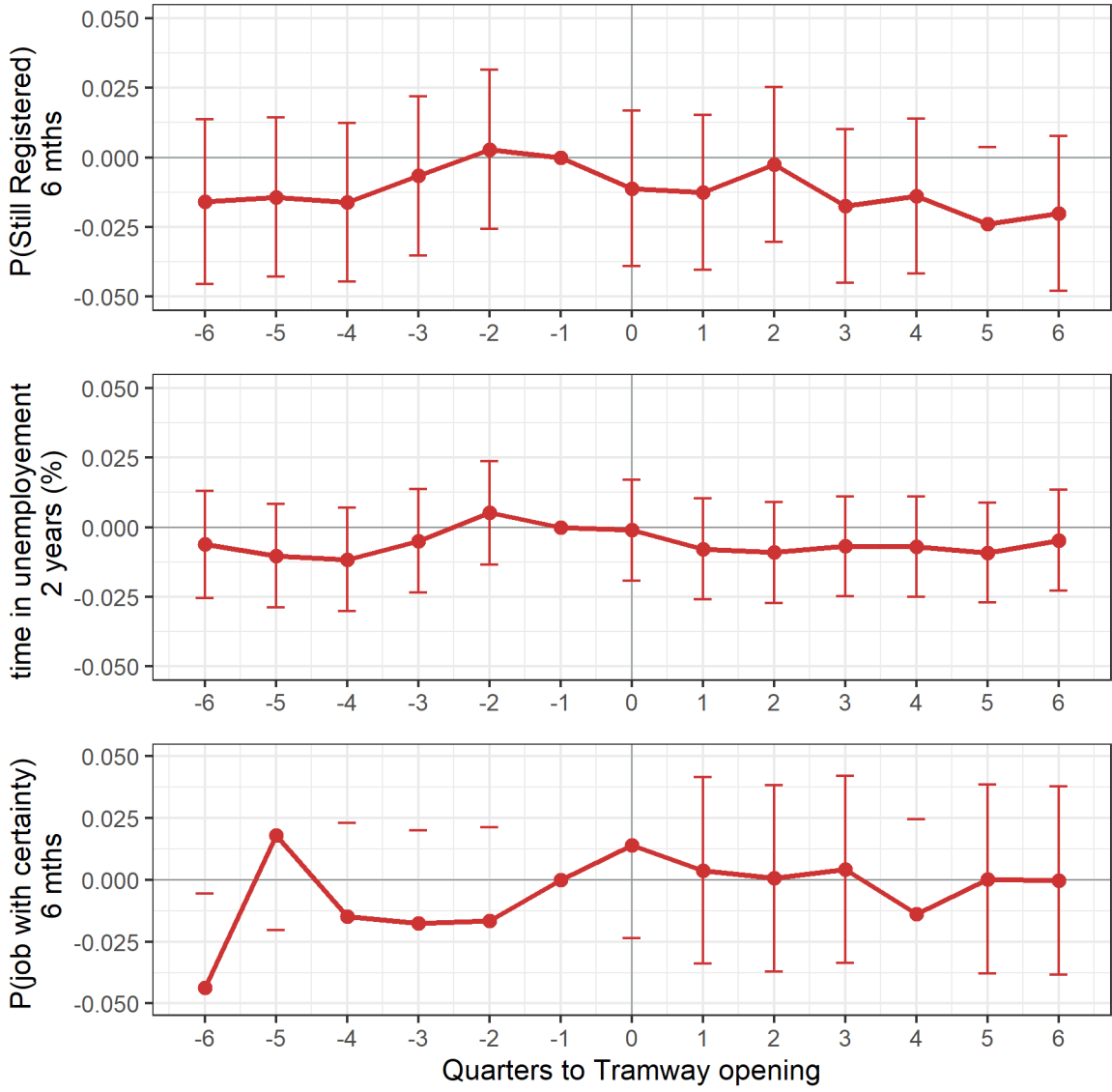
A.2.4 Results on Common Openings

Table A.3: Difference in Difference estimates

	<i>Dependent variable:</i>		
	P(Still registered 6 months) (1)	Number of spells 1 year (2)	P(job with certainty 6 mth) (3)
LWT	-0.003 (0.007)	-0.002 (0.005)	0.010 (0.006)
Minimum Detectable Effect	0.018	0.011	0.015
Mean Outcome	0.41	0.45	0.135
Observations	92,378	92,378	2,390
R ²	0.159	0.160	0.412
Adjusted R ²	0.155	0.156	0.299
Residual Std. Error	0.452 (df = 91936)	0.289 (df = 91936)	0.403 (df = 2004)

Note:

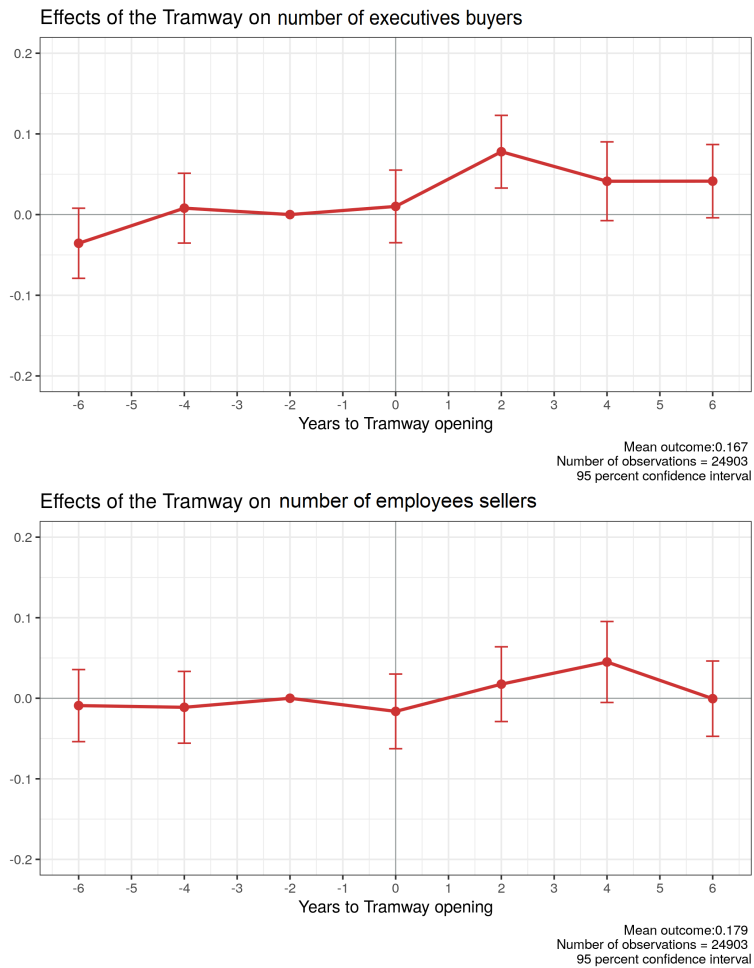
*p<0.1; **p<0.05; ***p<0.01
 statistical significance a = 0.05; statistical power (1) = 80 percent



A.3 Housing market

A.3.1 Occupation of buyers and sellers

Figure A-1: Occupation of inflow/outflow urbanites



Notes: this graph plot the β_k of equation 1.1; 95% Confidence interval

Source: Perval

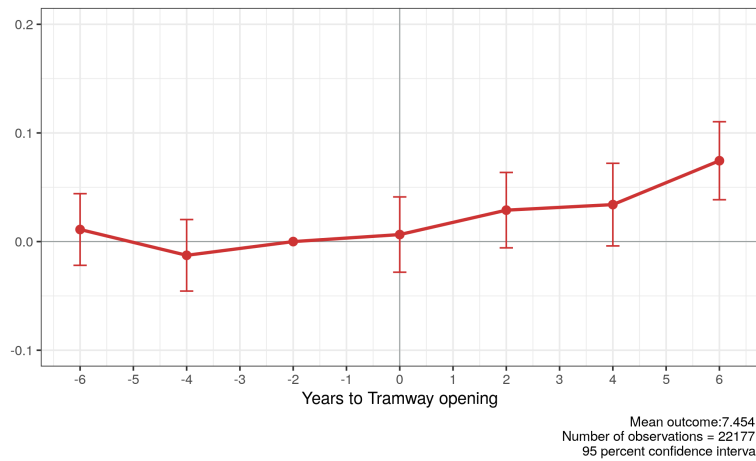
Figure A-2: Profession and LRT arrival



Notes: β_{t_k} of equation 1.1; 95% Confidence interval Source: Perval

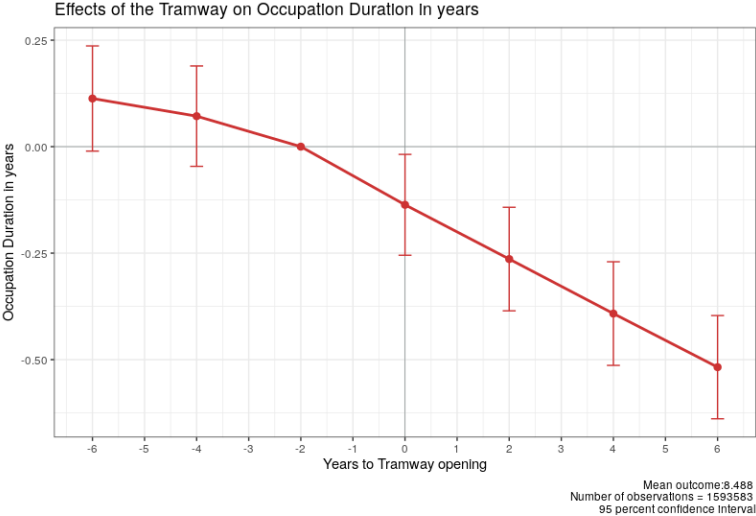
A.3.2 Robustness checks on housing market

Figure A-3: Prices and LRT arrival without new buildings



Notes: this graph plot the β_{t_k} of equation 1.1; 95% confidence interval Source: Perval

Figure A-4: Market activity and LRT arrival without new buildings



Notes: this graph plot the β_k of equation 1.1; 95% confidence interval
Source: FILOCOM

A.3.3 Heterogeneity

Figure A-5: Housing Prices and LRT arrival by city size (different bunches)

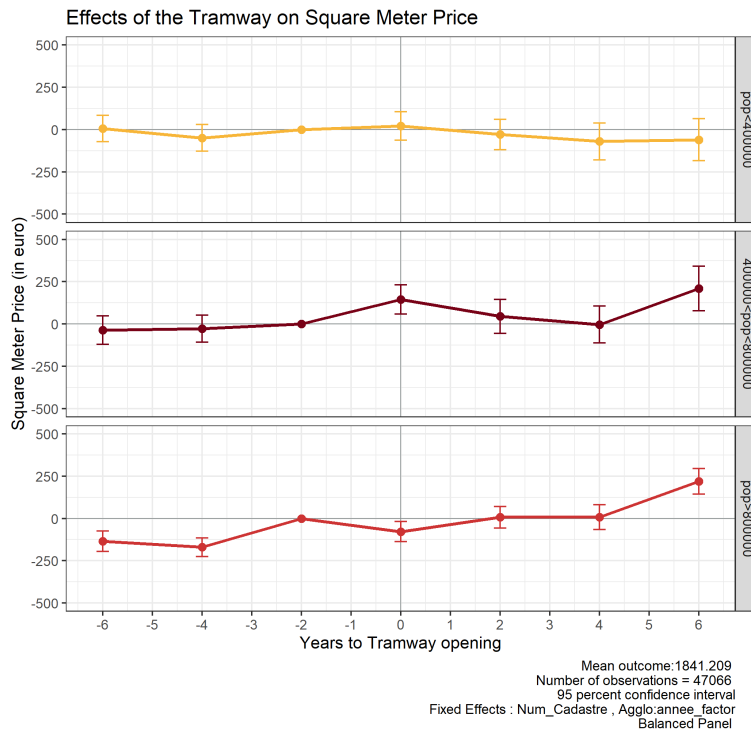
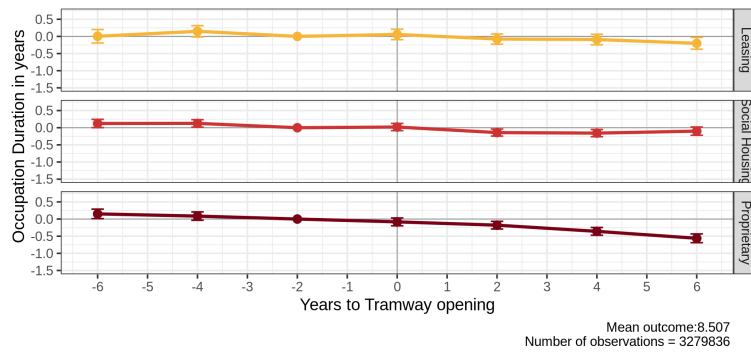


Figure A-6: Occupation duration and construction works by occupation status



Appendix B

Optimal Spatial Policies with Local Public Goods and Location Preferences

B.1 Model

B.1.1 Local Public Good Demand

We generalize the arguments in Boadway (1982) who separately studies residence and property taxes in a two-city and homogeneous location preference model to our framework with many cities $J > 2$, heterogeneous preferences and simultaneous tax instruments. First, note that (2.10) and (2.11) can be combined to solve for h_j ($w_j, r_j, T_j, G_j, \tau_j^h, \{\Pi_k\}_k, \{\tau_k^p\}_k$). Normalizing all prices with respect to p and with a slight abuse of notations, the local government

$$\max v_j \left(w_j + \sum_k \Pi_k (1 - \tau_k^p) + T_j - \tau_j^h - r_j h_j, h_j, \mathbb{G}_j(G_j, N_j), \mathcal{G} \right) \quad (\text{B.1})$$

over $\{\tau_j^h, \tau_j^p, G_j\}$ subject to

$$\Pi_j = F_j^Y + r_j F_j^H + p_j^G F_j^G - w_j (L_j^Y + L_j^H + L_j^G) \quad (\text{B.2})$$

$$N_j = \frac{v_j^{1/\sigma}}{\sum_k v_k^{1/\sigma}} \quad (\text{B.3})$$

$$L_j^Y + L_j^G + L_j^H + L_j^O = N_j \quad (\text{B.4})$$

$$F_j^H (L_j^H) = N_j h_j \quad (\text{B.5})$$

$$F_j^G(L_j^G) = G_j \quad (\text{B.6})$$

$$w_j = \frac{dF_j^Y(L_j^Y)}{dL_j^Y} \quad (\text{B.7})$$

$$w_j = r_j \frac{dF_j^H(L_j^H)}{dL_j^H} \quad (\text{B.8})$$

$$w_j = p_j^G \frac{dF_j^G(L_j^G)}{dL_j^G} \quad (\text{B.9})$$

$$p_j^G G_j = \tau_j^h N_j + \tau_j^p \Pi_j \quad (\text{B.10})$$

where policy instruments of other jurisdictions are considered fixed by the local government (Cournot - Nash equilibrium).

Plugging in as many constraints as possible, one can show that the first-order condition for τ_j^h yields

$$\underbrace{\frac{N_j}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j}}_{\text{Myopia Term}} + \underbrace{\frac{v_j}{N_j} \frac{\partial \ln v_j}{\partial \ln N_j} \Big|_{\tau} \frac{\partial N_j}{\partial \tau_j^h}}_{\text{Anticipation Term}} = 0 \quad (\text{B.11})$$

where $\frac{\partial \ln v_j}{\partial \ln N_j} \Big|_{\tau}$ is the change in local utility only coming from migration responses – affecting the tax base, local labour and goods markets, profits and public good congestion – holding constant all policy instruments. The term $\frac{\partial N_j}{\partial \tau_j^h}$ is the total or “policy” variation of N_j with respect to a change in τ_j^h when all other policy instruments stay constant.

The first two terms on the left hand-side correspond to the optimization of a myopic local government. One recognizes the Samuelson rule generalized to accommodate congestion. The last term corresponds to the migration anticipation term for a non-myopic local planner. Using (B.3), one can further show that

$$\frac{\partial N_j}{\partial \tau_j^h} \left(\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} \right) = N_j (1 - N_j) \frac{1}{v_j} \left(\frac{N_j}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j} \right) - N_j \sum_l \frac{\partial \ln v_l}{\partial \ln N_l} \frac{\partial N_l}{\partial \tau_j^h} \quad (\text{B.12})$$

and that

$$\frac{\partial N_k}{\partial \tau_j^h} \left(\sigma - \frac{\partial \ln v_k}{\partial \ln N_k} \right) = -N_k N_j \frac{1}{v_j} \left(\frac{N_j}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j} \right) - N_k \sum_l \frac{\partial \ln v_l}{\partial \ln N_l} \frac{\partial N_l}{\partial \tau_j^h} \quad \text{for } k \neq j \quad (\text{B.13})$$

Substituting in the last term of (B.12) in (B.13) one gets

$$\frac{\partial N_k}{\partial \tau_j^h} = \frac{\partial N_j}{\partial \tau_j^h} \frac{N_k}{N_j} \frac{\sigma - \frac{\partial \ln v_j}{\partial \ln N_j}}{\sigma - \frac{\partial \ln v_k}{\partial \ln N_k}} - \left(\frac{N_j}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j} \right) \frac{N_k}{v_j} \frac{1}{\sigma - \frac{\partial \ln v_k}{\partial \ln N_k}} \quad \text{for } k \neq j \quad (\text{B.14})$$

Plugging (B.14) in (B.12) for each $l \neq j$ we get

$$\frac{\partial N_j}{\partial \tau_j^h} = \frac{N_j}{v_j} A_j \times \left(\frac{N_j}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j} \right) \quad (\text{B.15})$$

where

$$A_j = \frac{1 - N_j + \sum_k N_k \frac{\partial \ln v_k}{\partial \ln N_k} \left(\sigma - \frac{\partial \ln v_k}{\partial \ln N_k} \right)^{-1}}{\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} + \sum_k N_k \frac{\partial \ln v_k}{\partial \ln N_k} \left(\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} \right) \left(\sigma - \frac{\partial \ln v_k}{\partial \ln N_k} \right)^{-1}}$$

so that finally first-order conditions for τ_j^h can be expressed as

$$\left(\frac{N_j}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j} \right) \left(1 + \frac{\partial \ln v_j}{\partial \ln N_j} \Big|_{\tau} \times A_j \right) = 0 \quad (\text{B.16})$$

and the only way to nullify (B.16) is to satisfy a local Samuelson rule.

The first-order condition for τ_j^p yields

$$\underbrace{\Pi_j \left(\frac{1}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j} \right)}_{\text{Myopia Term}} + \underbrace{\frac{v_j}{N_j} \frac{\partial \ln v_j}{\partial \ln N_j} \Big|_{\tau} \frac{\partial N_j}{\partial \tau_j^p}}_{\text{Anticipation Term}} = 0 \quad (\text{B.17})$$

One can see that (B.11) and (B.17) cannot hold simultaneously at interior solutions for τ_j^h and τ_j^p if the local planner is myopic about migration. Hence, the only way to have interior solutions for both head taxes and profit taxes is to have a non-myopic local planner. Using (B.3), one can further show that

$$\begin{aligned} \frac{\partial N_j}{\partial \tau_j^p} \left(\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} \right) &= \Pi_j N_j (1 - N_j) \frac{1}{v_j} \left(\frac{1}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial c_j} - \frac{\partial v_j}{\partial c_j} \right) \\ &\quad + N_j \sum_{l \neq j} R_l(N_l) \frac{N_l}{v_l} \frac{\partial v_l}{\partial c_l} - N_j \sum_l \frac{\partial \ln v_l}{\partial \ln N_l} \frac{\partial N_l}{\partial \tau_j^p} \end{aligned} \quad (\text{B.18})$$

$$\begin{aligned} \frac{\partial N_k}{\partial \tau_j^p} \left(\sigma - \frac{\partial \ln v_k}{\partial \ln N_k} \right) &= -\Pi_k N_k \frac{1}{v_k} \frac{\partial v_k}{\partial c_k} - N_j N_j \Pi_j \frac{1}{v_j} \left(\frac{1}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial G_j} - \frac{\partial v_j}{\partial c_j} \right) \\ &+ N_k \sum_{l \neq j} R_l(N_l) \frac{N_l}{v_l} \frac{\partial v_l}{\partial c_l} - N_k \sum_l \frac{\partial \ln v_l}{\partial \ln N_l} \frac{\partial N_l}{\partial \tau_j^p} \end{aligned} \quad (\text{B.19})$$

$$\begin{aligned} \frac{\partial N_k}{\partial \tau_j^p} &= \frac{\partial N_j}{\partial \tau_j^p} N_k \frac{\sigma - \frac{\partial \ln v_j}{\partial \ln N_j}}{\sigma - \frac{\partial \ln v_k}{\partial \ln N_k}} - \Pi_k N_k \frac{1}{v_k} \frac{\partial v_k}{\partial c_k} \frac{1}{\sigma - \frac{\partial \ln v_k}{\partial \ln N_k}} \\ &- \Pi_j \frac{1}{v_j} \left(\frac{1}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial G_j} - \frac{\partial v_j}{\partial c_j} \right) \frac{(1 - N_j) N_k + N_j N_j}{\sigma - \frac{\partial \ln v_k}{\partial \ln N_k}} \quad \text{for } k \neq j \end{aligned} \quad (\text{B.20})$$

so

$$\Pi_j \left(\frac{1}{p_j^G} \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial G_j} - \frac{\partial v_j}{\partial c_j} \right) \left(1 + \frac{\partial \ln v_j}{\partial \ln N_j} \Big|_{\tau} \times B_j \right) + C_j \sum_{k \neq j} \Pi_k N_k \frac{v_j}{v_k} \frac{\partial v_k}{\partial c_k} = 0 \quad (\text{B.21})$$

where

$$\begin{aligned} B_j &= \frac{1 - N_j + \sum_k N_k \frac{\partial \ln v_k}{\partial \ln N_k} \left(\sigma - \frac{\partial \ln v_k}{\partial \ln N_k} \right)^{-1} (N_k(1 - N_j) + N_j N_j)}{\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} + \sum_k N_k \frac{\partial \ln v_k}{\partial \ln N_k} \left(\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} \right) \left(\sigma - \frac{\partial \ln v_k}{\partial \ln N_k} \right)^{-1}} \\ C_j &= \frac{1}{\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} + \sum_k N_k \frac{\partial \ln v_k}{\partial \ln N_k} \left(\sigma - \frac{\partial \ln v_j}{\partial \ln N_j} \right) \left(\sigma - \frac{\partial \ln v_k}{\partial \ln N_k} \right)^{-1}} \end{aligned}$$

The existence of the last term in the left hand side of (B.21) ensures that the local Samuelson rule implied by (B.16) can be respected as an interior condition for τ_j^h . Absent this last term, the first term in large brackets in (B.21) would have to be zero which would be incompatible with the Samuelson rule.

B.1.2 A Two-Region Example

Traded and local public goods are produced using CRS technologies with exogenous local productivity $z_j = z_j^Y = z_j^G$ that is constant in both sectors and varies between cities with $z_1 > z_2$. This is the only source of spatial heterogeneity. Labour demand optimization yields

$$w_1 = z_1 > w_2 = z_2$$

Using (2.12) and (2.14), it implies that $p_j^G = p$ for all j . Agent i living in j inelastically supplies one unit of labour. She consumes the nationally traded good, housing and has utility

$$v_{ij} = v_j \mu_{ij}$$

where

$$v_j = \left(c_j^{1-\alpha} h_j^\alpha \right)^{1-\phi} (\mathbf{G})^\phi$$

Endogenous public goods $\mathbf{G} = \frac{1}{p} \tau_j^h N_j^{1-\kappa}$ are financed by the residence tax τ_j^h only and increase with population N_j with constant agglomeration elasticity $1 - \kappa > 0$. Normalizing $p = 1$, household budget is

$$z_j + T_j + \Pi = c_j + r_j h_j + \tau_j^h$$

where $\Pi = r_1 (L_1^H)^{\frac{\eta}{1+\eta}} + r_2 (L_2^H)^{\frac{\eta}{1+\eta}} - w_1 L_1^H - w_2 L_2^H$ are profits from the housing sector. Demand for traded and non-traded goods is $c_j = (1 - \alpha) (1 - \phi) (w_j + T_j + \Pi)$ and $r_j h_j = \alpha (1 - \phi) (w_j + T_j + \Pi)$ while public good demand is $\tau_j^h = \phi (w_j + T_j + \Pi)$. Combining these expressions yields

$$v_j = \frac{w_j + T_j + \Pi}{r_j^{\alpha(1-\phi)}} N_j^{(1-\kappa)\phi}$$

omitting multiplicative constants. Assuming constant housing supply elasticity η , we combine housing supply $r_j = w_j \frac{\eta+1}{\eta} h_j^{\frac{1}{\eta}} N_j^{\frac{1}{\eta}}$ with housing demand to get

$$r_j^{1+\eta} = \left(\frac{\eta+1}{\eta} \right)^\eta w_j^\eta N_j^\eta \alpha (1 - \phi) (w_j + T_j + \Pi)$$

which finally yields

$$v_j = (w_j + T_j + \Pi)^{1 - \frac{\alpha(1-\phi)}{1+\eta}} N_j^{(1-\kappa)\phi - \frac{\alpha(1-\phi)}{1+\eta}}$$

omitting multiplicative constants again.

The μ_{ij} 's are distributed Extreme Value Type-I $\{0, \sigma\}$ with dispersion $\sigma > 0$. Demand for region j is

$$N_j = \frac{v_j^{1/\sigma}}{v_1^{1/\sigma} + v_2^{1/\sigma}}$$

The central government sets up a per capita tax and transfer scheme $\{T_1, T_2\}$ where T_1 is chosen freely and T_2 endogenously adjusts to balance the budget i.e. $N_1 T_1 + N_2 T_2 = 0$.

Equilibrium An equilibrium given T_1 is characterized by T_2 , Π and $\{N_j, L_j^Y, L_j^H, L_j^G, T_j, r_j\}_j$ such that

$$\begin{aligned}
\frac{\sigma - (1 - \kappa)\phi + \frac{\alpha(1-\phi)}{1+\eta}}{1 - \frac{\alpha(1-\phi)}{1+\eta}} \ln \left(\frac{N_1}{N_2} \right) &= \ln \left(\frac{z_1 + T_1 + \Pi}{z_2 + T_2 + \Pi} \right) \\
N_1 + N_2 &= 1 \\
N_1 T_1 + N_2 T_2 &= 0 \\
L_1^Y + L_1^H + L_1^G &= N_1 \\
L_2^Y + L_2^H + L_2^G &= N_2 \\
N_1 \frac{1}{r_1} \alpha (1 - \phi) (z_1 + T_1 + \Pi) &= \left(L_1^H \right)^{\eta/(1+\eta)} \\
N_2 \frac{1}{r_2} \alpha (1 - \phi) (z_2 + T_2 + \Pi) &= \left(L_2^H \right)^{\eta/(1+\eta)} \\
\phi (z_1 + T_1 + \Pi) N_1^{1-\kappa} &= z_1 L_1^G \\
\phi (z_2 + T_2 + \Pi) N_2^{1-\kappa} &= z_2 L_2^G \\
\Pi &= r_1 \left(L_1^H \right)^{\frac{\eta}{1+\eta}} + r_2 \left(L_2^H \right)^{\frac{\eta}{1+\eta}} - z_1 L_1^H - z_2 L_2^H \\
r_1^{1+\eta} &= \left(\frac{\eta + 1}{\eta} \right)^\eta z_1^\eta N_1 \alpha (1 - \phi) (z_1 + T_1 + \Pi) \\
r_2^{1+\eta} &= \left(\frac{\eta + 1}{\eta} \right)^\eta z_2^\eta N_2 \alpha (1 - \phi) (z_2 + T_2 + \Pi)
\end{aligned} \tag{B.22}$$

where we impose that dispersion forces – land congestion and location preferences – are stronger than agglomeration forces i.e.

$$\sigma + \frac{\alpha(1-\phi)}{1+\eta} > (1 - \kappa)\phi$$

to ensure that the equilibrium is unique, stable and that the planner's objective is concave. Walras' law ensures that the market for the traded good also clears i.e.

$$z_1 L_1^Y + z_2 L_2^Y = N_1(1 - \alpha) (1 - \phi) (z_1 + T_1 + \Pi) + N_2(1 - \alpha) (1 - \phi) (z_2 + T_2 + \Pi)$$

Small reform in the laissez-faire economy Let us introduce a small transfer dT_1 in region 1 from $T_1 = T_2 = 0$ while T_2 adjusts endogenously to balance the central budget. Implicitly differentiating the first three equilibrium equations of (B.22), population grows in region 1 according to

$$\frac{\sigma - (1 - \kappa)\phi + \frac{\alpha(1-\phi)}{1+\eta}}{1 - \frac{\alpha(1-\phi)}{1+\eta}} \frac{dN_1}{dT_1} = N_1 \left(\frac{N_2}{z_1 + \Pi} + \frac{N_1}{z_2 + \Pi} \right) + \frac{d\Pi}{dT_1} N_2 N_1 \left(\frac{1}{z_1 + \Pi} - \frac{1}{z_2 + \Pi} \right)$$

and, using profit maximization from the three production sectors, profits change according to

$$\frac{d\Pi}{dT_1} = \frac{\frac{\alpha(1-\phi)}{1+\eta}}{1 - \frac{\alpha(1-\phi)}{1+\eta}} (z_1 - z_2) \frac{dN_1}{dT_1} \quad (\text{B.23})$$

so that

$$\frac{dN_1}{dT_1} = \frac{N_1 \left(\frac{N_2}{z_1 + \Pi} + \frac{N_1}{z_2 + \Pi} \right)}{\frac{\sigma - (1-\kappa)\phi + \frac{\alpha(1-\phi)}{1+\eta}}{1 - \frac{\alpha(1-\phi)}{1+\eta}} - N_2 N_1 \left(\frac{1}{z_1 + \Pi} - \frac{1}{z_2 + \Pi} \right) \frac{\frac{\alpha(1-\phi)}{1+\eta}}{1 - \frac{\alpha(1-\phi)}{1+\eta}} (z_1 - z_2)} > 0 \quad (\text{B.24})$$

since $z_1 > z_2$. Note that it implies $\frac{d\Pi}{dT_1} > 0$.

Using a standard envelope argument, welfare of households marginally indifferent between 1 and 2 is not affected to a first order. Notice that the μ_{ij} 's of infra-marginals are unaffected. Log utility of infra-marginal residents in both cities changes as follows

$$\begin{aligned} \frac{d \ln v_1}{dT_1} &\propto \frac{1}{z_1 + \Pi} + \frac{1}{z_1 + \Pi} \frac{d\Pi}{dT_1} + \frac{(1-\kappa)\phi - \frac{\alpha(1-\phi)}{1+\eta}}{1 - \frac{\alpha(1-\phi)}{1+\eta}} \frac{1}{N_1} \frac{dN_1}{dT_1} \\ \frac{d \ln v_2}{dT_1} &\propto -\frac{1}{z_2 + \Pi} \frac{N_1}{N_2} + \frac{1}{z_2 + \Pi} \frac{d\Pi}{dT_1} - \frac{(1-\kappa)\phi - \frac{\alpha(1-\phi)}{1+\eta}}{1 - \frac{\alpha(1-\phi)}{1+\eta}} \frac{1}{N_2} \frac{dN_1}{dT_1} \end{aligned}$$

The sign of welfare change in each region obtains by substituting in (B.23) and (B.24)

$$\begin{aligned} \text{sign} \left\{ \frac{dv_1}{dT_1} \right\} &= \text{sign} \left\{ N_1 \frac{z_1 - z_2}{z_2 + \Pi} (1-\kappa)\phi + \sigma \right\} \\ \text{sign} \left\{ \frac{dv_2}{dT_1} \right\} &= \text{sign} \left\{ N_2 \frac{z_1 - z_2}{z_1 + \Pi} (1-\kappa)\phi - \sigma \right\} \end{aligned} \quad (\text{B.25})$$

Case 1: Agglomeration \leq Congestion In this case $(1-\kappa)\phi \leq \frac{\alpha(1-\phi)}{1+\eta}$. We can safely have $\sigma \rightarrow 0$ while retaining a unique stable equilibrium. When $\sigma \rightarrow 0$, welfare changes are strictly positive in both regions since $\lim_{\sigma \rightarrow 0} N_1 > 0$ and $\lim_{\sigma \rightarrow 0} N_2 > 0$ and Π is bounded from above by Π^{\max} . It is Pareto-improving to introduce a small subsidy $dT_1 > 0$ and the small tax $dT_2 < 0$ that balances the budget. When $\sigma > 0$, derivative in region 1 is always positive so that the only Pareto improving candidate policy is $dT_1 > 0$. One can find a sufficient condition for the laissez-faire to be efficient i.e. a condition under which derivative in 2 is always strictly negative

$$\sigma > (1-\kappa)\phi \frac{z_1 - z_2}{z_1}$$

To see this, use (B.25) and the fact that $N_2 < 1$ and $\Pi > 0$.

Case 2: Agglomeration > Congestion In this case $(1 - \kappa)\phi > \frac{\alpha(1-\phi)}{1+\eta}$. One can only allow a minimum of $\sigma \rightarrow (1 - \kappa)\phi - \frac{\alpha(1-\phi)}{1+\eta} > 0$ to retain a unique equilibrium. In this limiting case we have

$$\begin{aligned} \text{sign} \left\{ \lim_{\sigma \rightarrow 0} \frac{dv_1}{dT_1} \right\} &= \text{sign} \left\{ (1 - \kappa)\phi - \frac{\alpha(1 - \phi)}{1 + \eta} + (1 - \kappa)\phi \lim_{\sigma \rightarrow 0} N_1 \frac{z_1 - z_2}{z_2 + \Pi} \right\} > 0 \\ \text{sign} \left\{ \lim_{\sigma \rightarrow 0} \frac{dv_2}{dT_1} \right\} &= \text{sign} \left\{ \lim_{\sigma \rightarrow 0} \left(N_2 \frac{z_1 - z_2}{z_1 + \Pi} - 1 \right) (1 - \kappa)\phi + \frac{\alpha(1 - \phi)}{1 + \eta} \right\} \end{aligned} \quad (\text{B.26})$$

A sufficient condition for the impossibility of any Pareto improving reform when $\sigma \rightarrow (1 - \kappa)\phi - \frac{\alpha(1-\phi)}{1+\eta}$ – hence whatever the value of $\sigma > (1 - \kappa)\phi - \frac{\alpha(1-\phi)}{1+\eta}$ – is that agglomeration forces are too strong relative to congestion forces i.e.

$$(1 - \kappa)\phi > \frac{z_1 \alpha(1 - \phi)}{z_2 (1 + \eta)}$$

To see this, use (B.25) and the fact that $N_2 < 1$ and $\Pi > 0$. Note that with CRS technology for supplying the local non-traded good ($\eta \rightarrow \infty$ i.e. perfectly elastic housing supply), no Pareto improving reforms exists.

B.1.3 Planner's Problem

Given exogenous Pareto weights $\{\omega_i\}_i$, the optimal allocation is the vector

$$\{v_j, c_j, h_j, G_j, N_j, \mathcal{O}_j, L_j^Y, L_j^G, L_j^H, L_j^{\mathcal{O}}\}_j$$

that maximizes

$$W = \mathbb{E} [\omega_i \ln u_i(v_1, \dots, v_j)]$$

Note that the planner is constrained to give the same c_j, h_j and G_j to all individuals of j hence the same v_j . The Lagrangian for the planner's problem is

$$\begin{aligned}
L = & \mathbb{E} [\omega_i \ln u_i(v_1, \dots, v_J)] \\
& - \sum_j \lambda_j N_j [v_j - v_j(c_j, h_j, G_j(G_j, N_j), \mathcal{G}(\{\mathcal{O}_k\}_k))] \\
& - \sum_j E_j \left[N_j - \frac{v_j^{1/\sigma}}{\sum_k v_k^{1/\sigma}} \right] \\
& - \pi^Y \sum_j [N_j c_j - F_j^Y(L_j^Y)] \\
& - \sum_j \pi_j^G [G_j - F_j^G(L_j^G)] \\
& - \sum_j \pi_j^O [\mathcal{O}_j - F_j^O(L_j^O)] \\
& - \sum_j \pi_j^H [N_j h_j - F_j^H(L_j^H)] \\
& - \sum_j \pi_j^L [L_j^Y + L_j^G + L_j^H + L_j^O - N_j]
\end{aligned} \tag{B.27}$$

The first term is the planner's objective that incorporates individuals' incentive constraints when recognizing that $\ln u_i = \max\{\ln v_j + \ln \mu_{ij}\}_j$. The second constraint is simply the definition of v_j . The third term is the aggregate incentive constraint that limits the planner's freedom in assigning workers to cities. Note that $N_j \leq \frac{v_j^{1/\sigma}}{\sum_k v_k^{1/\sigma}}$ for all j guarantee that $\sum_j N_j \leq 1$. The remaining terms are resource and market clearing constraints. $\{\lambda_j, E_j, \pi^Y, \pi_j^H, \pi_j^G, \pi_j^L, \pi_j^O\}_j$ are multipliers. Below we give the first-order conditions for $\{v_j, c_j, h_j, G_j, N_j, \mathcal{O}_j, L_j^Y, L_j^G, L_j^H, L_j^O\}_j$.

First-order condition for v_j :

$$\sigma(\Omega_j - \lambda_j v_j) + E_j - \sum_k N_k E_k = 0 \tag{B.28}$$

where

$$\Omega_j \equiv \frac{1}{N_j} \mathbb{E} [\omega_i \mathbb{1}_{[v_{ij} = \max\{v_{ik}\}_k]}] \tag{B.29}$$

First-order conditions for c_j, h_j and G_j :

$$\begin{aligned}\lambda_j \frac{\partial v_j}{\partial c_j} &= \pi^Y \\ \lambda_j \frac{\partial v_j}{\partial h_j} &= \pi_j^H \\ \lambda_j N_j \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial G_j} &= \pi_j^G\end{aligned}\tag{B.30}$$

First-order conditions for L_j^Y, L_j^G, L_j^H and L_j^O :

$$\pi^Y \frac{\partial F_j^Y}{\partial L_j^Y} = \pi_j^G \frac{\partial F_j^G}{\partial L_j^G} = \pi_j^H \frac{\partial F_j^H}{\partial L_j^H} = \pi_j^O \frac{\partial F_j^O}{\partial L_j^O} = \pi_j^L\tag{B.31}$$

First-order condition for N_j :

$$\lambda_j N_j \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial N_j} - E_j - (\pi^Y c_j + \pi_j^H h_j) + \pi_j^L = 0\tag{B.32}$$

First-order condition for \mathcal{O}_j :

$$\sum_k \lambda_k N_k \frac{\partial v_k}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \mathcal{O}_j} = \pi_j^O\tag{B.33}$$

To get to expression (2.32) in the text, substitute (B.30) and (B.31) in expression (B.32). To get to expression (2.33), substitute (B.30) and (B.31) in expression (B.33).

B.2 Calibration

B.2.1 Public Good Demand Calibration

In order to get a sense of the value of the congestion parameter κ , we follow the seminal approaches of Borchering and Deacon (1972) and Bergstrom and Goodman (1973) and calibrate a model of local public good demand. In section 2.4, we modelled how non-myopic jurisdictions maximize residents' utility $v_j(c_j, h_j, G_j)$ over head tax τ_j^h and property tax τ_j^p knowing the per capita government transfer T_j subject to the municipality budget constraint, and embed this optimization in a general equilibrium framework with mobile households. We reproduce here the local Samuelson rule that emerges:

$$\frac{p_j^G}{N_j} \frac{\partial v_j}{\partial c_j} = p \frac{\partial v_j}{\partial G_j} \frac{\partial G_j}{\partial G_j}\tag{B.34}$$

To bring equation (B.34) to empirical analysis, we assume a generalized constant elastic-

ity of substitution shape for v_j

$$v_j(c_j, h_j, G_j) = (\alpha_C c_j^{-\rho_C} + \alpha_H h_j^{-\rho_H} + \alpha_G G_j^{-\rho_G})^{1/\rho} f_j(X_j)$$

where c_j and h_j are consumption of traded and local non-traded goods, $G = \frac{G}{N^\kappa} \frac{1}{h(T)}$ is congested local public goods, $f_j(X_j)$ is a taste shifter and

$$\rho = \frac{1 - \sigma}{\sigma}$$

$$\sigma = \frac{\theta_C}{1 + \rho_C} + \frac{\theta_H}{1 + \rho_H} + \frac{\theta_G}{1 + \rho_G}$$

with $\{\theta_C, \theta_H, \theta_G\}$ being consumption, housing and public spending budget shares. Generalized CES utility approximates constant non-unitary price and income elasticities provided that budget shares do not vary too much (see Sato 1972). Under this constant share assumption, the Samuelson rule (B.34) directly translates into

$$\rho_G \alpha_G (G_j)^{-\rho_G - 1} = \rho_C \alpha_C \frac{p_j^G}{p} \frac{1}{N_j^{1-\kappa}} (c_j)^{-\rho_C - 1} f_j(X_j)$$

Using the constant share assumption for c_j and multiplying by p_j^G , we get the following public good expenditure function,

$$\frac{E_j}{N_j} = \frac{p_j^G G_j}{N_j} \equiv (p)^{\frac{1}{1+\rho_G}} \left(p_j^G\right)^{\frac{\rho_G}{1+\rho_G}} (N_j)^{\frac{\rho_G}{1+\rho_G}(\kappa-1)} (w_j + T_j + \Pi)^{\frac{1+\rho_C}{1+\rho_G}} T_j^\gamma f_j(X_j) \quad (\text{B.35})$$

which allows to separately calibrate ρ_G and κ , knowing the value of ρ_C . Note that $E_j = p_j^G G_j$ where $p^G = \left(\frac{\zeta p_s^G}{1-\psi}\right)^{1-\psi} \left(\frac{p_f^G}{\psi}\right)^\psi$ when $G = G_s^\psi G_f^{1-\psi}$ and where ζ is a constant capturing the fact that durable public goods are financed over time through debt repayment. Many variables should be observed by the econometrician. In particular, equation (B.35) justifies using a weighted geometric average of observed public spending on the left hand side even though real outputs are unobserved.

We bring expression (B.35) to regression analysis after taking logs. As we observe all 2,000 municipal federations representing 36,000 French municipalities in all even years between 2002 and 2014, we use the panel structure of our data to identify the relationship between per capita spending and within-federation changes in population and other confounders. Time-invariant local confounders over 2002-2014 are absorbed by MF fixed effects in f_j , while time-specific remaining shocks in local prices are absorbed by flexible region-specific time effects. To account for residual time variation within MF, we control for local house prices and local wages. Finally, we flexibly control for within-MF time variation in

Table B.1: Structural Elasticities for $\frac{1}{1+\rho_C} = 0.5$

	(1)	(2)	(3)
Price Elasticity $\left(\frac{1}{1+\rho_C}\right)$	0.478	0.487	0.521
	[0.278;0.685]	[0.271;0.708]	[0.273;0.745]
Congestion Elasticity (κ)	0.586	0.517	0.444
	[0.395;0.747]	[0.305;0.682]	[0.224;0.629]
FE	✓	✓	✓
Controls: Local Prices	✓	✓	✓
Controls: Industry & Occupation		✓	✓
Year FE ×			MA

Note: This Table reports estimates of structural elasticities. We flexibly control for the share of the population in various industry sectors and occupations. MA stands for metropolitan area. Bias-corrected point estimates and 95% confidence intervals are computed with a wild cluster bootstrap procedure based on 1,000 resamplings of residuals, where clusters are MAs.

industry sector and occupational composition X_j^1 .

To derive "structural" elasticities from the reduced form estimates of equation (B.35), we use estimates for consumption price elasticity $\frac{1}{1+\rho_C}$ from studies on French households. We compute an average price-elasticity of consumption without housing of $\frac{1}{1+\rho_C} = 0.32$ from Faure et al. (2012) and $\frac{1}{1+\rho_C} = 0.62$ from Abramovici (1994). We report structural elasticities for $\frac{1}{1+\rho_C} = 0.5$ in Table B.1 and carry out a sensibility analysis of parameter κ for values of $\frac{1}{1+\rho_C} \in \{0.3, 0.4, 0.5, 0.6\}$ in Figure B-1. Our calibrated κ is between 0.44 and 0.59, meaning that estimates for public good agglomeration elasticity $1 - \kappa$ lie between 0.41 and 0.56.

B.2.2 Constancy of Expenditure Shares

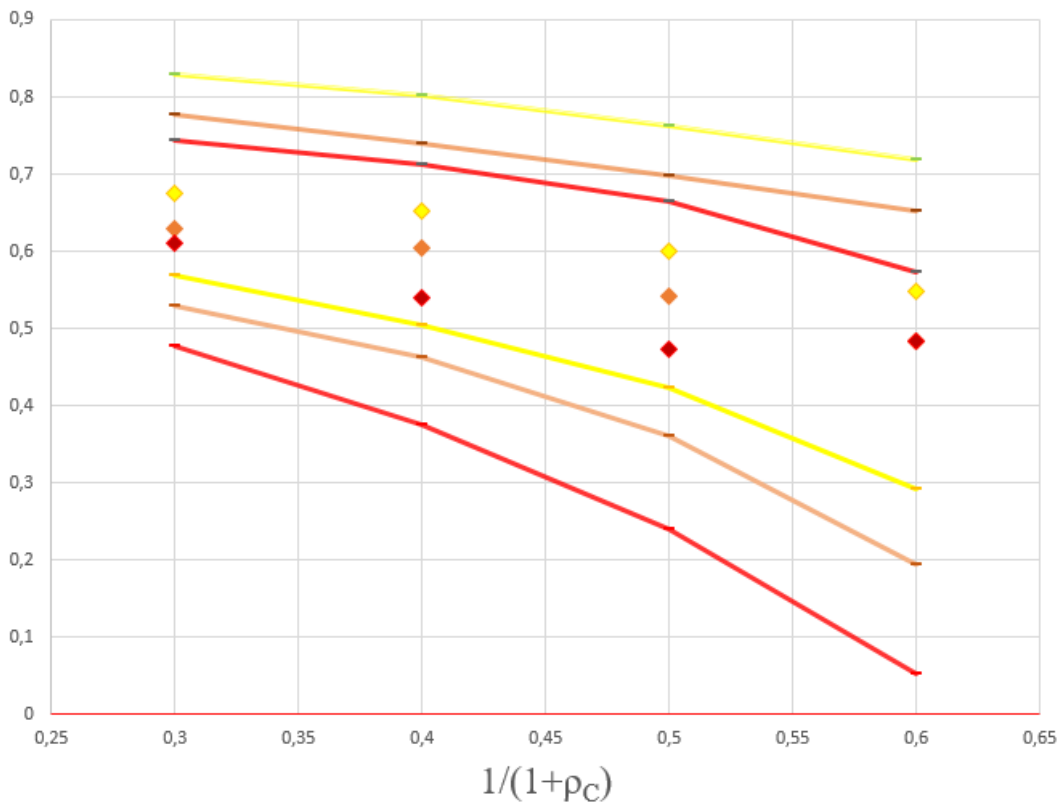
The use of a generalized CES utility in the model for public good demand exposed and appendix B.2.1 relies on the constancy of expenditure shares approximation. Using housing and public good expenditures present in our dataset, we take this hypothesis to an empirical test. Exact rent r_j^h dataset being unavailable outside of the main French metropolitan areas, we use here discounted housing prices per square meter r_j as a measure of rent. Public expenditures are defined as in section 2.3 and scaled by the residents contribution share to municipal budget τ .

$$E_j^h = h_j \cdot r_j = h_j \frac{R}{1+R} p_j^h$$

$$E_j^g = \tau \left(\zeta p_{s,j}^G G_{s,j} + p_f^G G_{f,j} \right)$$

¹We predicted MF outcomes net of individual characteristics. However, industry sector and occupational composition bears a geographic component that is independent of individuals and may still affect local demand for public goods.

Figure B-1: Sensibility Analysis for κ



Note: This graphs shows the sensibility of our estimation of κ to both the hypothesis on ρ_C and the chosen specification in Table B.1 : Yellow stands for (1), Orange for (2) and Red for (3), with ρ_C varying from 0.3 to 0.6.

Table B.3: Linear Regression Share Estimates

	(1)	(2)
	Housing Expenditure p.c.	Public Good Expenditures p.c.
Income p.c.	0.137*** (0.028)	0.035*** (0.009)
Controls: Industry & Occupation	✓	✓
Year FE X	UA	UA
R-squared	0.790	0.610
Observations	7731	7768

Note: UA stands for metropolitan area. Standard errors are clustered at the UA level. * significant at 10%; ** significant at 5%; *** significant at 1%.

Expenditure shares can be considered constant throughout cities for a representative individual if the hypothesis of linearity of income in per capita expenditure across cities, which writes $H_0 : \beta = 1$, cannot be rejected for the following cross-sectional specification

$$\ln E_{jt} = \alpha + \beta \ln y_{jt} + X_{jt} \cdot \gamma + \lambda_{at} + \epsilon_{jt}$$

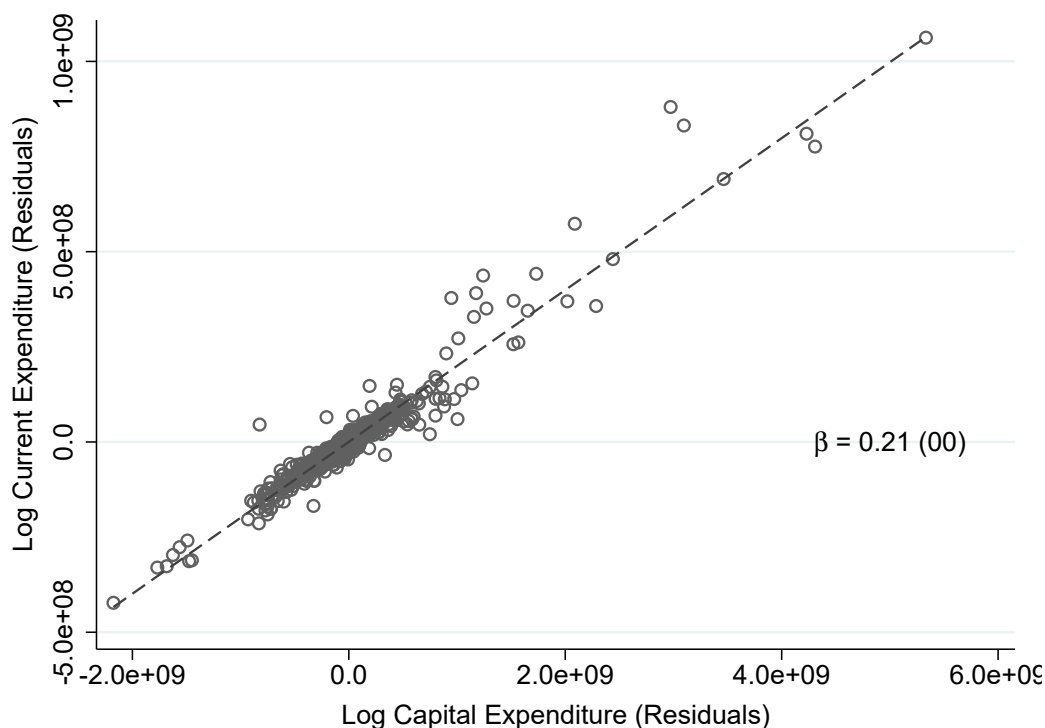
in which we allow for metropolitan area specific time-trends and control for city socio-demographic characteristics X_{jt} . Tables B.2 reports the results of the test, from which it appears that the constant share hypothesis is consistent with our data. Table B.3 reports the results of a linear specification which coefficients are the shares of expenditures in each sector. Estimates of housing expenditure share are smaller than existing estimates (typically around 30%), but recall that we include subsidies to local governments in our definition of total disposable income.

Table B.2: Cross-Sectional Estimates

	(1)	(2)
	log(Housing Expenditure p.c.)	log(Public Good Expenditures p.c.)
log(Income p.c.)	1.036*** (0.264)	0.960*** (0.246)
Controls: Industry & Occupation	✓	✓
Year FE X	UA	UA
p-value $H_0 : (\beta = 1)$	0.8910	0.8712
R-squared	0.789	0.616
Observations	7731	7768

B.2.3 Calibration of Public Good Index

Figure B-2: Calibration of ψ

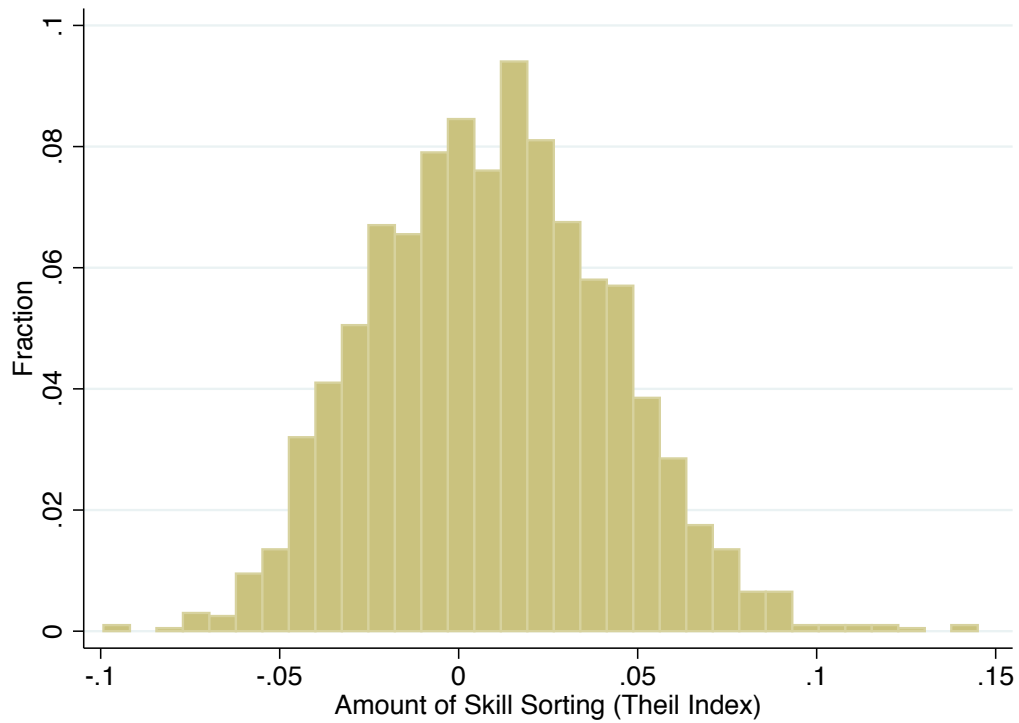


Note: This graph shows the relationship between log current expenditure and log capital expenditure, both residualized with respect to $UA \times \text{year}$ fixed effects. Current expenditure are the sum of yearly staff expenditure, maintenance spending, payments for external services and operating subsidies to third parties. Capital expenditure are the current book value of durable facilities and are the sum of all public assets such as schools, transportation infrastructure, parks improvements, sports facilities, museums, art collections, investment subsidies to local clubs, minus the raw value of the land and financial assets.

	log(Operating Expenditure)		Operating Expenditure
log(Capital Expenditure)	1.024*** (0.009)	Capital Expenditure	0.212*** (0.010)
Controls	✓	Controls	✓
Year FE X	UA	Year FE X	UA
R-squared	0.966	R-squared	0.957
Observations	9710	Observations	9710

B.3 Complementary empirical results

Figure B-3: Skill Sorting



Note: This graph shows the amount of skill sorting across MFs in 2008. The Theil is defined for each MF as $\sum_k \text{share}_k \times \ln(\text{share}_k / \text{share}_k^{\text{ref}})$ where share_k is the 2008 share of the MF population with education level $k \in \{1, 2, 3, 4\}$ and $\text{share}_k^{\text{ref}}$ the corresponding share in national population. Perfect sorting would yield MFs with Theil around $-\ln(\text{share}_k^{\text{ref}}) \in [2.2; 2.8]$ depending on education level k . No sorting yields MFs with Theil around 0. As can be seen, skill sorting is very low in our setting.

Table B.4: Reduced-Form Estimates

	(1)	(2)	(3)
Log Population (β_N)	-0.222*** (0.054)	-0.258*** (0.050)	-0.281*** (0.064)
Log Resources (β_Y)	0.964*** (0.225)	0.980*** (0.229)	1.019*** (0.269)
FE	✓	✓	✓
Controls: Local Prices	✓	✓	✓
Controls: Industry & Occupation		✓	✓
Year FE ×			MA
p-value $H_0 : (\beta_Y = 1)$	0.8732	0.9287	0.9445
R-squared	0.973	0.973	0.978
Observations	8226	8226	7730

Note: Dependent variable is the log of our per capita spending index $\frac{E}{N}$. We flexibly control for the share of the population in various industry sectors and occupations. MA stands for metropolitan area. Standard errors are clustered at the MA level. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table B.5: Long Difference Estimates

	(1)	(2)	(3)
$\Delta \log(\text{Population})$	-0.198*** (0.064)	-0.265*** (0.060)	-0.274*** (0.077)
$\Delta \log(\text{Resources p.c.})$	1.051*** (0.277)	1.086*** (0.281)	1.181*** (0.340)
FE	✓	✓	✓
Controls: Local Prices	✓	✓	✓
Controls: Industry & Occupation		✓	✓
Year FE ×			MA
R-squared	0.973	0.974	0.979
Observations	4092	4092	3844

Note: Dependent variable is the log of our per capita spending index $\frac{E}{N}$. We flexibly control for the share of the population in various industry sectors and occupations. MA stands for metropolitan area. Standard errors are clustered at the MA level. * significant at 10%; ** significant at 5%; *** significant at 1%.

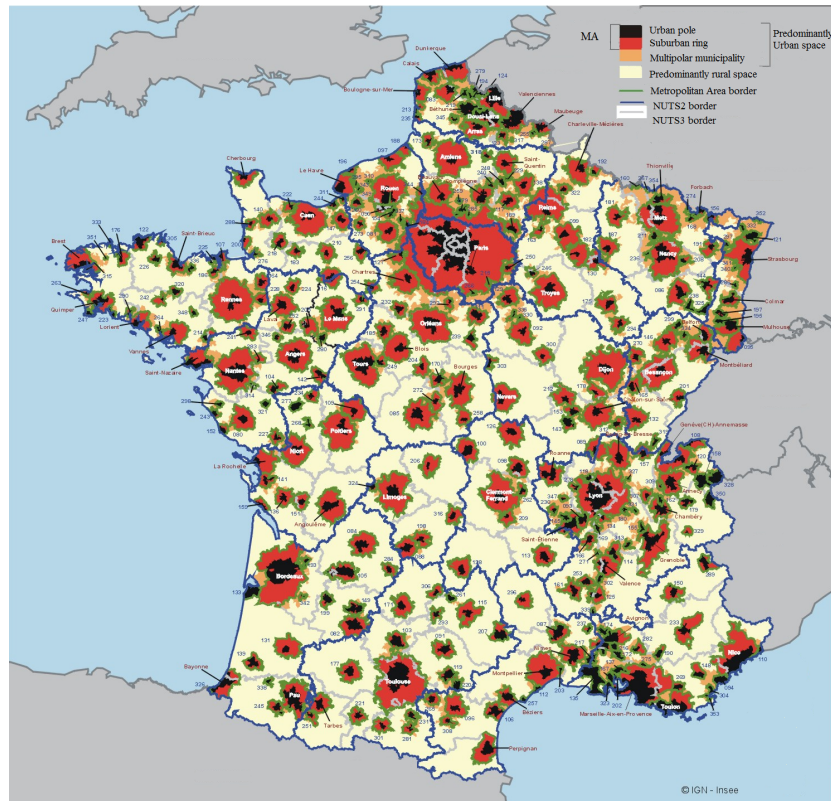
Appendix C

The Carbon 'Carprint' of Urbanisation

C.1 Statistical zonings

C.1.1 French Metropolitan Areas

Figure C-1: French Metropolitan Areas in 2001 and 2006



C.1.2 A monocentric typology of French Municipalities

- A city-center of a MA is either a Municipality concentrating more than 50% of the MA's population or, if no Municipality is this large, the largest-inhabited Municipality in a MA and any other Municipality that has at least 50% of the population figure of this largest Municipality. As such, small MAs generally have only one city-center, whereas larger MAs may have more than one.
- An inner suburb of a MA refers to a Municipality within an urban pole that is not a city-center.
- An outer suburb of a MA refers to a Municipality outside the urban pole of a MA, from which 40% of the population commute to work the urban pole.

As illustrated in Appendix C.1.1, the INSEE defines two other categories of Municipalities which do not belong to Metropolitan Areas, thereby not studied here:

- Multipolar Municipalities refer to Municipalities under the influence of several MAs without being part of a particular MA: 40% of their population work in surrounding MAs, none of which is alone above this threshold.
- The predominantly rural space includes all remaining Municipalities outside the influence of any MA.

C.2 Fractality

C.2.1 What is fractality?

The underlying hypothesis, albeit never explicit, behind the use of density as the most representative dimension of the built environment is that the urban fabric is homogeneous enough to be described by a mean value. As exposed by Batty and Kim (1992), the relevance of this metric is debatable, a typical counterexample being a leapfrogging city in which mean density hides huge disparities between built-up areas and bare ground.

When it comes to urban geography, these irregularities in the built fabric are quite common: some neighborhoods are composed of small detached houses, whereas others are built around large blocks of flats. To describe these differences, we require an index that measures the way in which buildings cover space, and not only density.

Mandelbrot (1967) uses a powerful metaphor to explain why geometric measures such as length, surface or density lose most of their descriptive power for highly irregular objects. He notes that it is difficult to calculate the length of the coast of Britain, as it is crawling with small irregular creeks. The contour of maps of Britain printed at very different scales would

differ strongly, as the tiniest creeks only appear when we zoom in sufficiently on the map. Any simple measure of coastal length only imperfectly describes its real morphology. In the same spirit, the 'density' of a leapfrogging city does not reflect the complexity of its urban form.

Mandelbrot (1982) proposed a new metric to classify these objects: the 'fractal dimension', which is the 'degree of inhomogeneity' of a geometric object. The most common and robust way to calculate this dimension, which is also known as the Minkowski-Bouligand definition,¹ is the following:

- Denote $(a_n)_{n \in \mathbb{N}}$ a series converging to zero, and cover the fractal object with a lattice of squares of size a_n ;
- Count the number $N(a_n)$ of squares in the lattice that intersect the fractal object;
- The fractal dimension is given by the limit $D = \lim_{a_n \rightarrow 0} \frac{\log(N(a_n))}{\log(1/a_n)}$.

This concept is called "dimension" due to its connection to the classic concept of geometrical dimension in the case of a classic object. The surface area of such an object is $Area = A \cdot a^D$ where A is a factor of form,² D the dimension, and a the typical scale of the object. The fractal dimension represents the same D for non-regular objects that do not have typical scale a .

For instance, if we cover a line of length L (an object of dimension 1) with the lattice of squares of size a_n , we find that $N(a_n) = \frac{L}{a_n}$. Thus, $\frac{\log(N(a_n))}{\log(1/a_n)} = \frac{\log(L) + \log(1/a_n)}{\log(1/a_n)} \xrightarrow{n \rightarrow +\infty} 1$.

In the similar case of a square of size L (and area L^2), we find that the number of squares of size a_n needed to cover it is $N(a_n) = \frac{L^2}{a_n^2}$. Therefore, $\frac{\log(N(a_n))}{\log(1/a_n)} = \frac{2 \cdot \log(L) + 2 \cdot \log(1/a_n)}{\log(1/a_n)} \xrightarrow{n \rightarrow +\infty} 2$.

The formula for the Minkowski-Bouligand dimension coincides with the geometric dimension for classical objects.

The fractal dimension can vary continuously from 0 to 2.

- $D < 1$ refers to a collection of unconnected points: mass is concentrated in occasional rare objects (typically scarce farms in rural areas);
- D close to 1 refers to objects organised along a pattern of lines (typically a road-village);
- D between 1 and 1.3 refers to a collection of sparse clusters (typically a leapfrogging residential city);

¹See Schroeder (1991).

²For instance, $A = 1$ for a square and $A = \pi$ for a disk.

- D from 1.3 to 1.6 refers to a continuous fabric of large, geometrically disposed buildings (typically housing complexes such as French 1960's *Grands Ensembles*);
- D from 1.6 to 1.8 refers to attached housing separated by streets of different sizes (for instance, the *Haussmannian* style of central Paris);
- D close to 2 refers to a quasi-homogeneous coverage of the geographic map (buildings separated by very tiny streets and courtyards, such as the inner historical center of central Paris).

C.2.2 The box-counting algorithm

The best numerical calculation of the Minkowski-Bouligand fractal dimension comes from the box-counting algorithm in Liebovitch and Toth (1989). After counting the number N of square boxes of size a_n covering a geometric object for different scales a_n , the number of boxes can be seen as an approximation of the area:

$$N(a_n) \approx A \cdot (a_n)^D.$$

With a log-log specification, we can write:

$$\log(N(a_n)) \approx \log(A) + D \cdot \log(a_n) = \alpha + D \cdot \log(a_n) + \epsilon_n.$$

We can then estimate D by regressing the number of boxes on the size of the box at different scales. We follow Thomas et al. (2010) and use the R-squared from this regression as an indicator of the fractal (or non-fractal) behavior of the geometric object. If the lower limit $R^2 = 0.999$ is not attained, the object may not be fractal or may exhibit multifractal behaviour, so that it has two different morphologies. This is likely to occur for municipalities with very different neighborhoods. In France, contrary to many other countries, municipalities are small enough to have fairly homogeneous morphologies, so that there is a maximum one-slope break. All French municipalities measured turn out to be fractal, with a minority (28% of the total) being multifractal.

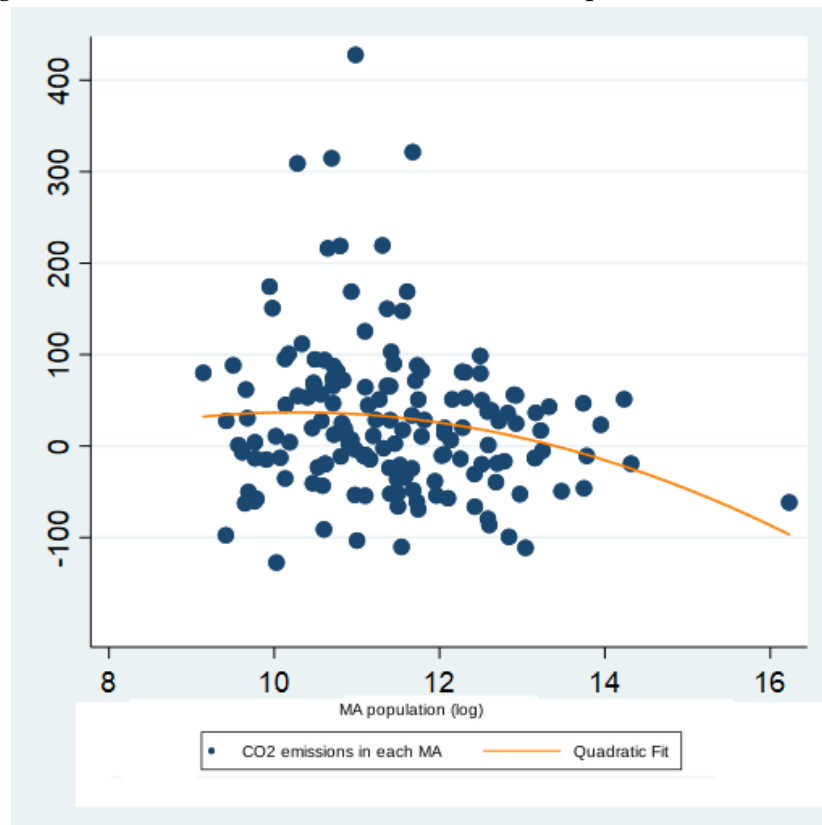
Note that all the results presented above are robust to changes in the limit scale and fractal calculation method.

C.3 Additional descriptive statistics

Table C.1: Descriptive statistics on the household fuel mix by city size

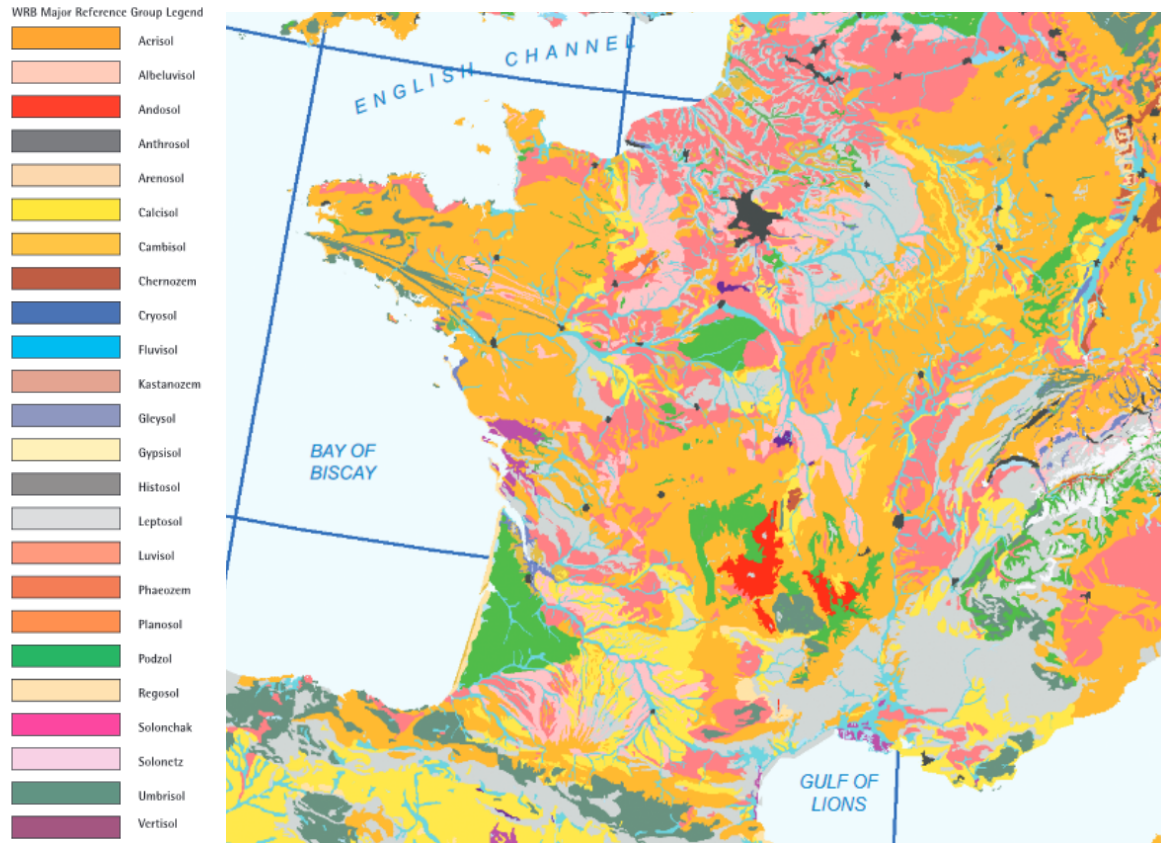
Average share of gasoline	Mean	Std. Dev.	Min	Max
Small MAs (First tercile)	51%	18%	0%	100%
Medium MAs (Second tercile)	52%	11%	31%	76%
Big MAs (Third tercile)	57%	3%	52%	59%

Figure C-2: MA size and estimated fuel consumption from our sample



C.4 European Soil Data Base

Figure C-3: Topsoil mineralogy categories from ESDB



Note: The ESDB database is the result of a collaborative project involving all the European Union Member States and neighbouring countries. The map displays a simplified representation of the spatial variability of the topsoil mineralogy in France (WRB Reference Group). The raw database has been processed to extract the most dominant soil type at the municipality level. We aggregate this 2-digit (25 levels) classification at a 1 digit precision (4 levels) that we use for instrumentation.

C.5 Other specifications to take spatial sorting into account

C.5.1 Uncoupling socioeconomic and spatial effects

To assess the influence of our city and neighborhood metrics, we could first residualise fuel consumption with respect to socioeconomic characteristics of the household. This would allow to take into account the mean effect of socioeconomic characteristics without taking into account the interactions of this variable with geographic characteristics, and thus constitutes one way to neutralise sorting. This would take the following form

$$Fuel_{i(k,t)} = X_{i(t)}\theta + u_t + \widehat{Fuel}_{i(k,t)}, \quad (C.1)$$

where $Fuel_{i(k,t)}$ is the fuel consumption (in gallons) of household i living in Municipality k at time t , and $X_{i(t)}$ a vector of the household characteristics including income per CU (in log), the number of working and non-working adults, the number of children under 16, and the age, age-squared, sex, education and occupation of the household head.

Then, we would regress the residuals of equation C.1 on geographic characteristics of the city. and then city and neighborhood.

$$\begin{aligned} \widehat{Fuel}_{i(k,t)} = & \alpha + \beta Population_{MA(k),t} + \delta Surface_{MA(k),t} \\ & + \gamma Density_{k,t} + Design_{k,t}\zeta + \eta Diversity_{k,t} + u_t + \varepsilon_{i(k,t)}, \end{aligned} \quad (C.2)$$

where $Population_{MA(k),t}$ is the population of the MA of residence and $Surface_{MA(k),t}$ its surface. Coming to our 3Ds, $Density_{k,t}$ is the log of population density in the residence Municipality, $Design_{k,t}$, the vector of log-variables capturing the design of the residential environment, and $Diversity_{k,t}$, the Herfindahl index capturing the diversity of residential amenities.

Table C.2 shows the results of the regression on individual characteristics. Column (1) displays the point estimates from the sample of all urban households, and column (2) those from the sample of car owners only, as a first attempt to test for household selection across the urban space.

Table C.3 presents the effects of urban form and city size variables in such a specification. We observe notably that the effects of density and road access are wiped out, in this case. This implies that some socioeconomic characteristics are strongly correlated with these dimensions of urban form. In particular, at the equilibrium of the construction market, if there are no housing constraints, the most dense areas of the city correspond to the highest land prices and thus to the wealthiest part of the city population.

Table C.2: Residualized household fuel consumption : OLS estimations

Dependent Variable: Fuel consumption (gallons)	All households (1)	Motorized households (2)
HOUSEHOLD CHARACTERISTICS		
Log(Total income/CU)	53.9*** (5.19)	42.3*** (6.07)
No. of working adults	125.7*** (12.47)	112.2*** (14.16)
No. of non-working adults	69.3*** (7.81)	67.2*** (9.24)
No. of young children (< 16 y.o.)	11.1*** (3.34)	4.4 (3.14)
Age (Head of household)	5.9*** (0.75)	6.6*** (0.96)
Age-squared (Head of household)÷100	-7.3*** (0.56)	-8.7*** (0.86)
Female (Head of household)	-59.0*** (10.00)	-51.8*** (10.72)
Education dummies (Head of household)	✓	✓
Occupation dummies (Head of household)	✓	✓
Observations	15,609	12,889
R-squared	0.188	0.119

Notes: (i) OLS estimates drawn from equation (3.3); (ii) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) For the sake of clarity, the constant and coefficients associated with education and occupation dummies are not reported.

Sources: *Budget des Familles* survey (INSEE, 2001 and 2006)

Table C.3: Residualized household fuel consumption and residence-type in French MAs: Adding the three D's

Dependent Variable: Fuel consumption (gallons)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Log(MA population)	-13.6*** (4.33)	-13.6*** (4.37)	-13.6*** (4.36)	-13.7*** (4.36)	-13.6*** (4.36)	-13.6*** (4.36)	-13.6*** (4.36)	-13.5*** (4.34)	-13.6*** (4.37)	
Log(MA surface)	-2.6 (5.72)	-2.7 (5.73)	-2.6 (5.73)	-2.6 (5.72)	-2.6 (5.73)	-2.6 (5.73)	-2.7 (5.73)	-2.7 (5.72)	-2.7 (5.73)	
DENSITY										
Log(Density of pop. in residence)		-32.6*** (4.31)							-7.9+ (5.53)	-7.9+ (5.54)
DESIGN										
Log(Distance from residence to CBD)			53.8*** (8.41)						10.0* (5.53)	10.0* (5.53)
Log(Rail potential in the rest of the MA)				-195.8*** (5.58)					-101.2*** (21.16)	-101.0*** (21.10)
Log(Road potential in the rest of the MA)					-177.1*** (34.31)				39.8 (29.65)	39.7 (29.62)
Log(Density of pub. transit in residence)						-46.2*** (3.31)			-7.8* (4.22)	-7.9* (4.22)
Fractal dimension in residence							-279.2*** (48.12)		-105.6** (49.29)	-105.8** (49.34)
DIVERSITY										
Herfindahl index in residence								140.9*** (23.27)	36.9** (14.64)	37.2** (14.60)
Year dummies	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609	15,609
R-squared	0.021	0.043	0.041	0.034	0.033	0.039	0.042	0.027	0.047	0.035

Notes: (i) OLS estimates; (ii) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, as well as the age, age-squared, sex, education and occupation of the household head; For the sake of clarity, neither these coefficients nor the constant are shown.

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGL, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

Table C.4: Residualized household fuel consumption and urban form: Causal estimations

Dependent Variable: Fuel consumption (gallons)	OLS (1)	2SLS (2)	Heckit (3)	dx/dy Probit (4)
CITY SIZE				
log(MA population)	-13.6*** (4.37)	-13.6*** (4.32)	-4.0 (7.96)	-0.041*** (0.005)
log(MA surface)	-2.7 (5.73)	-2.6 (5.72)	-10.5 (7.37)	0.032*** (0.007)
DENSITY				
Log(residential population density)	-7.9 (5.53)	168.7 (154.61)	-4.0 (5.84)	-0.024*** (0.007)
DESIGN				
Log(distance from residence to CBD)	10.0* (5.53)	284.7 (253.12)	4.6 (9.62)	0.028*** (0.008)
Log(Density of pub. transit in residence)	-7.8* (4.22)	6.0 (24.63)	-2.8 (6.81)	-0.018*** (0.006)
Fractal dimension in residence	-105.6** (49.29)	-392.4+ (252.22)	-77.3 (54.88)	-0.254*** (0.047)
Log(Road potential in the rest of the MA)	39.8 (29.65)	57.7 (87.75)	-10.4 (48.59)	0.245*** (0.033)
Log(Rail potential in the rest of the MA)	-101.2*** (21.16)	-96.1** (42.79)	-62.6 (44.54)	-0.190*** (0.031)
DIVERSITY				
Herfindahl index in residence	36.9** (14.64)	145.4+ (92.35)	37.4** (17.12)	0.031 (0.026)
Education dummies (Head of household)				
Occupation dummies (Head of household)				
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.047	0.111		
Cragg-Donald F-Stat		2.579		ρ : -0.193
C-Stat (p-value)		3.443 (0.179)		σ : 295.1
Hansen J-Stat (p-value)		6.509 (0.482)		λ : -57.02
Shea Partial R-squared (density)		0.00268		

Notes: (i) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) For the sake of clarity, the dummy coefficients and the constant are not reported; (iv) The instruments are population density in 1901 (in log), distance to the largest Municipality of the home MA in 1806 (in log), as well as topsoil mineralogy and available water capacity).

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

C.5.2 Absence of controls for socioeconomic characteristics

Another approach to the sorting issue would be not to control for any socioeconomic characteristics. As expected, such an approach has little impact on the effects of city-level characteristics (if included), since the socioeconomic mix at the city level is not expected to vary too much from one city to another. However, the effect of surface rises by 25% which is consistent with the fact that the poorest, who consume less fuel *ceteris paribus*, are located at the edge of the city in the French sorting pattern.

Within city variables are largely affected : Both the effects of density and distance to CBD increases by 50%. However, the direction of the variation is counterintuitive, due to the interaction with highly correlated MA-level variables. The effect of fractal dimension, and diversity also rise by 25%, while the effect of rail access remains stable. Interestingly, the effect of road potential is reinforced by 50%, which is consistent with central areas –that exhibit the higher road access– being occupied by the wealthiest urbanites.

Table C.5: Household fuel consumption and urban form: Causal estimations without socioeconomic controls with 3D centered at the MA-level

Dependent Variable: Fuel consumption (gallons)	OLS (1)	2SLS (2)	Heckit (3)	dx/dy Probit (4)
CITY SIZE				
log(MA population)	-13.0*** (4.46)	-13.0*** (4.45)	-10.3** (5.02)	-0.038*** (0.005)
log(MA surface)	-5.0 (6.17)	-4.9 (6.15)	-9.5+ (6.16)	0.020*** (0.006)
DENSITY				
Log(residential population density)	-16.8*** (6.07)	-38.5*** (8.72)	-16.0*** (5.58)	-0.018*** (0.006)
DESIGN				
Log(distance from residence to CBD)	26.5*** (7.55)	17.3** (7.69)	28.1*** (8.06)	0.036*** (0.008)
Log(Density of pub. transit in residence)	-13.1*** (4.47)	-8.2+ (5.15)	-13.3** (5.77)	-0.024*** (0.006)
Fractal dimension in residence	-123.9*** (45.75)	-32.1 (54.23)	-128.4*** (40.60)	-0.182*** (0.042)
Log(Road potential in the rest of the MA)	97.0*** (34.69)	119.1*** (37.50)	90.9*** (29.83)	0.217*** (0.031)
Log(Rail potential in the rest of the MA)	-117.7*** (24.72)	-116.0*** (25.91)	-120.6*** (29.85)	-0.191*** (0.028)
DIVERSITY				
Herfindahl index in residence	40.2*** (15.31)	25.8+ (17.15)	41.3** (17.81)	0.011 (0.025)
Education dummies (Head of household)				
Occupation dummies (Head of household)				
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.164		
Cragg-Donald F-Stat		719.1		ρ : 0.368
C-Stat (p-value)		0.510 (0.475)		σ : 307.4
Hansen J-Stat (p-value)		8.477 (0.0756)		λ : 113.2
Shea Partial R-squared (density)		0.187		

Notes: (i) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) For the sake of clarity, the dummy coefficients and the constant are not reported; (iv) The instruments are population density in 1901 (in log), distance to the largest Municipality of the home MA in 1806 (in log), as well as topsoil mineralogy and available water capacity).

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

Table C.6: Household fuel consumption and urban form: Causal estimations without socioeconomic controls with 3D non-centered at the MA-level

Dependent Variable: Fuel consumption (gallons)	OLS (1)	2SLS (2)	Heckit (3)	dx/dy Probit (4)
CITY SIZE				
log(MA population)	13.0** (5.62)	23.2*** (8.08)	15.5** (6.83)	-0.005 (0.007)
log(MA surface)	-27.5*** (6.73)	-32.4*** (7.22)	-32.5*** (6.41)	-0.003 (0.006)
DENSITY				
Log(residential population density)	-19.4*** (5.98)	-36.6*** (9.78)	-19.0*** (4.80)	-0.017*** (0.005)
DESIGN				
Log(distance from residence to CBD)	21.4*** (7.25)	9.3 (8.09)	21.5*** (7.22)	0.030*** (0.007)
Log(Density of pub. transit in residence)	-11.1*** (3.30)	-8.1** (3.57)	-10.7*** (4.02)	-0.016*** (0.004)
Fractal dimension in residence	-108.8*** (38.97)	-47.3 (34.88)	-107.9*** (32.73)	-0.165*** (0.034)
Log(Road potential in the rest of the MA)	33.8*** (6.53)	33.2*** (6.39)	35.0*** (6.39)	0.032*** (0.006)
Log(Rail potential in the rest of the MA)	-60.2*** (8.70)	-57.7*** (7.77)	-58.5*** (10.81)	-0.078*** (0.009)
DIVERSITY				
Herfindahl index in residence	33.2** (14.61)	19.9 (20.64)	33.0** (16.23)	0.019 (0.024)
Education dummies (Head of household)				
Occupation dummies (Head of household)				
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.164		
Cragg-Donald F-Stat		635.6		ρ : 0.304
C-Stat (p-value)		0.295 (0.587)		σ : 305
Hansen J-Stat (p-value)		14.02 (0.00724)		λ : 92.59
Shea Partial R-squared (density)		0.169		

Notes: (i) Robust standard errors in parentheses (MA level); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, + $p < 0.15$; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) For the sake of clarity, the dummy coefficients and the constant are not reported; (iv) The instruments are population density in 1901 (in log), distance to the largest Municipality of the home MA in 1806 (in log), as well as topsoil mineralogy and available water capacity).

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

C.6 Other specifications with city-level and neighborhood level variables

C.6.1 with MA-centered 3Ds

Table C.7: Household fuel consumption and urban form: OLS estimations

Dependent Variable: Fuel consumption (gallons)	All households (1)	Motorized households (2)
CITY SIZE		
log(MA population)	-14.3*** (4.30)	-7.6* (4.51)
log(MA surface)	-4.8 (5.84)	-10.3+ (6.38)
DENSITY		
Log(Density of pop. in residence)	-10.3* (5.35)	-8.9+ (5.96)
DESIGN		
Log(Distance from residence to CBD)	15.7*** (5.84)	13.3* (6.94)
Log(Density of pub. transit in residence)	-9.7** (4.15)	-6.6 (4.72)
Fractal dimension in residence	-102.9** (46.43)	-98.4** (47.72)
Log(Road potential in the rest of the MA)	45.6+ (30.49)	20.0 (30.65)
Log(Rail potential in the rest of the MA)	-99.5*** (21.74)	-78.1*** (23.49)
DIVERSITY		
Herfindahl index in residence	36.4** (14.63)	38.9** (15.55)
Household characteristics		
Education dummies (Head of household)	✓	✓
Occupation dummies (Head of household)	✓	✓
Year dummies	✓	✓
Observations	15,609	12,889
R-squared	0.234	0.157

Notes: (i) OLS estimates drawn from equation (3.3); (ii) Robust standard errors in brackets (MA level); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; (iii) For the sake of clarity, the constant and coefficients associated with education, occupation and year dummies are not reported; (iv) The household characteristics include income per CU (in log), the number of working and non-working adults, the number of children under 16, and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown.

Table C.8: Household fuel consumption and urban form: Causal estimations

Dependent Variable: Fuel consumption (gallons)	OLS (1)	2SLS (2)	Heckit (3)	dx/dy Probit (4)
CITY SIZE				
log(MA population)	-14.3*** (4.30)	-14.3*** (4.28)	-15.3*** (4.51)	-0.037*** (0.004)
log(MA surface)	-4.8 (5.84)	-4.8 (5.82)	-7.2 (5.91)	0.019*** (0.005)
DENSITY				
Log(residential population density)	-10.3* (5.35)	-17.3* (10.09)	-9.2* (5.38)	-0.010* (0.005)
DESIGN				
Log(distance from residence to CBD)	15.7*** (5.84)	12.8* (6.89)	19.4*** (7.43)	0.019*** (0.006)
Log(Density of pub. transit in residence)	-9.7** (4.15)	-8.1* (4.62)	-11.8** (5.36)	-0.017*** (0.005)
Fractal dimension in residence	-102.9** (46.43)	-73.5 (60.30)	-122.7*** (38.37)	-0.134*** (0.036)
Log(Road potential in the rest of the MA)	45.6+ (30.49)	52.8* (29.40)	47.8* (26.62)	0.132*** (0.026)
Log(Rail potential in the rest of the MA)	-99.5*** (21.74)	-99.0*** (22.27)	-117.1*** (26.69)	-0.155*** (0.024)
DIVERSITY				
Herfindahl index in residence	36.4** (14.63)	31.8** (15.18)	35.6** (17.24)	0.006 (0.022)
Household characteristics				
Education dummies (Head of household)	✓	✓	✓	✓
Occupation dummies (Head of household)	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.164		
Cragg-Donald F-Stat		435.9		ρ : 0.462
C-Stat (p-value)		2.318 (0.128)		σ : 297.7
Hansen J-Stat (p-value)		12.89 (0.116)		λ : 137.5
Shea Partial R-squared (density)		0.172		

Notes: (i) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) For the sake of clarity, the dummy coefficients and the constant are not reported; (iv) The household characteristics include income per CU (in log), the number of working and non-working adults, the number of children under 16, and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown; (v) The instruments are population density in 1901 (in log), distance to the largest Municipality of the home MA in 1806 (in log), as well as topsoil mineralogy and available water capacity).

C.6.2 with non MA-centered 3Ds

Table C.9: Household fuel consumption and urban form: OLS estimations

Dependent Variable: Fuel consumption (gallons)	All households (1)	Motorized households (2)
<hr/>		
CITY SIZE		
log(MA population)	12.3** (5.20)	15.4** (6.11)
log(MA surface)	-22.1*** (6.51)	-26.5*** (7.44)
<hr/>		
DENSITY		
Log(Density of pop. in residence)	-14.3*** (4.86)	-12.8** (5.08)
<hr/>		
DESIGN		
Log(Distance from residence to CBD)	14.3** (5.73)	12.1* (6.63)
Log(Density of pub. transit in residence)	-8.0*** (3.05)	-6.3* (3.32)
Fractal dimension in residence	-79.4** (38.08)	-79.7** (37.10)
Log(Road potential in the rest of the MA)	21.7*** (6.22)	21.6*** (6.49)
Log(Rail potential in the rest of the MA)	-60.1*** (8.09)	-52.2*** (8.90)
<hr/>		
DIVERSITY		
Herfindahl index in residence	26.2* (13.44)	28.0** (14.14)
<hr/>		
Household characteristics		
Education dummies (Head of household)	✓	✓
Occupation dummies (Head of household)	✓	✓
Year dummies	✓	✓
<hr/>		
Observations	15,609	12,889
R-squared	0.235	0.158

Notes: (i) OLS estimates drawn from equation (3.3); (ii) Robust standard errors in brackets (MA level); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; (iii) For the sake of clarity, the constant and coefficients associated with education, occupation and year dummies are not reported; (iv) The household characteristics include income per CU (in log), the number of working and non-working adults, the number of children under 16, and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown.

Table C.10: Household fuel consumption and urban form variables centered at the MA-level:
Causal estimations

Dependent Variable: Fuel consumption (gallons)	OLS (1)	2SLS (2)	Heckit (3)	dx/dy Probit (4)
CITY SIZE				
log(MA population)	12.3** (5.20)	14.3** (7.24)	13.6** (6.62)	-0.006 (0.006)
log(MA surface)	-22.1*** (6.51)	-23.0*** (6.88)	-26.2*** (6.23)	0.004 (0.005)
DENSITY				
Log(residential population density)	-14.3*** (4.86)	-17.7** (7.25)	-13.8*** (4.64)	-0.013*** (0.004)
DESIGN				
Log(distance from residence to CBD)	14.3** (5.73)	11.9* (7.06)	18.0*** (6.73)	0.018*** (0.006)
Log(Density of pub. transit in residence)	-8.0*** (3.05)	-7.5** (2.94)	-9.6** (3.74)	-0.010*** (0.003)
Fractal dimension in residence	-79.4** (38.08)	-67.3* (35.23)	-95.9*** (31.07)	-0.103*** (0.028)
Log(Road potential in the rest of the MA)	21.7*** (6.22)	21.6*** (6.17)	25.3*** (5.94)	0.017*** (0.005)
Log(Rail potential in the rest of the MA)	-60.1*** (8.09)	-59.6*** (7.78)	-69.8*** (9.61)	-0.070*** (0.008)
DIVERSITY				
Herfindahl index in residence	26.2* (13.44)	23.6* (14.22)	25.5+ (15.80)	-0.000 (0.020)
Household characteristics				
Education dummies (Head of household)	✓	✓	✓	✓
Occupation dummies (Head of household)	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.235	0.166		
Cragg-Donald F-Stat		634.2		ρ : 0.461
C-Stat (p-value)		0.052 (0.820)		σ : 297.3
Hansen J-Stat (p-value)		6.948 (0.139)		λ : 137.1
Shea Partial R-squared (density)		0.169		

Notes: (i) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (ii) The sigma term is the root of the variance of the errors, and rho the correlation between the errors in the model and selection equations; (iii) For the sake of clarity, the dummy coefficients and the constant are not reported; (iv) The household characteristics include income per CU (in log), the number of working and non-working adults, the number of children under 16, and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown; (v) The instruments are population density in 1901 (in log), distance to the largest Municipality of the home MA in 1806 (in log), as well as topsoil mineralogy and available water capacity).

C.7 Alternate projections

C.7.1 Projection with MA-centered 3D variables

Figure C-4: MA size and the CO₂ 'carprint' of the sample mean household (kg/year)

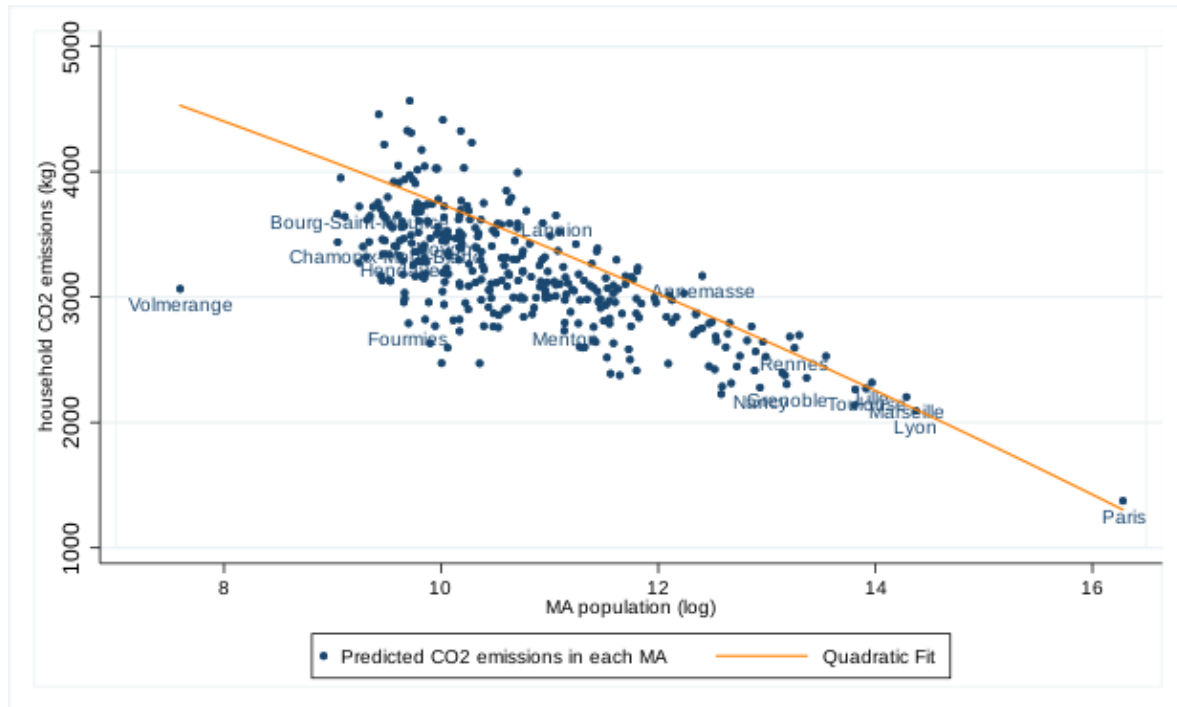


Figure C-4 reports the results of a projection similar those of chapter 3, using two city-level variables : MA population and MA surface, supplemented by centered variables for the 3Ds. Such an approach uses the 3D variables only to describe intra-city variations in morphology, but relies on city-size variables to describe inter-city variations. This strong hypothesis that city size is a good descriptor of inter-cities fuel consumption variations directly translates into a linear, decreasing relationship between projected fuel consumption and city size.

Actually, such an approach theoretically eliminates all potential sources of non-linearities, and therefore gives birth to this model-based linear relation. However, one can raise doubts that this adequately represent the effective fuel consumption - city size relationship. Figure C-2 reports a tentative estimation of this relation from our sample, which suggests, even if it is obviously blurred by very small sample size in small MAs, that the empirical relationship is bell-shaped, as found by the projections carried out in Chapter 3.

C.7.2 Projection with city-level and neighborhood level variables

Figure C-5 reports the results of a projection similar those of chapter 3, using two city-level variables : MA population and MA surface, supplemented by non-centered variables for

the 3Ds. One can observe that the bell shaped curve is similar to the one built in chapter 3 without the two city-level variables : MA population and MA surface. This suggests that the two approaches are actually very similar. A principle of parsimony thus dictates to choose the simplest specification, namely the 3D one adopted in chapter 3.

Figure C-5: MA size and the CO₂ 'carprint' of the sample mean household (kg/year)

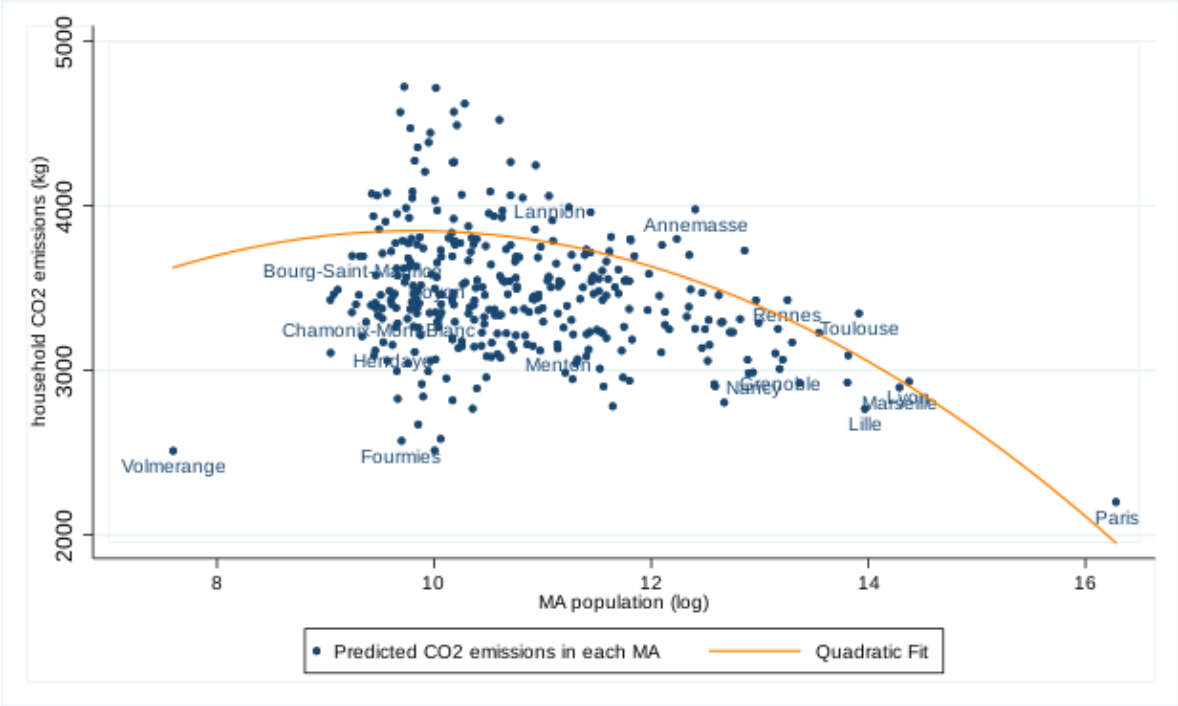


Table C.11: MA size and the CO₂ 'carprint' of the sample mean household (Paris and Volmerange excluded)

Dependent Variable: Car CO ₂ emissions	OLS coefficients (Std. Dev.)	
Log(MA-size)	815.1**	(217.7)
Log(MA-size) ²	-40***	(9.6)
Constant	-625.5	(1230.8)
Observations	349	
R-squared	0.121	

Notes: Standard errors in parentheses: ***p<0.01.

C.8 Additional regression results

Table C.12: Household fuel consumption and urban form: First-stage regressions

Endogenous variables	(1) Density
EXCLUDED INSTRUMENTS	
Log(Density of pop. in residence 1901)	0.3*** (0.05)
Topsoil mineralogy 1	0.2* (0.09)
Topsoil mineralogy 2	0.2* (0.10)
Topsoil mineralogy 3	-0.1 (0.16)
Hydrogeology 1	0.0 (0.12)
Hydrogeology 2	-0.1 (0.08)
Hydrogeology 3	-0.2** (0.12)
Hydrogeology 4	-0.1 (0.11)
Hydrogeology 5	-0.2* (0.09)
DESIGN	
Log(Distance from residence to CBD)	-0.1** (0.07)
Log(Density of pub. transit in residence)	0.2*** (0.02)
Fractal dimension in residence	2.6*** (0.23)
Log(Road potential in the rest of the MA)	0.2*** (0.04)
Log(Rail potential in the rest of the MA)	0.1*** (0.05)
DIVERSITY	
Herfindahl index in residence	-1.4*** (0.20)
Household characteristics	✓
Year dummies	✓
Observations	15,609
Partial R-squared	0.201
F-Stat for excluded instruments	435.9

Notes: (i) First-stage regression from equation (3.7); (ii) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (iii) The household characteristics include income per CU (in log), the number of working and non-working adults, the number of children under 16 and the age, age-squared, sex, education and occupation of the household head; For the sake of clarity, neither the coefficients, nor the constant are shown.

C.9 Complementary results on the bell-shaped curve

C.9.1 The mean household 'carprint' when income varies across cities

Table C.14: Greenest MAs: CO₂ 'carprint' of the mean household with corrected income (kg/year)

City	MA pop.	OLS	Rank	2SLS	Rank	Heckit	Rank
Paris	1.180e+07	2113	3	2145	1	2044	3
Chauny	22117	2067	1	2151	2	2000	1
Volmerange-les-Mines	1990	2106	2	2292	3	2001	2
Villerupt	19019	2254	4	2306	4	2160	4
Bolbec	15750	2317	7	2339	5	2222	6
Fourmies	16324	2289	5	2352	6	2202	5
Tergnier	23383	2312	6	2383	7	2247	7
Eu	32631	2320	8	2395	8	2270	8
Saint-Louis	89549	2344	9	2419	9	2295	10
Sedan	31395	2385	12	2433	10	2311	12
Nogent-le-Rotrou	20852	2368	11	2434	11	2304	11
L'Aigle	19894	2387	13	2449	12	2334	14
Provins	22320	2364	10	2458	13	2280	9
Charleville-Mézières	104934	2436	15	2485	14	2374	16
Lille	1.165e+06	2446	17	2508	15	2354	15
Noyon	22553	2399	14	2509	16	2332	13
Montereau-Fault-Yonne	26109	2531	25	2526	17	2451	24
Saint-Quentin	101438	2464	18	2537	18	2417	20
Abbeville	37459	2471	20	2547	19	2425	22
Maubeuge	114125	2520	24	2558	20	2436	23
Menton	68826	2719	59	2572	21	2654	61
Caudry	14322	2495	21	2584	22	2413	19
Vitry-le-François	34206	2440	16	2584	23	2375	17
Longwy	40650	2599	29	2586	24	2496	28
Le Havre	290826	2611	33	2595	25	2553	34
Saint-Pol-sur-Ternoise	10714	2469	19	2602	26	2378	18

Table C.13: Household fuel consumption and urban form: 2SLS with different sets of geological instruments for both Density and Distance

Instruments	(1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
	2SLS	Mineralogy (top)	2SLS	Mineralogy (top)	2SLS	Mineralogy (top)	2SLS	Mineralogy (top)	2SLS	Water (top)	2SLS	Water (top)	2SLS	Water (top)	2SLS	Water (top)
Variables	Water (top)	Density 1901	Erodibility	Density 1901	Organic content	Density 1901	Depth to rock	Density 1901	Erodibility	Density 1901	Organic content	Density 1901	Depth to rock	Density 1901	Distance 1806	All
DENSITY	Distance 1806		Distance 1806		Distance 1806		Distance 1806		Distance 1806		Distance 1806		Distance 1806			
Log(Density of pop. in residence)	-11.1*	(6.11)	-11.6*	(6.58)	-11.9*	(6.58)	-14.0**	(6.52)	-13.8**	(6.27)	-12.3*	(6.37)	-15.0**	(6.08)	-13.9**	(6.57)
DESIGN																
Log(Dist. from residence to CBD)	25.6***	(5.37)	23.8***	(5.52)	24.9***	(5.58)	23.4***	(5.38)	23.0***	(5.26)	24.8***	(5.45)	23.1***	(5.17)	23.7***	(4.94)
Log(Dens. of pub. transit in resid.)	-8.1**	(3.20)	-8.2**	(3.22)	-7.9**	(3.18)	-7.5**	(3.23)	-7.6**	(3.23)	-7.8**	(3.25)	-7.2**	(3.26)	-7.5**	(3.29)
Fractal dimension in residence	-53.1	(45.47)	-56.7	(45.14)	-51.3	(47.73)	-46.0	(46.81)	-48.6	(47.60)	-49.7	(49.07)	-42.0	(47.14)	-45.6	(49.42)
Log(Road pot. in the rest of the MA)	11.1+	(7.18)	12.2+	(7.45)	11.5+	(7.04)	12.5*	(7.34)	12.8*	(7.21)	11.7*	(6.94)	12.8*	(7.31)	12.4*	(7.23)
Log(Road pot. in the rest of the MA)	-59.8***	(9.08)	-59.6***	(9.21)	-59.5***	(9.29)	-58.8***	(9.20)	-58.9***	(9.16)	-59.4***	(9.30)	-58.5***	(9.05)	-58.9***	(9.16)
DIVERSITY																
Herfindahl index in residence	29.8*	(15.34)	28.9*	(15.58)	28.7*	(15.23)	25.7+	(15.76)	25.9*	(14.98)	28.1*	(14.70)	24.2+	(15.17)	25.8*	(14.84)
Household characteristics	✓		✓		✓		✓		✓		✓		✓		✓	
Year dummies	✓		✓		✓		✓		✓		✓		✓		✓	
Observations	14,801		14,801		14,801		14,801		14,801		14,801		14,801		14,801	
R-squared	0.170		0.170		0.170		0.170		0.170		0.170		0.170		0.170	
C-Stat (p-value)	7.015 (0.030)		6.142 (0.046)		9.515 (0.009)		8.024 (0.018)		6.796 (0.033)		8.856 (0.012)		8.288 (0.016)		10.37 (0.006)	
Hansen J-Stat (p-value)	3.075 (0.688)		9.898 (0.194)		4.346 (0.630)		2.866 (0.825)		6.351 (0.385)		1.879 (0.866)		3.151 (0.677)		36.17 (0.240)	
Cragg-Donald F-Stat	760.4		620		691.7		704.3		710.4		801.9		784.9		219.1	
Shea Partial R ² (density)	0.275		0.273		0.276		0.278		0.276		0.271		0.329			
Shea Partial R ² (distance)	0.495		0.501		0.499		0.516		0.509		0.499		0.511			

Notes: (i) Robust standard errors in parentheses (MA level); ***p<0.01, **p<0.05, *p<0.10, +p<0.15; (ii) The household characteristics include income per CU (in log), the number of working and non-working adults, the number of children under 16, and the age, age-squared, sex, education and occupation of the household-head; For the sake of clarity, neither these coefficients nor the constant are shown;
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO® (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Historique des populations communales* (INSEE, 2020), European Soil Database (ESDB) v2.0 (European Commission's JRC, 2001) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

Table C.15: Dirtiest MAs: CO₂ 'carprint' of the mean household with corrected income (kg/year)

City	MA pop.	OLS	Rank	2SLS	Rank	Heckit	Rank
Bourg-Saint-Maurice	10357	3607	349	3735	352	3569	349
Chamonix-Mont-Blanc	13127	3457	322	3718	351	3390	321
Saint-Gaudens	27175	3549	341	3704	350	3514	343
Oloron-Sainte-Marie	22382	3561	343	3692	349	3523	345
Belley	16547	3527	338	3679	348	3487	339
Niort	134927	3534	339	3676	347	3498	341
Sarlat-la-Canéda	18022	3639	352	3674	346	3591	351
Les Herbiers	14833	3542	340	3673	345	3464	334
Cahors	40175	3581	348	3665	344	3562	348
Lannion	63425	3628	351	3658	343	3606	352
Ancenis	19308	3579	346	3656	342	3507	342
Auch	36934	3551	342	3648	341	3520	344
Ussel	14074	3491	330	3644	340	3441	331
Clisson	16496	3563	344	3633	339	3497	340
Fontenay-le-Comte	26391	3445	319	3619	338	3381	315
Annemasse	244178	3608	350	3603	337	3571	350
Louhans	15598	3468	329	3595	336	3387	318
Aubenas	44546	3566	345	3593	335	3534	347
Loudéac	14217	3463	328	3590	334	3397	323
Privas	21267	3581	347	3585	333	3529	346
Mâcon	93073	3508	333	3585	332	3472	335
La Roche-sur-Yon	107584	3521	337	3583	331	3474	336
Saintes	55834	3491	331	3583	330	3440	330
Issoire	29209	3435	315	3580	329	3386	317
Sallanches	43413	3462	326	3574	328	3388	319
Fos-sur-Mer	15734	3406	305	3570	327	3326	295

C.9.2 Robustness checks on the bell-shaped curve

Figure C-6: MA size and the CO₂ 'carprint' of the sample mean household (kg/year, Paris and Volmerange excluded)

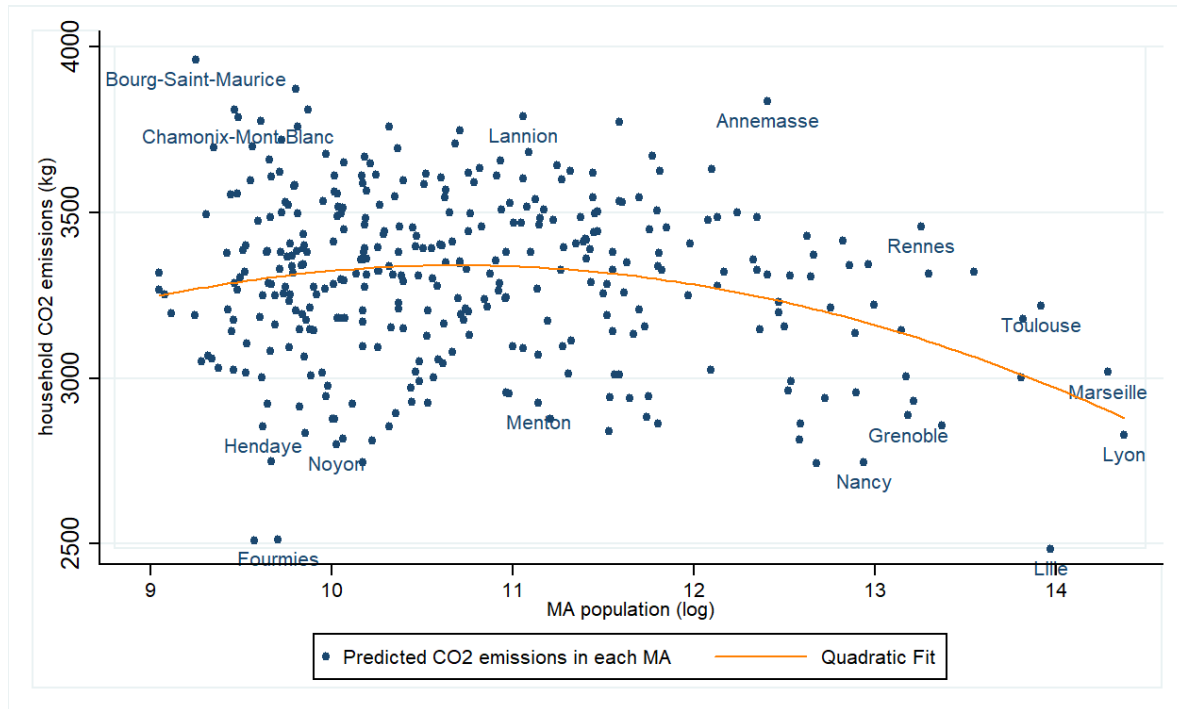


Table C.16: MA size and the CO₂ 'carprint' of the sample mean household (Paris and Volmerange excluded)

Dependent Variable: Car CO ₂ emissions	OLS coefficients (Std. Dev.)	
Log(MA-size)	870.7***	(193.1)
Log(MA-size) ²	-41.6***	(8.6)
Constant	-1127.6	(1079.3)
Observations	350	
R-squared	0.140	

Notes: Standard errors in parentheses: ***p<0.01.