The Carbon 'Carprint' of Suburbanization: New Evidence from French Cities

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Abstract

This paper investigates the impact of urban form on household fuel consumption and car emissions in France. We in particular analyze three features of cities commonly referred to as the "3 D's" (Cervero & Kockelman 1997): Density, Design and Diversity. Individual data allow us to identify the effects of urban form and the spatial sorting of households on emissions. We also use instrumental variables to control for other endogeneity issues. Our results suggest that, by choosing to live at the fringe of a metropolitan area instead of the city center, a representative household would consume approximately six extra tanks of fuel per year. More generally, doubling residential Density would result in an annual saving of approximately two tanks per household. However, larger gains would result from better urban Design (job-housing centralization, improved rail/bus routes to central business districts, reduced pressure for road construction and a less fragmented built environment in urban areas) while improved Diversity (the concentration of various local amenities such as shops and public facilities) can also help lower fuel consumption. Another important finding is that the relationship between the metropolitan population and car emissions in France is bell-shaped, contrary to that in the US, suggesting that small cities do compensate for their lack of Density/Diversity by environmentally-friendly Design.

JEL codes: Q41, R11, R20, R41.
Keywords: Sprawl, car emissions, CO_2 footprint, driving, public transport, smart cities.

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"We should build cities in the countryside, because the air is cleaner there".
Quotation credited to Alphonse Allais.

Introduction

As concerns about global warming rise, the reduction of greenhouse-gas (GHG) emissions has moved gradually to the central agenda of policymakers. To curb emissions, policy makers have so far favored tools such as carbon taxes over spatial policies, which have largely remained in the shadows. However, if household emissions are partly determined by geography, and if spatial mobility is hampered by housing constraints or historical legacy, local spatial policies may improve both efficiency and equity compared to global emission-reduction schemes (Glaeser & Kahn 2010). The recent *Yellow Vests* movement in France poignantly underlined that fuel expenditure largely depends on urban geography and local living conditions.[1] This social unrest shed a bright light on the issues raised by an uniform carbon tax levied on fuel when many households are trapped in car-dependent areas by urban segregation.

Urban planning may be a cornerstone case for local carbon policies. GHG emissions in developed countries are currently increasingly driven by private energy consumption, and especially car emissions that have proved difficult to tax. Urban planning offers an alternative way of reducing these emissions. Moreover, a more sustainable urban form can help to reduce car dependence, and therefore the political and social opposition to potential carbon taxes. This paper analyses the interplay between car emissions and urban form in France, with a particular focus on the forces counteracting sprawl resulting from job-housing centralization, public-transit systems and building morphology.

Urban-economic theory has long underscored the fundamental trade-off between real-estate prices and transport costs (Fujita 1989). As populations grow, income reaches a certain level and travel costs fall below a certain threshold, individuals tend to live farther away from city-centers either to save on housing costs or to live in larger houses. As new land developments are more likely found in these low-density areas, the urban surface increases at a faster rate than the population, fostering sprawl.

Since the mid-1950s, many factors have produced lower travel costs in industrialized countries: decades of low energy prices, the enhanced mobility provided by the automobile revolution, massive investments in road networks and so on. As the post-war baby-booms and income-booms sustained growth, low-density residential suburbanization became the dominant mode of urban expansion in many countries, giving birth to automobile-dependent urban

[1] The two last attempts by the French government to levy carbon taxes both generated violent social turmoil. In October 2013, the 'Red Hats' (*Bonnets Rouges*) movement of French farmers in Brittany spurred French authorities to shelve a project for highway tolls on heavy vehicles (the *écotaxe*). In 2018, the French government's plan to increase gasoline taxes to account for the true social cost of internal combustion transport led to massive social unrest, especially in suburban and rural areas: the 'Yellow Vests' (*Gilets Jaunes*) movement, which seems to have sounded the death knell for transport-related carbon taxes in France.

forms at the urban fringe.[2] As underlined by Brueckner (2000) and Brueckner & Helsley (2011), the urban growth resulting from these fundamental forces cannot be criticized as socially undesirable unless market failures distort the outcomes. However, urban sprawl creates harmful impacts in a variety of socioeconomic and environmental spheres: the substantial consumption of non-renewable resources, loss of soil bio-diversity and reductions in carbon sinks, and transport congestion and air pollution. More importantly for the purpose of this paper, dispersed automobile-dependent development has also increased urban segregation and the number of vehicle-miles traveled by suburbanites, contributing to fuel global warming through higher automobile externalities (Parry, Walls & Harrington 2007).

In the context of higher energy prices combating climate change, car-dependant urban forms have become of particular concern for two reasons. First, the transport sector, and especially the road sector, is a significant and growing contributor to GHG externalities in most countries, accounting for up to 24% of CO_2 emissions worldwide in 2015,[3] and over half of their 1990-2015 growth (International Energy Agency 2017).[4] As the urban form affects driving patterns, the transport-related energy consumption of cities is of growing concern for urban research. Second, pricing environmental externalities would impose a disproportionate tax burden on suburban neighborhoods, which rank amongst the most-deprived in France, due to urban segregation.[5]

Newman & Kenworthy (1989) were the first to draw worldwide attention to the urban form - fuel consumption relationship. Comparing 32 cities across the world, they showed that per-capita gasoline consumption was far higher in US cities than elsewhere, which they attributed to one particular feature of US cities relative to others: lower density. However, it is difficult to infer strong policy recommendations from this seminal analysis, as there are considerable differences across countries that may be correlated with density, such as income, land regulation and public-transport networks. Even within countries, the impact of density on travel demand can be blurred by social composition effects. For instance, US inner cities have a disproportionate share of low-income, elderly and young residents, who are less able to afford to own and run a car. By contrast, US suburbs have a disproportionate share of families or income groups with high levels of car ownership and travel requirements for work, education and extra-curricular activities. If fuel consumption reflects households' intrinsic preferences for housing or travel, any attempt to tackle sprawl may misfire, with relatively few benefits from more-compact cities, as individuals may not behave differently in denser areas.

[2]Empirical evidence of this decentralization is provided in Baum-Snow (2020) and Baum-Snow & Turner (2017) for the US, Baum-Snow et al. (2017) for China, and Mayer & Trevien (2017) and Garcia-López, Hémet & Viladecans-Marsal (2017) for France.

[3]According to International Energy Agency (2017), the road sector alone accounted for 88% of European transport emissions in 2015.

[4]In France, CO_2 emissions fell by 16.6% over 1990-2015, but the share of transport in these emissions rose by 11.4% (Commissariat Général au Développement Durable 2017). Since 2016, the transport sector has been responsible for over 30% of French CO_2 emissions. The road sector accounts for the lion's share (around 95%) of transport-related emissions, and a very large share (over 55%) of road emissions is generated by cars in France.

[5]There is a strong core-periphery pattern of income segregation in France, where affluent households tend to live close to city-centres, and lower-income households in more remote neighborhoods (Brueckner, Thisse & Zenou 2002).

Over the past thirty years, a large body of empirical research has evaluated the causal impact of urban form on travel demand in the US.[6] However, we continue to find conflicting policy recommendations, as sprawl is responsible for travel expansion in certain places, but not in others. For instance, Glaeser & Kahn (2010) find that there are substantial variations in CO_2 intensity across major US cities, and that most of this variation comes from car emissions. The authors call for policy action in the form of a lump-sum tax levied on the rateable value of properties sold in sprawling areas.[7] Conversely, Brownstone & Golob (2009) argue that, in California, the impact of density is not large enough to justify a compactness policy, as even a slight fall in fuel consumption would require unrealistic extensions of the housing stock or excessive cramming of individuals. More recently, Duranton & Turner (2018) asserted that compaction policies would not be as effective as gasoline taxes or congestion charges in reducing driving in US cities.

While the environmental costs of urban sprawl have been extensively investigated in North America, this is not the case in Europe.[8] However, since the mid-1950s European cities expanded their surface area by 80%, whereas population grew by only 30%. In France, over the last decade, the surface area of urban space has increased by an unprecedented figure of 20 percentage points (INSEE 2013). Metropolitan areas now cover 50% of the surface of mainland France, as against only 30% a decade ago. In this context, one first contribution of our paper is to extend the body of research to Europe, where the role of sprawl on fuel consumption has been only little investigated and its associate car-dependence may well dampen the acceptability of a carbon fuel tax.

Within Europe, France is of interest for two reasons. First, French cities have two particular characteristics that most of their American counterparts do not have: (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 morphology, due to large spatial differences in historical heritage and urban planning. French travel behaviors and modal choices thus differ sharply from those in the US. Second, as noted above, there is particularly strong social resistance to the implementation of carbon taxes in France. Nevertheless, the French National Low-Carbon Strategy (2020) committed to 45% lower transport emissions 1990-2030, and carbon neutrality by 2050 (2019 Climate-Energy Law and 2019 European Council). Even so, the external costs associated with burning fuel largely exceed the excise taxes levied on it in France,[9] and road transport remains excluded from the EU Emissions Trading System, the cornerstone of the European policy to reduce GHG emissions. In this context, urban spatial structure remains a key tenet for policy makers, as it provides them with greater leeway to curb carbon emissions

[6] Key contributions here include Bento et al. (2005), Brownstone & Golob (2009), Glaeser & Kahn (2010), and Duranton & Turner (2018). For more extensive reviews, see Ewing & Cervero (2001), Handy (2005), as well as the meta-analyses in Ewing & Cervero (2010) and Stevens (2017).

[7] Zheng et al. (2011) and Morikawa (2012) provide a similar analysis for Chinese and Japanese cities respectively.

[8] Noticeable exceptions are Gill & Moeller (2018) for German municipalities, and Kleinpeter & Lemaître (2009) and Bleuze et al. (2009) for French municipalities.

[9] The OECD Economic Survey (2015) provides an estimate for France (https://www.oecd.org/eco/surveys/France-2015-overview.pdf), and Parry & Small (2005) estimates for Great Britain and the US.

through spatial policies affecting land, housing and commuting patterns.

Another important contribution of our paper is to consider how a large set of urban-form measures, including a novel indicator of morphology, affect driving patterns, in combination with both Heckman and IV strategies that allow us to tackle sorting and other endogeneity issues better than in most previous work. We analyze in particular the influence of three broad urban-form dimensions referred to as the "3 D's": 'Density', 'Design' and 'Diversity' (Cervero & Kockelman 1997). Density has been the most extensively studied feature of these, as it is an essential dimension of the built environment. The spatial Design of cities is less-often considered, although a number of contributions have looked at access to jobs and transport networks. Diversity remains by far the least-explored determinant of transport use, with a small number of papers capturing this dimension via indicators such as entropy measures of the land-use mix. We here examine the joint impact of these 3 D's on car emissions in France, and also appeal to an innovative measure of city-Design, the fractal dimension, that enables us to capture spatial disparities in urban morphology due to historical legacy.

We are able to provide new policy insights that can be drawn from considering these 3 D's jointly in France. Our results suggest that, by choosing to live at the fringe of a metropolitan area instead of the city center, the average household uses around six more tanks of fuel per year. More generally, doubling residential Density would save approximately two tanks per household per year. However, larger gains can be expected from better Design - namely greater job centralization, improved rail routes and buses to business districts, reduced pressure for road construction and a more pedestrian-friendly built environment - especially if coupled with more Diverse local amenities. Another important finding is that the relationship between metropolitan population and car emissions is not linear in France, contrary to that in the US (Borck & Pflüger 2019). Households in small French cities do not drive much because of either a good job-housing balance or less pressure for road construction. Design therefore counteracts the driving incentives stemming from low density. As cities grow, trips become longer due to extensive road networks and longer commuting distances, until the population is sufficient to sustain public transit that will likely curb car emissions. The tipping point at which French cities can potentially achieve a low-carbon 'carprint' is around 100,000 inhabitants.

Last, our results are consistent with theoretical contributions such as Gaigné, Riou & Thisse (2012), Larson & Yezer (2015), Legras & Cavailhès (2016) and Borck & Tabuchi (2019), who conclude that more compact cities are not always desirable when the general-equilibrium environmental effects of urban structure and polycentricity are taken into account.

The remainder of the paper is structured as follows. Section 1 describes the data used, and Section 2 introduces the estimation strategy and outlines our main empirical results. Section 3 then calculates estimated car emissions, ranks French cities by these emissions, and asks whether there is an optimal city size. Last, Section 4 concludes.

1 Data on fuel consumption and urban form

To analyze the interplay between car-related emissions and urban form, we use confidential household micro-data and a comprehensive set of urban-form indicators, combining elements of residential density, urban-fabric design and sectoral diversity.

1.1 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 construct the entire accounts, i.e. expenditures and resources, of a representative sample of households living in French Municipalities.[10] 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 10,000 households (and 25,000 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 other incomes (such as transfers from relatives). It also includes a rich set of household characteristics: municipality of residence,[11] family composition (number of children, workers, job seekers and retired) and the educational attainment,[12] occupation,[13] 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

[10]Note that this is not panel data however, as households are not followed over time.

[11]This information is subject to statistical disclosure: the French public authorities waived the rights to confidentiality and provided us with access to the geo-coded version of the data.

[12]Classified 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.

[13]Occupations are classified 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.

budgetary items, among which fuel expenditure broken down into gasoline, diesel and Liquefied Petroleum Gas (hereafter LPG) expenditure.[14] We use the French average price of each type of fuel in 2001 and 2006 to convert these expenditures into volumes.[15]

Table 1 shows the descriptive statistics of the main BdF variables. We measure household income as the sum the resources (apart from extraordinary revenues) of all household individuals, divided by the number of Consumption Units (hereafter CU).[16] 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.[17] With one tank of fuel typically being 50 litres in France (approximately 13 gallons), annual average fuel consumption is about 20 tanks in France.

Table 1: Descriptive statistics on fuel consumption and household characteristics

Year	2001		2006	
Household variables	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
Fuel consumption (gallons)	308 (346)	8,180	243 (286)	4,303
No. of working adults	1.02 (0.90)	5	1.02 (0.88)	5
No. of non-working adults	0.87 (0.83)	6	0.84 (0.84)	6
No. of young children (< 16 y.o.)	0.54 (0.92)	7	0.55 (0.93)	6
Number of vehicles	1.24 (0.80)	8	1.31 (0.84)	9
Age (head of household)	51 (16.7)	99	50 (16.9)	99
Income (€)	28,871 (21,458)	464,450	32,416 (24,907)	688,617
Income per CU (€)	17,562 (12,883)	464,450	19,969 (14,026)	459,078
Total number of households	10,260		10,211	
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.

1.2 The metrics of urban sprawl

We supplement the BdF database with a number of metrics of urban form at the Municipality and Metropolitan-Area levels. Although Municipalities are our unit of observation for Density and Diversity, the Design of the entire Metropolitan Area affects car usage. In France, a Metropolitan Area (MA hereafter) is composed of a cluster of urban Municipalities[18] hosting a

[14]The BdF survey collects mostly monetary data on consumption expenditures, but also includes specialized subsurveys on some items (like transport, housing, leisure and holidays) that produce more-qualitative information on household behavior.

[15]This will allow us to calculate car emissions, as we can transform volumes into CO_2 emissions using the conversion factors provided by the French Ministry of Ecological and Solidarity Transition (see Section 3). 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. See, for example, https://www.prix-carburants.gouv.fr/.

[16]The 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.

[17]One litre is equivalent to 0.2641 US gallons or, conversely, one US gallon is equivalent to 3.785 litres.

[18]There are around 36,000 Municipalities in continental France. An urban unit is defined by a Municipality or group of Municipalities forming a single unbroken spread of urban development (with no distance between habitations of over 200 meters) and having together a population of over 2,000 inhabitants. Rural Municipalities are those that do not belong to an urban unit.

minimum number of jobs[19] (the "urban pole" of the MA) surrounded by a group of Municipalities that exhibit a considerable degree of social and economic integration with this pole (at least 40% of the MA workforce has to be employed in the pole). The definition of a French MA thus hinges on three underlying criteria: morphology (the continuity of the built-up environment, which draws the line between urban and rural areas), demography (a minimum threshold of inhabitants) and functioning (a minimum number of jobs and commuting patterns). As the MA groups together Municipalities with similar commuting patterns, it is at a particularly relevant scale for the investigation of the impact of urban design on fuel consumption.

We take two complementary approaches. The first relies on the monocentric paradigm and considers MAs as series of concentric rings of Municipalities ranging from city-centers to rural areas that are under the influence of city-centers, and offers a simple typology of car-related emissions within a MA. The second is in line with the classification first proposed by Cervero & Kockelman (1997), and characterizes MAs as a collection of residential Municipalities differing along three dimensions of their built environment: Density, Diversity and Design (the "3 D's").

1.2.1 A simple monocentric classification of Municipalities

Our first approach builds on the monocentric classification used by INSEE with five categories of Municipalities.

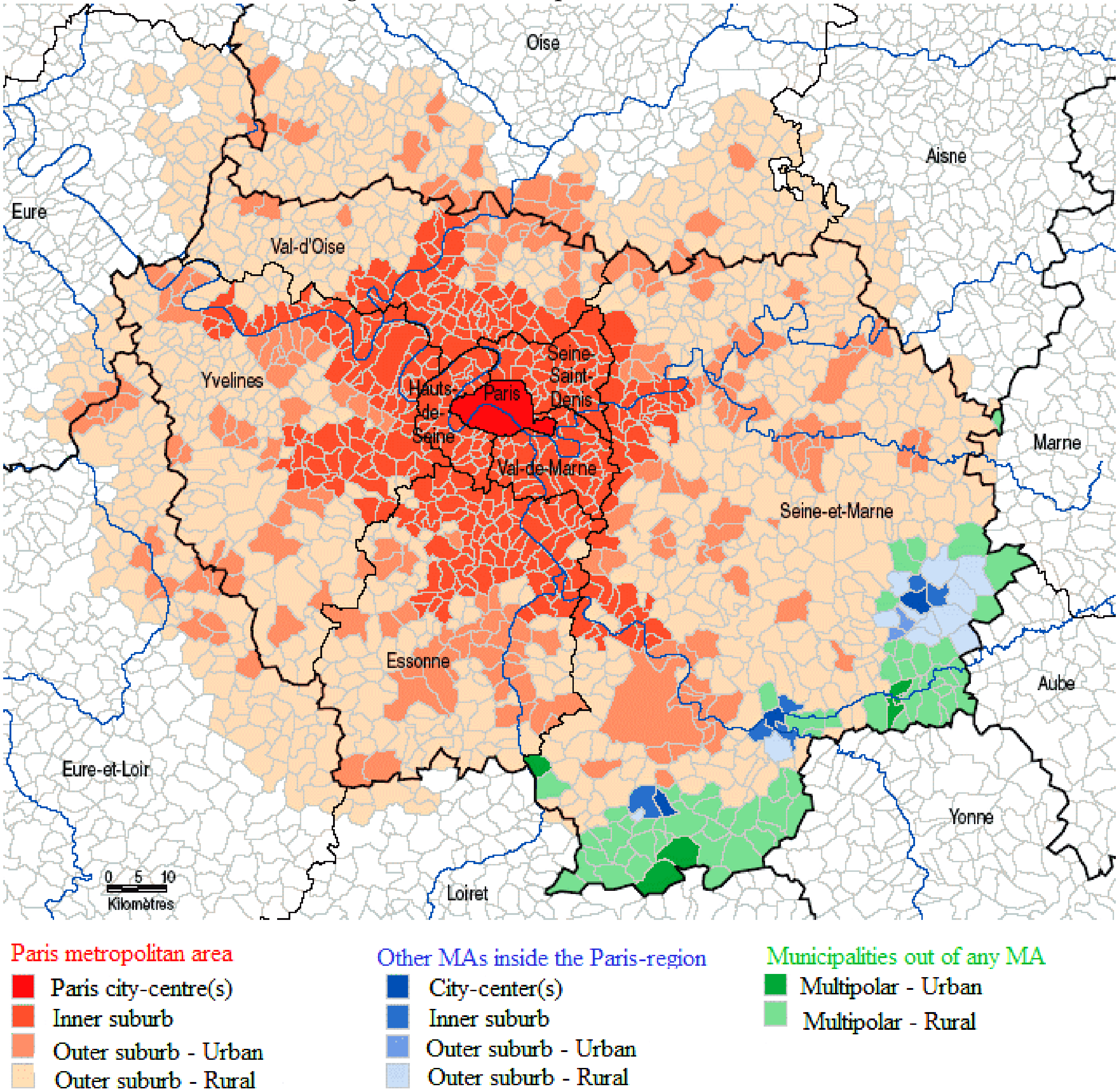
- The city-center of an MA is either the Municipality with more than 50% of the MA's population or, if no Municipality is this large, the largest-inhabited Municipality in the MA and any other Municipality that has at least 50% of the population figure of this largest Municipality. As such, small MAs generally have only one city-center, whereas larger MAs may have more than one, as illustrated in Figure 1 for the Paris MA, which has 20 city-centers (aggregated in the dark-red area depicting downtown Paris).
- The inner suburbs of a MA refer to all Municipalities of an urban pole that are not city-centers (illustrated for Paris by the dark salmon-red areas in Figure 1).
- The outer suburbs of a MA refer to the Municipalities outside the urban pole of the MA, but in which 40% of the population work in the pole. They can be either urban or rural (the salmon-red and light salmon-red Municipalities in Figure 1).[20]
- Multipolar Municipalities refer to non-urban 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 green Municipalities in Figure 1).

[19] French MAs are periodically redefined. From 1999 to 2010, the threshold was 5,000 jobs. In 2001 and 2006, France had 352 MAs spread out over 50% of mainland France, and covering approximately 85% of its population and employment (see the map in Appendix A).

[20] A rural municipality has less than 2,000 inhabitants, or more than 2,000 inhabitants but no continuously built-up land mass, or less than half of its residents in the built-up area.

- The rural space comprises all Municipalities outside the predominantly-urban space and outside the influence of any MA (see Figure 6 in Appendix A).

Figure 1: The Metropolitan Area of Paris



Notes: The smallest spatial units are French Municipalities; The urban pole of Paris is the sum of its 20 city-centers (dark-red area) and of its inner suburbs (dark salmon-red areas); the blue lines are rivers (the Seine and its tributaries) and the black lines the border of NUTS2 and NUTS3 regions.

This classification relies on functional and morphological criteria, and is therefore particularly relevant for the description of urban sprawl, as inner/outer suburbs, multipolar and rural Municipalities represent sequential steps of land development. However, as it does not provide information on the mechanisms behind fuel consumption in areas of sprawl, we turn to more precise indicators of urban form.

1.2.2 A set of quantitative measures of sprawl: the three D's

In our second approach, urban form is described by a number of indices of Density, Design and Diversity.

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 travel demand 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).[21]

Table 2 lists the summary statistics on the urban form of French municipalities. It shows that the average population density is around 3,000 inhabitants per km^2 in our sample, but may reach up 25,971 inhabitants per km^2 in 2006 for central Paris.

Table 2: Descriptive statistics of urban form

YEAR	2001		2006	
Urban-Form Variables	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
DENSITY				
Population Density	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
Density of pub. transit in residence (stops/km^2)	4.64 (7.32)	33.47	4.96 (7.61)	33.57
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 urban Municipalities	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.

Design Urban Design complements the quasi-mechanical effect of Density on fuel consumption. However, it has a greater scope of influence than local density as it determines modal choices and travel destinations within MAs.

[21] This 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 Corine-Land-Cover, instead of the total surface area. Both measures produce similar results, and we use standard density hereafter.

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 'as the crow flies' distance between the home Municipality and the 'Central Business District' (CBD) of the home MA[22] to measure the household's centrality or remoteness.[23] In Table 2, the average distance to CBD is around 9 km in France, but can be over 70 km in large MAs such as Paris.

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.[24] To measure the connection of the household to the MA, we construct 'Transport Potential' indicators[25] 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 in the BD-TOPO database are calculated as follows:

$$TP_{k,t}(x) = \sum_{k' \in \text{MA}, k' \neq k} \frac{dens_{k',t}(x)}{dist_{kk'}}, \tag{1}$$

where k is the Municipality of residence, $k' = 1, ..., K$ are the other Municipalities in the MA and $dist_{kk'}$ the distance between the centroids of Municipalities k and k'.[26] The variable x is a measure of the transport services 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 weighted by the extent of traffic from the BD-TOPO.[27] The variable $dens_{k',t}(x)$ is thus the density of x per km^2 of acreage in municipality k' at time t.

However, transport is not only important for movement within a MA. For shorter trips, modal substitutability depends strongly on transit systems (bus, tram and rail) that are accessible close to the household. 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 den-

[22]The CBD is the Municipality with the largest number of jobs in the MA.

[23]Alternate metrics are the effective average distance from residence to all municipal jobs in the MA, calculated from population censuses. Our key findings continue to hold with these measures, as will be shown below.

[24]See among others Ewing & Cervero (2001).

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

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

[27]In the BD-TOPO, road infrastructure is ranked by traffic intensity, which allows us to disentangle the impact of large and small arteries.

sity of all public transport stops (railways, subways, trams and buses) in the Municipality of residence.[28]

The fractal dimension as a walkability measure While buses and trains are substitutes for cars for medium and long trips, walking may be the most relevant mode for everyday trips. Previous work has 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.[29] We here consider a synthetic morphological index widely-used by quantitative geographers over the past two decades, but not by economists: the fractal dimension of the local built-up area. This index, which is a common characterization in natural sciences of irregular geometries, has been used since Frankhauser (1998) as an efficient way of classifying urban morphologies. For instance, Keersmaecker, Frankhauser & Thomas (2003) use this index to classify the morphology of Brussels suburbs, and find that sprawling areas have a low fractal dimension.

Urban planners generally believe that a mixed fabric of streets and buildings of different sizes makes destinations (home, shops, jobs) more accessible and more conveniently reached by pedestrians (Cervero & Kockelman 1997), whereas large housing complexes foster car use and are much less pedestrian-friendly. Due to the contrasted history of French urban planning, very different morphologies currently coexist in French cities. While towns with historical heritage have highly-connected networks of narrow historical streets, many other French municipalities exhibit morphologies reminiscent of the typical 1960's car-dependant urban designs, such as large housing complexes separated by car parks, emblematic of the Athens Charter in Le Corbusier (1933). More recently, walkability became the guiding principle of French urban planning, starting in 1980, with the development of an 'Open Block' vision of the built-environment theorized by Christian de Portzamparc (2010).

We use the building footprint from the BD-TOPO to calculate the fractal dimension of French urban fabric.[30] 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 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 detached-housing developments (leapfrogging). Medium dimensions (1.3 to 1.6) refer to large housing complexes typical of French inner suburbs.[31] Larger figures (1.7 to 2) embody the more-complex

[28]In 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 km^2).

[29]See Cervero & Kockelman (1997) and Ewing et al. (2015) for extensive reviews.

[30]More details on this calculation are provided in Appendix B.

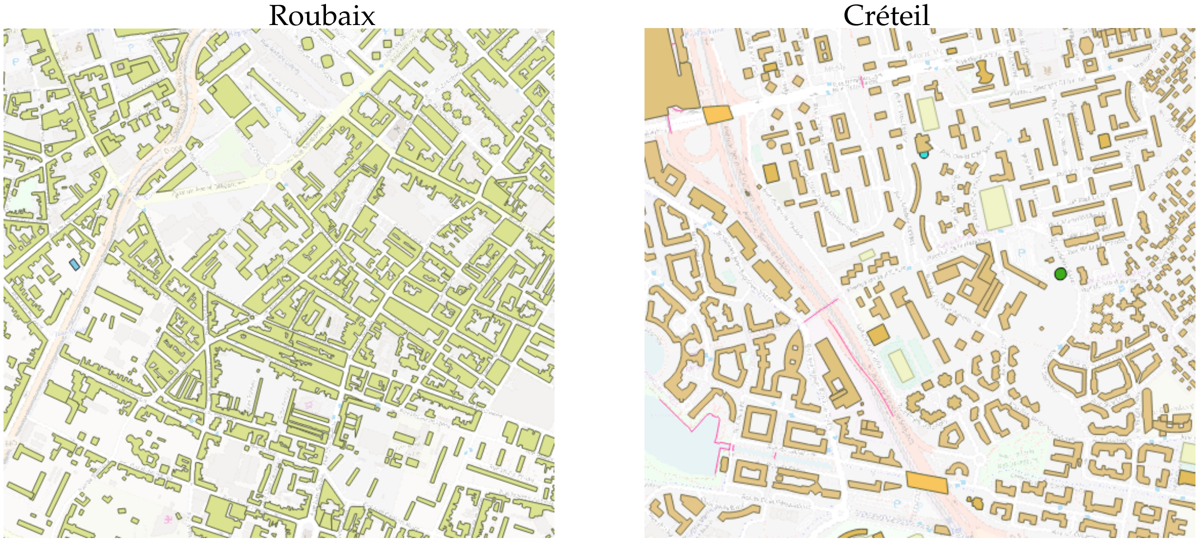
[31]The average fractal dimension of suburban Municipalities with '*Grands Ensembles*' is 1.6.

built environments typical of old city centers, with buildings blocks of different sizes arranged around squares, avenues or narrow streets.[32]

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. 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 two inner suburbs of the Paris and Lille MAs: *Créteil* and *Roubaix*. Both Municipalities have similar densities ($7,939$ inhab./km^2 and $7,262$ inhab/km^2 respectively in 2006), and similar distances to the CBD and transport potentials,[33] but differ strongly in their fractal dimension, as illustrated in Figure 2. *Créteil* has regular blocks of flats crossed by motorways, built from the mid 1950's to the early 1970's by a disciple of *Le Corbusier*, whereas *Roubaix* exhibits low-rise attached dwellings located along narrow streets dating back to the 19$^{\text{th}}$ 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 found in central Paris.

Figure 2: Differences in the fractal dimension of two municipalities similar in all other respects

Roubaix | Créteil



Fractal Dimension: 1.81 | Fractal Dimension: 1.65

Source: BD-TOPO (NGI, 2006) and authors' own calculations.

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

[32]The figure for *Haussmanian* patterns typical of the 19$^{\text{th}}$ century, for example in central Paris, can exceed 1.8.

[33]For instance, they both have subway lines that connect them to the city center in under 30 minutes.

increase with the number of activities available.

We measure Diversity via a Herfindahl index of Municipal leisure activities, 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 Municipality) and each employee (start and end date of each job spell, earnings, occupation, part-time/full time, permanent/temporary contract, occupation and working time).[34] We use the three-digit level of the 'Economic Nomenclature Synthesis' (NES) to calculate the market shares of the following activities in the 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 Herfindhal index is then calculated as follows:

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

where $L^s_{k,t}$ is the number of jobs in sector s of Municipality k at time t, and S the total number of leisure activities taken into account.[35] This index ranges from $\frac{1}{S}$, the maximum level of Diversity, to 1, the minimum level of Diversity.

There are some very small rural municipalities for which the Herfindahl index cannot be calculated, as they have no employees in the leisure sector.[36] As we lose 808 observations (5% of the total) when we include our Diversity index in the regression, we provide two sets of estimates below (with and without this measure).

2 Empirical strategy and results

Our first assessment of the impact of urban sprawl on fuel consumption comes from a parsimonious econometric model with household residence being assigned to the monocentric Municipality classification. To understand which factors lie behind the relationship between fuel consumption and urban form, we then consider only urban Municipalities and consider how our 3 D's interact with urban residence-type. Last, we tackle sorting and other endogeneity issues to evaluate the causal impact of urban form on fuel consumption.

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

[35]We 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 calcualation 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.

[36]One half of the 36,000 French Municipalities have under 500 inhabitants, and one tenth under 100 inhabitants.

2.1 Suburbanization and fuel consumption: baseline estimations

The baseline econometric specification we estimate is the following:

$$Fuel_{i(k,t)} = \alpha_0 + \alpha_1 PCC_k + \alpha_2 PIS_k + \alpha_3 IS_k + \alpha_4 OS_k + \alpha_5 M_k + \alpha_6 R_k + X_{i(t)}\theta + u_t + \epsilon_{i(k,t)}, \quad (3)$$

where $Fuel_{i(k,t)}$ is the fuel consumption (in gallons) of household i in Municipality k at time t, and $X_{i(t)}$ a vector of household characteristics including income per CU (in logs), 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. Six dummies reflect the impact of sprawl: PCC_k, PIS_k, IS_k, OS_k, M_k and R_k indicate whether the Municipality of residence k is a Parisian City-Center, a Parisian Inner Suburb, a non-Parisian Inner Suburb, an Outer Suburb, a Multipolar Municipality or a Rural Municipality outside the urban space. Last, u_t is a year dummy and $\varepsilon_{i(k,t)}$ the error term. The $\alpha_{j=1,...,6}$ 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 first set of linear regressions appear in columns 1 and 2 of Table 3 for all households and urban households respectively, controlling for household characteristics and year fixed effects.

To extend our understanding of urban sprawl, we then turn to a semi-log specification including our different measures of the 3 D's for the sample of urban households:

$$Fuel_{i(k,t)} = \alpha + \beta Density_{k,t} + Design_{k,t}\delta + \gamma Diversity_{k,t} + X_{i(t)}\theta + u_t + \varepsilon_{i(k,t)}, \quad (4)$$

where $Density_{k,t}$ is the log of population density in the municipality of residence k at time t, $Design_{k,t}$, the vector of log-variables capturing the design of the residential environment (distance to CBD, road/rail transport potentials, local density of public-transport stops and local morphology), and $Diversity_{k,t}$, the Herfindahl index capturing the diversity of local amenities. The coefficients β, δ and γ measure the impact of each urban-form 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 $\beta \div 100$ 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. Columns 3 to 8 in Table 3 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.

[37] We 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: Household fuel consumption and residence-type: Pooled OLS estimations

Dependent Variable: Fuel consumption (gallons)	All Households (1)	Urban Households (2)
Log(Total income/CU)	69.4***	70.3***
	(4.705)	(4.218)
Number of working adults	126.5***	116.3***
	(4.688)	(12.531)
Number of non-working adults	74.0***	70.3***
	(3.977)	(7.776)
Number of young children (<16 years)	9.3***	8.7***
	(2.670)	(3.067)
Age (Head of household)	5.2***	4.2***
	(0.651)	(0.727)
Age-squared (Head of household) / 100	-6.8***	-5.9***
	(0.568)	(0.546)
Female (Head of household)	-37.2***	-40.8***
	(4.566)	(8.548)
Non-Parisian city-centre	Reference	
City-centre(s) of Paris	-150.0***	-147.0***
	(9.643)	(5.959)
Inner suburb of Paris	-47.1***	-44.2***
	(6.973)	(5.873)
Inner suburb out of Paris	41.3***	43.1***
	(5.520)	(7.080)
Outer suburb	83.7***	86.9***
	(6.641)	(9.102)
Multipolar municipality	105.9***	-
	(10.285)	
Rural municipality	85.3***	-
	(5.795)	
Household characteristics	✓	✓
Year fixed effects	✓	✓
Observations	20,471	15,609
R-squared	0.238	0.225

Notes: (i) OLS estimates of Equation (3); (ii) Robust standard errors in parentheses (at the MA level); ***p<0.01, **p<0.05, *p<0.10.
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).

Table 4: Household fuel consumption and residence-type in urban areas: Adding the three D's

Dependent Variable: Fuel consumption (gallons)	Urban households (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Non-Parisian city-centre		Reference						
City-centre(s) of Paris	-147.0***	-80.9***	-152.7***	-19.7	-82.3***	-98.7***	-104.7***	-148.4***
	(5.96)	(14.26)	(6.63)	(15.36)	(9.57)	(9.99)	(11.88)	(6.02)
Inner suburb of Paris	-44.2***	-15.7*	-68.3***	70.4***	19.2**	-30.5***	-34.7***	-45.5***
	(5.87)	(8.45)	(13.81)	(14.03)	(9.44)	(6.17)	(6.64)	(5.79)
Inner suburb outside Paris	43.1***	22.4***	28.0**	51.4***	52.5***	37.6***	20.5***	37.8***
	(7.08)	(6.91)	(11.58)	(7.07)	(6.97)	(6.34)	(7.65)	(7.33)
Outer suburb	86.9***	16.4	61.6***	98.2***	96.6***	64.6***	31.5**	57.4***
	(9.10)	(13.16)	(22.78)	(11.32)	(9.04)	(9.48)	(12.34)	(12.29)
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)					-24.0***			
					(2.73)			
Log(Density of pub. transit in residence)						-23.7***		
						(3.44)		
Fractal dimension in residence							-202.6***	
							(40.38)	
DIVERSITY								
Herfindahl index of leisure in residence								86.5***
								(20.50)
Household characteristics	✓	✓	✓	✓	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609	15,609	15,609	15,609	14,801
R-squared	0.225	0.233	0.225	0.228	0.228	0.230	0.231	0.232

Notes: (i) OLS estimates; (ii) Robust standard errors in parentheses (at the 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).

Fuel consumption and residence-type There are sharp differences in fuel consumption across Municipalities, depending on their position in urban and rural space, as shown in the first two columns of Table 3. For example, a household in Paris city center uses 150 gallons per year (column 1) less than an observationally-equivalent household in a non-Parisian city center, which represents a reduction of about 10 tanks per year, or half the mean annual French fuel consumption. Living in a Parisian inner suburb produces a smaller drop of 47 gallons per year (3.5 tanks), whereas living in a non-Parisian inner suburb increases consumption by approximately 41 gallons per year (3 fuel tanks). The diseconomy associated with the next rings of suburbs are even larger, at 84, 106 and 85 additional annual gallons (6.5, 8 and 6.5 tanks), for respectively an outer suburb, a multipolar and a rural Municipality. One interesting feature is that there is a significant difference between outer suburbs and multipolar Municipalities. In other words, living under the influence of several MAs does seem to increase travel demand. By way of contrast, there is no significant difference between outer suburbs and rural areas, which suggests that all of the benefits of an urban location fade away at the urban fringe. 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.

What mechanisms lie behind these spatial differences? We find a very significant impact of our 3 D's on fuel consumption. Their addition to our monocentric classification is shown in Table 4 and helps to understand the gaps between Municipalities in different rings. 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 explains a large part (but not all) of the Parisian effect. In contrast, residential density completely washes out the effect of living in an outer suburb: 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.[38] We thus extend our analysis to the two other D's.

Our Design variables turn out to have contrasting effects. The distance from the residence to the CBD magnifies the fuel-saving effect of living in Paris and the higher fuel consumption outside of 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 more significant: 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 counterpart. It therefore seems that the largest part of the ecologi-

[38]Note that we cannot calculate a Herfindahl index for every sample Municipality, which censors the observation numbers to households in cities with more than one employee in the leisure sectors.

cal effect of living in Paris comes from the rail-transit network, which is the most extensive in France. On the contrary, 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 ecological downtown-Paris 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-collinearity 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 (see Table 5 below). The density of local public transport (column 6) and the walkability of the built environment (column 7) partly alleviate the impact of all residence types, without making them insignificant, so that 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, so that a substantial part of the effect of living at the urban fringe comes from the leapfrogging morphology of outer-suburbs.

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

The addition of the concentric dummies to our 3 D's first indicates that Density, Design and Diversity are crucial determinants of fuel consumption *per se*. In addition, local public transport, morphology and leisure amenities are particularly important in dampening the negative environmental externalities associated with car use in dense areas such as central Paris, and are only partly captured by the simple monocentric classification.

It is therefore important to further investigate the urban form. Table 5 shows the results of regressing household fuel consumption on the 3D's in Equation (4), which is our most comprehensive specification. Column 1 displays the point estimates from the sample of urban households, and column 3 those from urban households with a car, as a first attempt to test for household selection across the urban space.

Fuel consumption and urban household characteristics Household characteristics attract similar estimated coefficients across all specifications.[39] 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 roughly doubles (is multiplied by 2.7) annual fuel consumption rises by 68.9 gallons (column 1), around 30% of average French annual household fuel consumption. Family composition also matters: an additional working adult in the household is associated with higher annual fuel consumption of 111.3 gallons. This is to be compared to the 68 additional gallons associated with an additional non-working adult, and

[39] As such, we will not show or discuss these estimates below.

Table 5: Household fuel consumption and urban form: OLS estimations

Dependent Variable: Fuel consumption (gallons)	Urban households	Motorized urban households
	(1)	(2)
HOUSEHOLD CHARACTERISTICS		
Log(Total income/CU)	68.9***	60.1***
	(4.31)	(5.55)
Number of working adults	111.3***	102.1***
	(14.18)	(14.60)
Number of non-working adults	68.0***	67.7***
	(8.06)	(8.94)
Number of young children (<16 years)	8.3***	3.7
	(2.89)	(3.10)
Age (Head of household)	3.4***	4.0***
	(0.67)	(0.92)
Age-squared (Head of household) / 100	-5.2***	-6.3***
	(0.53)	(0.85)
Female (Head of household)	-40.5***	-33.6***
	(7.97)	(10.48)
DENSITY		
Log(Density of pop. in residence)	-11.3**	-7.9*
	(4.53)	(4.77)
DESIGN		
Log(Distance from residence to CBD)	14.7***	13.7***
	(3.88)	(4.14)
Log(Density of pub. transit in residence)	-9.7***	-8.6**
	(3.03)	(3.37)
Fractal dimension in residence	-89.6**	-87.6**
	(39.67)	(37.94)
Log(Road potential in the rest of the MA)	17.6**	15.2**
	(7.57)	(7.55)
Log(Rail potential in the rest of the MA)	-59.4***	-49.9***
	(10.14)	(11.20)
DIVERSITY		
Residential Herfindahl index	28.5*	35.4**
	(15.33)	(15.97)
Education dummies (Head of household)	✓	✓
Occupation dummies (Head of household)	✓	✓
Year fixed effects	✓	✓
Observations	14,801	12,132
R-squared	0.240	0.160

Notes: (i) OLS estimates drawn from equation (4); (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 diploma and occupation categories 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).

the 8.3 gallons from having more than one young child. The effect of a working adult is then around 50% larger than that of a non-working adult, and 13 times that of two young children. 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 of the quadratic term significantly negative. Female-headed households use 40.5 gallons less fuel than male-headed households.[40] 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 household travel demand.

Fuel consumption and urban form Moving to our 3 D's, we continue to find a negative impact of **Density**, with a significant semi-elasticity ranging from -11.3 (column 1) for urban households to -7.9 (column 3) for those with a car. Doubling Municipal population would thus produce annual fuel savings of at most $\ln(2) \times 11.3 \cong 8$ gallons for urban residents. Put differently, a typical household in Toulouse consumes 8 more gallons per year than an observationally-equivalent household in Lyon (where density is twice that in Toulouse) via the density channel. These effects are larger comparing areas where density varies by orders of magnitude: a household in the most scarcely-populated French urban municipality (Chézy, with 6 inhabitants per km^2) consumes $\ln(25,971/6) \times 11.3 \cong 95$ more gallons (approximately 5 tanks, 25% of French household annual fuel consumption) per year than an equivalent household in Paris (the densest municipality in France, with 25,971 inhabitants per km^2 in 2006), all else equal. More generally, the impact of density is less marked in France than in other countries, as the estimated elasticity ($-\frac{11.3}{215} = -0.05$ at the mean of our sample in 2006) is half the average figure in the most recent meta-analysis of Stevens (2017).

Design metrics have a variety of effects. Halving the distance from residence to the CBD would save $\ln(2) \times 14.7 \cong 10$ gallons (column 1). Improving railway access leads to a fall in fuel consumption of an order of magnitude larger than the distance effect: doubling municipal rail potential helps residents save around 4 tanks per year (approximately 20% of the French household annual average fuel consumption). Conversely, road improvements increase fuel consumption, but with a smaller effect. As such, a rail network with wide urban coverage can be a very effective substitute for car use. Last, local public-transit systems and fractal morphologies yield further substantial significant environmental gains.

By way of comparison, Glaeser & 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 French cars[41];

[40]Although their coefficients are not shown for clarity reasons, the occupation and education dummies are generally also very significant.

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

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 & Kahn (2010) (only density and distance to CBD), the density semi-elasticity is 28 gallons, halving again the US-France gap.[42] 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 & Kahn (2010).

Urban morphology has a strong and significant environmental effect. A 10% difference in the fractal dimension, such as the *Roubaix-Créteil* gap above, translates into a reduction of $\ln(1.1) \times 89.6 \cong 8.5$ gallons per year (column 1), above and beyond the Density and Design channels.[43] As discussed above, the inclusion of a fractality index greatly reduces the estimated Density impact.

Diversity has also a positive but less significant impact on French fuel consumption. Doubling leisure diversity produces $0.24 \times 28.5 \cong 7$ fewer gallons per year (column 1), comparable to the effect of the Density and Design channels. Including Diversity in the regression also sharply reduces the estimated Density impact: excluding Diversity increases the density coefficient around one half.[44]

As a further robustness check, Table 10 in Appendix C shows the results from a less-conservative specification in which we exclude Diversity so as not to lose observations (columns 1 and 3). Logically, the point estimates on density and distance to CBD are somewhat larger, as diversity is one of the channels through which these two effects transit. In columns (2) and (4), we also include MA fixed effects to control for omitted or unobservable 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 fuel determinants remain significant, despite the fewer degrees of freedom, which makes us more confident about the identification power of our first 2 D's.

Last, Table 11 in Appendix C checks whether the results change when we consider the effective average distance from home to all of the jobs in the MA (calculated from population censuses), instead of the home-CBD distance. The results are virtually unchanged, except that the Herfindahl index becomes insignificant. As it is very difficult to find a good instrument for effective distance, we retain the first below.

[42]Without the fractal variable, the density coefficient roughly doubles, producing a density elasticity that is in line with that in the literature. The corresponding tables are available upon request.

[43]Moreover, this impact is robust to the inclusion of other simpler morphological variables, such as the share of built-up area and the density of crossroads. These additional regressions are available upon request.

[44]These complementary tables are available upon request.

2.2 Urban form and fuel consumption: Causal estimations

Two econometric issues arise in our baseline OLS estimates: the sorting of households across Municipalities and the endogeneity from potential confounders that are correlated with household location, and therefore with Density and Distance to the CBD.

Sorting As underlined by Brownstone & Golob (2009), Grazi, van den Bergh & van Ommeren (2008) and Kahn & Walsh (2015), lifestyle and individual preferences influence residential choices, as households live in locations that match their socioeconomic characteristics and travel predispositions. For instance, some do not mind driving and may even like it: these individuals may locate far from job centers, in low-density areas with remote public-transport services that they do not value anyway. Conversely, if those who dislike driving and prefer walking, cycling or taking public transport self-select into denser areas where these options are available, the effect of density on fuel consumption will likely be overestimated. Households with cars may differ in significant unmeasured ways from those without cars. It is worth noting that this self-selection bias may be mitigated here by our inclusion of many individual controls in the baseline regressions. Nevertheless, as we likely do not include all of the variables influencing residential choice, the error term in Equation (4) likely remains correlated with the explanatory variables, which may produce inconsistent estimates.[45]

We deal with household sorting across places via two sets of additional regressions. First, as noted above, we run OLS regressions on the subset of urban households with cars. We obtain very similar results (see column 2 of Table 5), the only difference being that the effect of public transport drops by 10 to 30%, consistent with car ownership being negatively correlated with the presence of public transport. In other words, the latter seems to be more a cause of car ownership than lower fuel consumption *per se*.

Second, we apply a Heckman (1979) two-step procedure with selection for car ownership. The first step of the 'Heckit' consists of the following Probit equation:

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

where $\text{Prob}\left(\text{car ownership}_{i(k,t)}\right)$ is the probability that household i in Municipality k own 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 (4).

In a second step, we re-estimate Equation (4) adding the inverse of the Mills ratio[46] from

[45] Note 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 households that own a car, who must at some point have spent money on fuel.

[46] Calculated as $Mills(x) = \frac{\bar{F(x)}}{f(x)}$, 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.

the Probit regression, and exclude the young-children dummy 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 is our estimation exclusion restriction.

Endogeneity To address remaining endogeneity concerns, we instrument the urban-form variables that are more likely correlated with unobserved determinants of residential choices, density and home distance to the CBD. We thus require instruments that affect fuel consumption only through the distribution of population settlements. Long lags of variables are *a priori* good candidates as they can remove any simultaneity bias caused by contemporaneous local shocks to fuel consumption. The first historical instrument we use is mortality density in each municipality in the early 1960's before the expansion of car use in France (Source: Census, 1962).[47] Mortality is highly correlated with total population (with a correlation coefficient of 0.94 for the Municipalities in the BdF surveys), and at the same time orthogonal to the error term, which encompasses the modern taste for driving.[48] To instrument the distance to the CBD, we calculate the number of kilometers separating the residence Municipality and the most-populated Municipality in the actual MA in 1806 (Source: *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* of the French National Institute of Demographic Studies; INED, 2003).[49]

As a last endogeneity check, we run a series of regressions including a third instrument for both density and distance to the CBD, to test the validity of our two preferred instruments above. We calculate the following lagged market potential '*à la*' Harris (1954):

$$MP_{k,1936} = \sum_{k' \neq k} \frac{dens_{k',1936}}{dist_{kk'}}, \tag{5}$$

where $dens_{k',1936}$ is density in municipality k' in 1936, drawn from a historical dataset listing the population of the 5,198 French Municipalities with over 5,000 inhabitants at least once between 1831 and 1982 (Source: *Fichiers Urbanisation de la France* of the French National Institute of Demographic Studies; INED, 1986). We chose 1936 as this is the year with the largest data

[47] This is the oldest census in which mortality is measured at the Municipality level.

[48] The correlation between fuel consumption and our instrument is -0.21.

[49] The first French census dates back to 1801, but we prefer to use the 1806 wave as Napoléon's French Empire covered all current French Municipalities at that date (and even extended outside the current French borders).

coverage.[50]

Table 6 provides the results fromm both our IV (column 2) and Heckman (column 3) approaches. Compared to column 1, which shows our baseline estimates, endogeneity leads to an underestimation of the distance effect of approximately 70%, whereas the point estimates on the fractal-dimension and road-potential variables fall by around 40%. The other coefficients are little affected by the instrumentation. The Shea partial R-squared statistic shows that our two preferred instruments explain a non-negligible share of the endogenous variables, once the potential inter-correlations between instruments are taken into account.[51] However, we should check that this does not come about at the expense of their strength. We carry out a more-formal assessment of our instruments via the weak-instrument tests in Stock & Yogo (2005). The instruments are not weak, as the Cragg-Donald F-statistics are far above the critical value reported for a 5% maximum IV bias (13.43).[52] 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 also far above 5%.

The right-hand panel of Table 6 lists the coefficients from our 'Heckit' (column 3) and Probit (column 4) regressions.[53] The selection bias for Density is only small. By way of contrast, the impact of distance to the CBD rises when selection is taken into account, consistent 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. Selection then leads to a general underestimation of the impact of the 3 D's on fuel consumption, with the bias being slightly larger for Design than for Density.[54]

As shown in column 4, the probit regression produces a significant positive lambda term, so that 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 access) reduces (increases) car ownership by a small amount, around 2%, while the marginal effects of rail access and morphological diversity are five to ten times larger.

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.

3 CO_2 car emissions and city-size: a bell-shaped curve

In the same spirit as Glaeser & Kahn (2010), we can use our causal estimates to predict the CO_2 car emissions produced by a standardized household in each French MA. We then identify the

[50] Using different years does not change the size of our estimates, but does lead to a loss of precision.

[51] The first-stage regressions appear in Appendix C Table 12.

[52] Appendix C Table 13 shows that results are qualitatively and quantitatively similar when we introduce 1936 market potential as an additional instrument.

[53] Only the marginal effects are listed for the Probit. These show how the (conditional) probability of car ownership changes with the value of a regressor, holding all of the other regressors constant.

[54] Appendix C Table 14 shows the results for the first two D's only. As in the OLS, the 2SLS point estimates of density and distance to CBD are larger, as they also include the effect of diversity.

Table 6: Household fuel consumption and urban form: Causal estimations

Dependent Variable: Fuel consumption (gallons)	Urban households		Heckman two-step	
	OLS	2SLS	Heckit	dx/dy Probit
	(1)	(2)	(3)	(4)
DENSITY				
Log(Density of pop. in residence)	-11.3**	-11.4**	-10.2**	-0.017***
	(4.53)	(5.72)	(4.57)	(0.005)
DESIGN				
Log(Distance from residence to CBD)	14.7***	25.1***	17.1***	0.013***
	(3.88)	(5.47)	(4.51)	(0.004)
Log(Density of pub. transit in residence)	-9.7***	-8.1***	-11.7***	-0.011***
	(3.03)	(2.87)	(3.59)	(0.003)
Fractal dimension in residence	-89.6**	-52.9	-110.4***	-0.132***
	(39.67)	(44.46)	(32.36)	(0.031)
Log(Road potential in the rest of the MA)	17.6**	11.4^{+}	19.8***	0.023***
	(7.57)	(7.46)	(6.60)	(0.006)
Log(Rail potential in the rest of the MA)	-59.4***	-59.7***	-68.6***	-0.080***
	(10.14)	(8.89)	(10.45)	(0.009)
DIVERSITY				
Herfindahl index of leisure in residence	28.5*	29.3**	28.1*	-0.013
	(15.33)	(15.37)	(17.10)	(0.023)
Household characteristics	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓
Observations	14,801	14,801	14,801	14,801
R-squared	0.240	0.170		
Cragg-Donald F-Stat		5,777		ρ : 0.46
Shea Partial R-squared (log density)		0.46		σ : 288
Shea Partial R-squared (log distance to CBD)		0.53		λ : 132

Notes: (i) Robust standard errors in parentheses (at the 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, 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; (iv) The instruments are mortality density in 1962 (in log) and distance to the largest municipality of the MA in 1806 (in log).
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), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

greenest and dirtiest cities according to this 'carprint', and ask how this is related to city size.

3.1 CO_2 car emissions of the sample-mean household across MAs

We calculate the driving footprint of a standardized household in each MA as follows. We first estimate how much fuel the mean household in the 2006 BdF survey[55] would consume in each urban municipality, based on either the 2SLS (Equation 6) or Heckman (Equation 7) estimates in Table 6:

$$\widehat{Fuel}_{m(j)} = \widehat{\alpha} + \widehat{\beta} \log Density_j + \log Design_j \widehat{\delta} + \widehat{\gamma} \log Diversity_j + \overline{X_i}\widehat{\theta}, \forall j, \tag{6}$$

$$\widehat{Fuel}_{m(j)} = \widehat{\alpha} + \widehat{\beta} \log Density_j + \log Design_j \widehat{\delta} + \widehat{\gamma} \log Diversity_j + \widehat{\lambda}\widehat{Mills} + \overline{Y_i}\widehat{\mu}, \forall j, \tag{7}$$

where $\overline{Y_i}$ is the vector of 2006 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 characteristics. 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.[56] We then use these estimates to calculate car emissions as before, except that we measure mean household income as that in the home Municipality, instead of 2006 BdF mean income:

$$\widehat{Fuel}_{m(j)CI} = \widehat{\alpha} + \widehat{\beta} \log Density_j + \log Design_j \widehat{\delta} + \widehat{\gamma} \log Diversity_j + \overline{Z_i}\widehat{\eta}, \forall j, \tag{8}$$

where $\overline{Z_i}$ 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 projections in the MA, weighted by the share of households with cars in each Municipality:

$$\widehat{Fuel}_{m(MA)} = \sum_{j \in MA} \left(\widehat{Fuel}_{m(j)} \times \text{Nb of motorized households}_j / \text{Nb of households}_{MA} \right). \tag{9}$$

Last, we calculate 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

[55] This is a household with 1.03 working adults, 0.83 non-working adults, 0.55 young children, a mean income of 28,872 Euros, headed by a man who is 49 years-old, working in an intermediate profession and with a high-school professional degree or apprenticeship.

[56] In detail, we run the following regression: $\log\left(Inc^{\text{BdF}}_{j,2006}\right) = \Phi_1 + \Phi_2 \log\left(Inc^{\text{tax}}_{j,2006}\right) + \xi_{j,2006}$. 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 CO_2 emissions.

of fuels in French vehicles, we use a different conversion factor for each energy type: 10.8 kg of CO_2 per gallon of gasoline, 12.2 kg of CO_2 per gallon of diesel, and 7.1 kg of CO_2 per gallon of LPG. 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 CO_2 per gallon of fuel.[57]

Tables 7 and 8 show the mean household car emissions in the 25 greenest and dirtiest French MAs.[58] 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.

Table 7: The Greenest French MAs: CO_2 'carprint' of the sample-mean-household (kg/year)

Name	OLS	Rank	2SLS	Rank	Heckit	Rank	MA pop.
Paris	2,209	1	2,213	1	2,136	1	11,769,424
Lille	2,563	3	2,580	4	2,476	2	1,164,717
Caudry	2,571	4	2,559	3	2,504	3	14,322
Fourmies	2,550	2	2,536	2	2,509	4	16,324
Saint-Etienne	2,798	7	2,823	10	2,736	5	318,993
Nancy	2,800	8	2,770	7	2,738	6	415,765
Montereau-Fault-Yonne	2,794	6	2,767	6	2,739	7	26,109
Bolbec	2,792	5	2,759	5	2,744	8	15,750
Noyon	2,846	10	2,790	8	2,795	9	22,553
Lunéville	2,852	11	2,805	9	2,806	10	27,549
Le Havre	2,845	9	2,856	15	2,808	11	290,826
Tergnier	2,862	13	2,842	12	2,811	12	23,383
Lyon	2,887	14	2,888	19	2,822	13	1,748,274
Villerupt	2,893	17	2,847	14	2,826	14	19,019
Saint-Quentin	2,861	12	2,828	11	2,835	15	101,438
Hendaye	2,932	25	2,914	25	2,844	16	14,993
Fécamp	2,888	16	2,846	13	2,848	17	30,233
Strasbourg	2,897	19	2,912	24	2,851	18	638,672
Reims	2,895	18	2,890	20	2,855	19	293,316
Boulogne-sur-Mer	2,887	15	2,860	16	2,858	20	133,195
Sète	2,921	22	2,980	38	2,869	21	73,674
Provins	2,928	24	2,896	22	2,870	22	22,320
Chauny	2,922	23	2,885	18	2,872	23	22,117
Calais	2,906	20	2,903	23	2,876	24	125,525
Grenoble	2,943	26	2,942	31	2,879	25	531,439

Whatever the estimation method, car emissions vary sharply across French MAs, from approximately 2.2 tons of CO_2 per year in Paris up to 3.8 tons of CO_2 per year in MAs such as Bourg-Saint-Maurice, Annemasse and Chamonix, which are all located in the French Alps.[59]

[57] Glaeser & Kahn (2010) use a slightly lower conversion factor of 19.564 lbs or 8.874 kg per gallon of fuel (one pound equals 0.45359 kg).

[58] Appendix C Tables 15 and 16 replicate this exercise with emissions calculated using the Corrected Incomes from Equation (8).

[59] Note 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 8: The Dirtiest French MAs: CO_2 'carprint' of the sample-mean household (kg/year)

Name	OLS	Rank	2SLS	Rank	Heckit .	Rank	MA pop.
Bourg-Saint-Maurice	3,896	352	3,845	352	3,956	352	10,357
Sarlat-la-Canéda	3,850	351	3,803	350	3,867	351	18,022
Annemasse	3,824	350	3,807	351	3,831	350	244,178
La Bresse	3,777	347	3,764	346	3,806	349	12,851
Ancenis	3,811	349	3,769	348	3,805	348	19,308
Lannion	3,765	346	3,742	344	3,787	347	63,425
Chamonix-Mont-Blanc	3,761	344	3,762	345	3,783	346	13,127
Les Herbiers	3,783	348	3,765	347	3,770	345	14,833
La Roche-sur-Yon	3,764	345	3,778	349	3,769	344	107,584
Bressuire	3,740	343	3,730	343	3,756	343	18,225
Sablé-sur-Sarthe	3,738	342	3,702	341	3,755	342	30,193
Aubenas	3,720	341	3,653	336	3,744	341	44,546
Livron-sur-Drôme	3,708	339	3,670	339	3,715	340	16,662
Sallanches	3,708	340	3,718	342	3,704	339	43,413
Loudéac	3,693	337	3,659	337	3,694	338	14,217
Ploërmel	3,696	338	3,644	334	3,692	337	11,450
Tulle	3,670	332	3,603	320	3,690	336	31,693
Cluses	3,684	336	3,669	338	3,677	335	65,442
Privas	3,681	335	3,602	319	3,672	334	21,267
Quimper	3,658	331	3,673	340	3,667	333	129,110
Mayenne	3,679	333	3,633	331	3,664	332	26,361
Louhans	3,680	334	3,648	335	3,656	331	15,598
Saintes	3,655	329	3,624	330	3,653	330	55,834
Châteaubriant	3,647	328	3,617	327	3,647	329	23,562
Saint-Gaudens	3,634	327	3,567	311	3,645	328	27,298

In other words, a French standardized household that decides to live in Bourg-Saint-Maurice (Chamonix) generates a driving footprint almost 100% (80%) larger than the 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 & Kahn (2010), a US standardized household produces between $18,000$ lbs or 8.2 tons of CO_2 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.

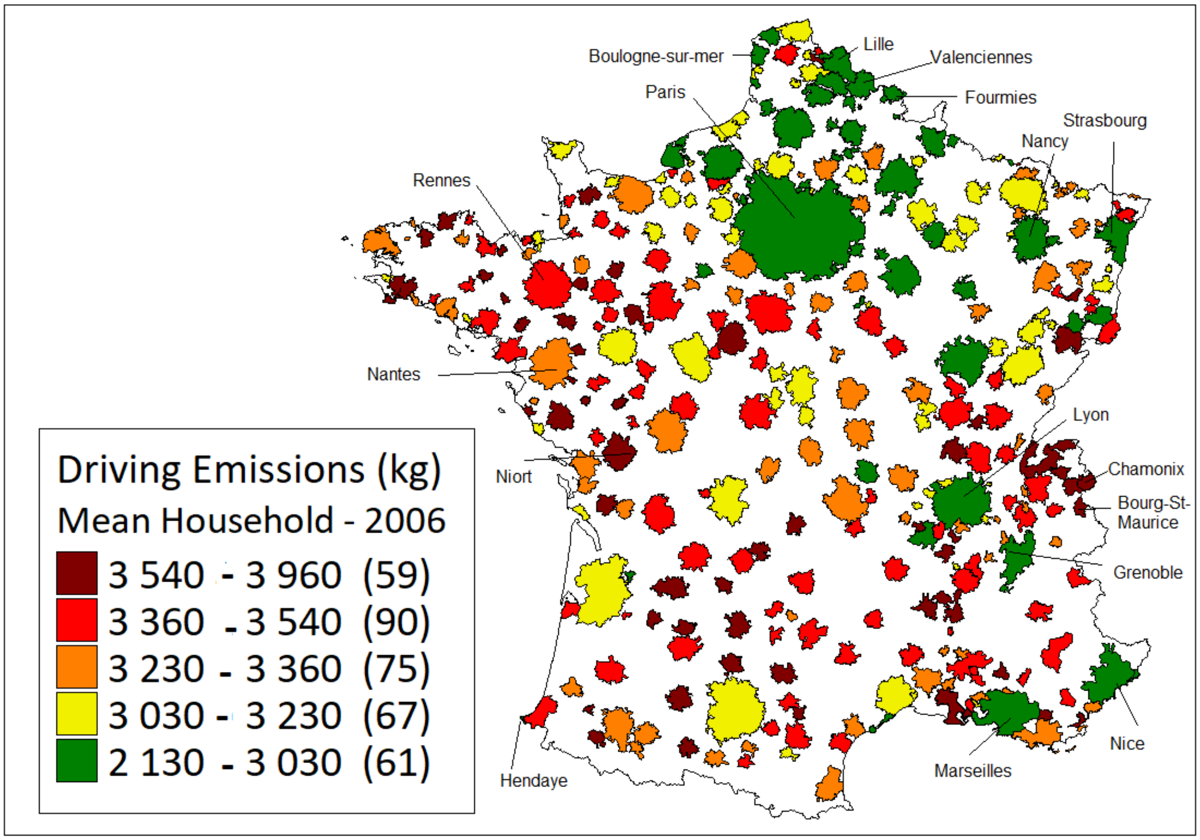
The CO_2 ranking of French MAs is fairly stable across estimation methods, though the Heckman emissions are slightly lower, and there are significant differences for a number of coastal or border MAs. For instance, MAs such as Fourmies, Hendaye and Boulogne-sur-Mer have lower emissions calculated via 2SLS, whereas for most MAs the estimated 2SLS coefficients are larger. These differences remain marginal however, as these areas have low driving footprints anyway, presumably because their development has been geographically constrained.

Appendix C Tables 15 and 16 show that while the rankings do not change when we allow Municipal income to vary (as in Equation 8), the predicted CO_2 emissions in MAs are lower.

3.2 Driving footprint and city-size: A bell-shaped curve

Figure 3 depicts the car emissions for a standardized household for all French MAs, using the Heckman estimates in Table 6 (column 5).[60]

Figure 3: Estimates of the CO_2 'carprint' of the sample-mean household (kg/year)



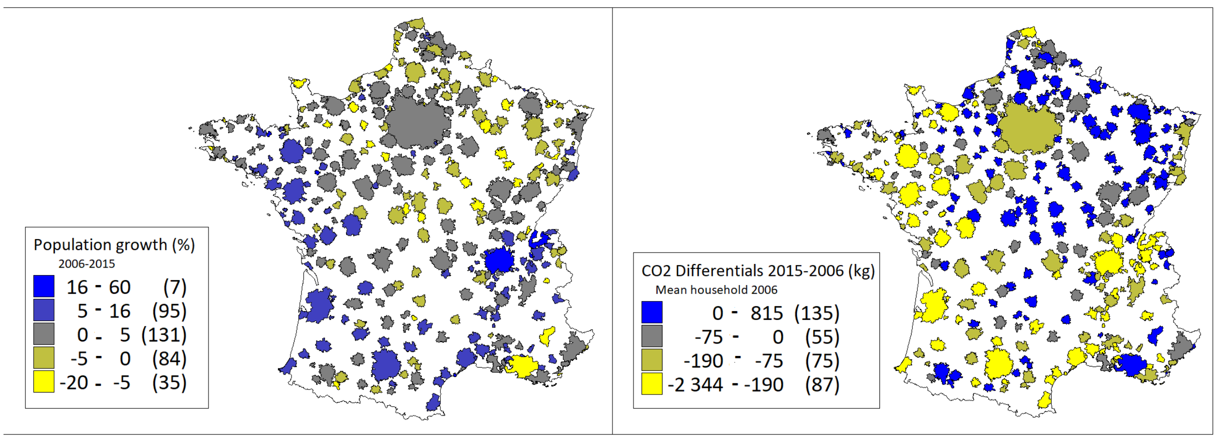
A salient geographic divide There is considerable spatial heterogeneity of household emissions across French MAs. Large MAs such as Paris, Lyon, Nice, Strasbourg and Lille exhibit low-carbon 'carprints' (under 3 tons of CO_2 per year per household), due to the combination of high population densities (up to 1,200 inhabitants per km^2 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) 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 Annemasse), as well as medium-sized Western cities (such as Niort), have high-carbon 'carprints' due to the large dispersion of their population in a geographically-scattered urban fabric, while

[60]The results are qualitatively very similar in the OLS and 2SLS estimates, which are not shown here.

medium-sized Eastern cities (such as Grenoble, Nancy and Valenciennes) 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. Note that the differences between low-carbon cities are far from negligible: a standardized household living Paris consumes 25% less fuel than an observationally-equivalent household 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 are important for policy makers, as Atlantic and Mediterranean cities have experienced strong urban growth over the past decade. Figure 4 depicts the 2006-2015 MA population growth (on the left) against the differences in predicted carbon emissions over the same period (on the right): the two patterns are mirror images, with a correlation coefficient at -0.8. It is however difficult to assess whether these changes have improved the French carbon footprint, as migration inflows may come either from large or small cities.

Figure 4: Population growth (left) and car emissions differences (right), 2006-2015

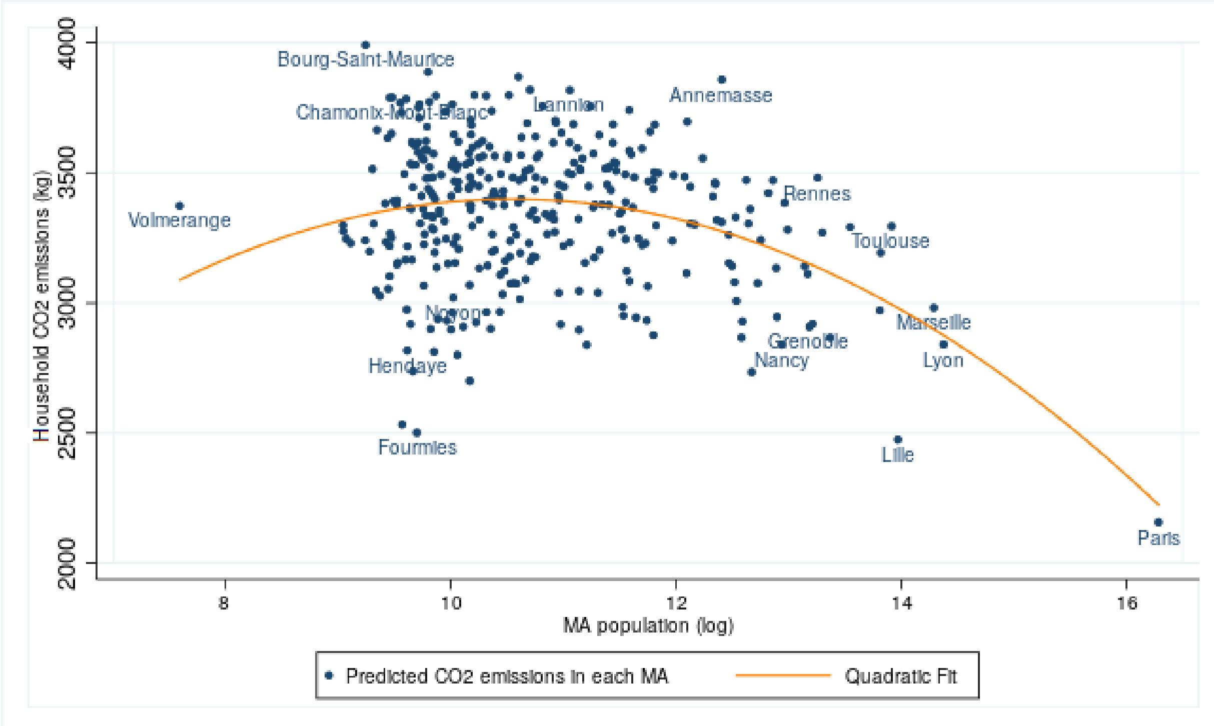


A bell-shaped curve Our estimates therefore suggest that Density, Diversity and Design together significantly affect household car emissions in France. Densely-populated MAs have lower driving footprints, as do MAs with good public-transport networks. As it is easier for large cities to afford mass-transit infrastructure, Density and Design feed on each other to sustain the low-carbon 'carprint' of large metropolitan areas. 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 sprawling (low-density suburbs) or not big enough to sustain large public-transport networks, and have extensive road networks, or a leapfrogging built environment (a low fractal dimension). Moreover, large cities save on carbon emissions as they are on average more diverse.

Figure 5 and Table 9 thus reveal an inverted U-shaped relationship between MA-size and mean household car emissions.[61] To understand the causes of this bell shape, we separate the

[61] Calculated from the Heckman estimates in Table 6. The results are qualitatively similar with OLS and 2SLS.

Figure 5: MA-size and the CO_2 'carprint' of the sample-mean household (kg/year)



effects of the 3 D's in our estimations.[62]

We find that Density has a strong negative linear effect on fuel consumption, as has commonly been found in the economic literature since Newman & Kenworthy (1989): larger MA populations translate into a higher density and larger car-emission savings.

The effect of Design is much more diverse. The smallest MAs are usually more pedestrian-friendly (a high fractal dimension) and have a good job-housing balance. However, as commuting distances and the road stock rise with MA size, driving first increases with city population. However, above the 300,000 inhabitant threshold, the development of public transport compensates for the other effects and generates drastic savings in car emissions, while ultimately the filling-in of empty spaces via urban-planning strategies may lead to greater walkability in large cities. Design generates an inverted U-shaped relationship between car emissions and city-size that was not documented in the existing literature.

The impact of Diversity varies in small MAs, depending on their existing sectoral specialization.[63] However, large MAs have high sectoral diversity that leads to lower carbon emissions from driving.

This confirms that, in small cities, households do not drive much either because of the good job-housing balance or the relatively low road stock. Design therefore compensates for the driving incentives stemming from low densities. As cities grow, trips become longer due to the

[62]Appendix E Figure 8 summarizes these findings.

[63]Even is this is not systematic, as small isolated MAs often have high sectoral diversity. Medium MAs are thus the least-diverse from this point of view. This reinforces the inverted U-shape resulting from Design.

Table 9: MA-size and the CO_2 'carprint' of the sample-mean household: estimations

CO_2 car emissions	OLS coefficients	(Std. Dev.)
Log(MA-size)	696.8***	(148.4)
Log(MA-size)^2	-32.9***	(6.5)
Constant	-357.7	(838.9)
Observations	352	
R-squared	0.112	

Notes: Standard errors in parentheses: ***p<0.01.

expansion of road networks and longer commuting distances, until public transit becomes sufficiently widespread to curb car emissions. Overall, the threshold at which French MAs can achieve a low-carbon 'carprint' is around 100,000 inhabitants.[64] 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.

4 Conclusion

While personal driving accounts for a rising percentage of GHG emissions, we have shown that there exist exciting opportunities for urban policies to curb these emissions: low-density neighborhoods far from job centers, with poor public transport, morphological homogeneity and a lack of urban diversity increase car-related emissions.

Increasing the Density of new residential developments, in inner cities or at the urban fringe of metropolitan areas where most new developments take place, may thus significantly reduce household carbon 'carprints' and manage cities more efficiently. We estimate that doubling residential density would result in roughly two fewer fuel tanks per year per household, over and above any effect from changes in income, employment status, occupation, education and family composition, and, more generally, residence selection. Even though these savings are small, they can be considerably enlarged when coupled with better access to job centers, improved public transort, reduced pressure for road construction and the strategic infill of empty spaces (a more 'fractal' development), which play a prominent role in car-emission reductions. Although compactness alone might not reduce emissions as much as other mitigating policies such as carbon taxes, an urban-policy package combining Densification with better Design and more Diversity can provide an excellent foundation for low-carbon cities in France. In this respect, we provide

[64]As shown in Table 17 and Figure 7 in Appendix D, this bell-shape is not driven by the two tails of the MA distribution, as it still holds when Paris and Volmerange-les-Mines are excluded from the sample.

quantitative arguments to back the "Smart City" ideals of integrated sustainable urban development.

The sharp spatial disparities in those 3 D's across the urban space in France produce notable geographic differences in car emissions across French cities, even for observationally-equivalent households. For instance, households with cars in inner Chamonix, the Alps' largest ski resort, produce around 80% more car emissions - about $1,650$ more CO_2 kg per year - than an equivalent household in inner Paris.

CO_2 emissions in French cities are bell-shaped in population, as opposed to the linear pattern found in most existing US work. Therefore, beyond the slogan promoting the ecological advantages of large compact cities, we show that there are also large potential energy savings in low-density small cities, which may spontaneously be as 'smart' as their large heavily-engineered counterparts. Conversely, medium cities - with around 100,000 inhabitants - may require more particular attention from policy-makers.

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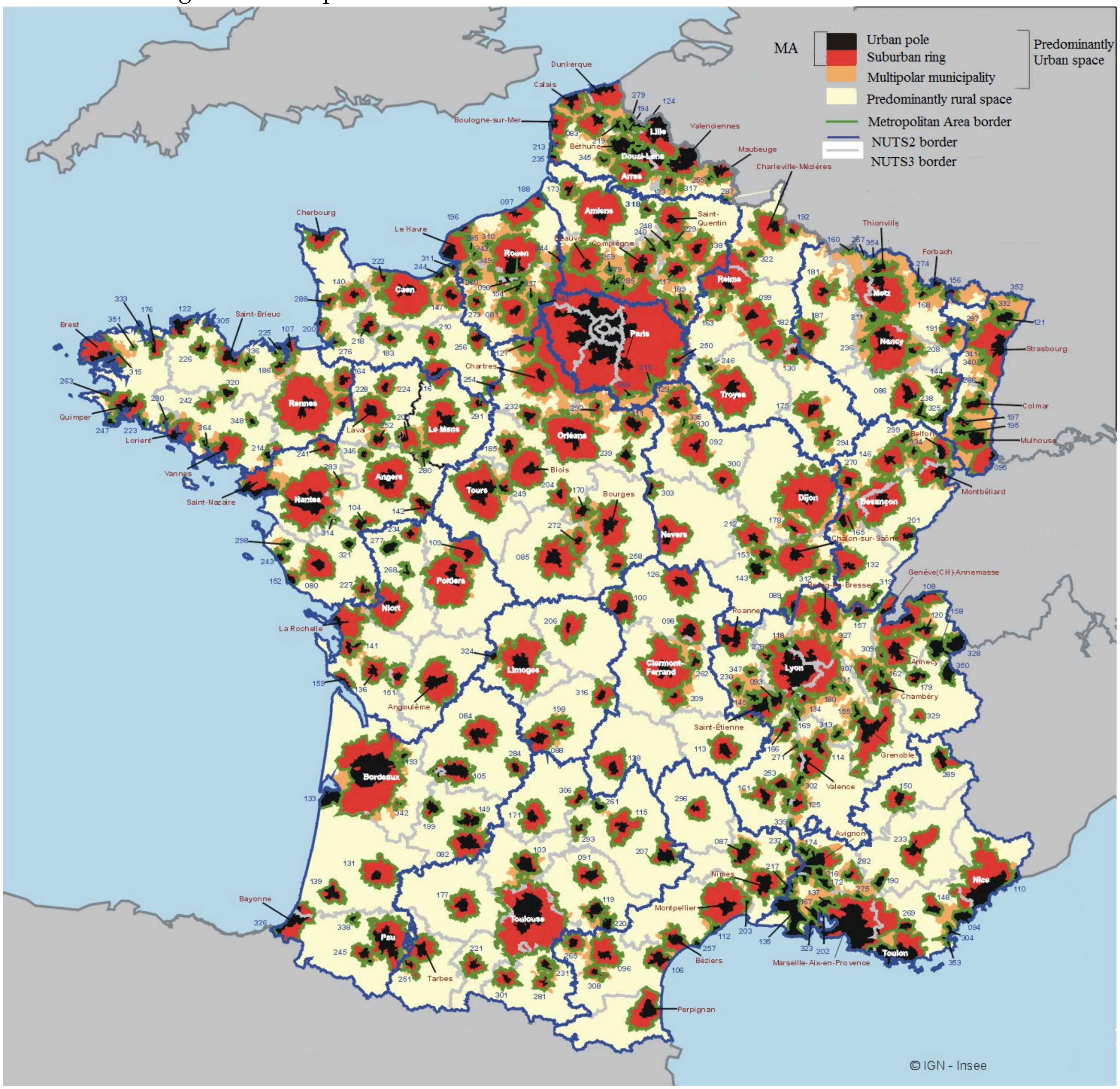
APPENDIX

A French Metropolitan Areas

Figure 6: Metropolitan Areas in mainland France in 2001 and 2006



B Fractality

B.1 What is fractality?

The underlying hypothesis, albeit never explicit, behind the use of density as an explanatory variable is that the urban fabric is homogeneous enough to be described by a mean value. This 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 (1982) coined the term 'fractal' to qualify intrinsically irregular objects where mass is not evenly distributed.[65] He 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,[66] 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 $D = \lim\limits_{a_n \to 0} \frac{log(N(a_n))}{log(1/a_n)}$.

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,[67] 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, $\frac{log(N(a_n))}{log(1/a_n)} = \frac{log(L)+log(1/a_n)}{log(1/a_n)} \underset{n\to+\infty}{\longrightarrow} 1$.
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, $\frac{log(N(a_n))}{log(1/a_n)} = \frac{2\cdot log(L)+2\cdot log(1/a_n)}{log(1/a_n)} \underset{n\to+\infty}{\longrightarrow} 2$.

The formula for the Minkowski-Bouligand dimension coincides with the geometric dimension for classical objects.

[65] Mandelbrot (1982) uses a powerful metaphor to explain why geometric measures such as length, surface or density lose most of their descriptive power for such irregular objects. For instance, it is difficult to calculate the length of the Britanny coast, as it is crawling with small irregular creeks. The contour of maps of Brittany printed at very different scales 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.

[66] See the comprehensive study of Schroeder (1991).

[67] For instance, $A = 1$ for a square and $A = \pi$ for a disk.

The fractal dimension can vary continuously from 0 to 2.

- If $D < 1$, we have a collection of unconnected points: mass is concentrated in occasional rare objects (typically scarce farms in rural areas);
- If D is close to 1, we have objects organised along a pattern of lines (typically a road-village);
- If D is between 1 and 1.3, we have a collection of sparse clusters (typically a leapfrogging residential city);
- If D is from 1.3 to 1.6, we have a continuous fabric of buildings separated by large spaces (typically housing complexes such as French 1960's *Grands Ensembles*);
- If D is from 1.6 to to 1.8, we have attached housing separated by large streets (for instance, the *Haussmannian* style of central Paris);
- If D is close to 2, the object covers the geographic map quasi-homogeneously (buildings separated by very tiny streets and courtyards, such as the inner historical center of central Paris).

B.2 The box-counting algorithm

The best numerical calculation of the Minkowski-Bouligand fractal dimension comes from the box-counting algorithm in Liebovitch & 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:

$$log\left(N(a_n)\right) \approx log(A) + D \cdot log(a_n) = \alpha + D \cdot log(a_n) + \epsilon_n.$$

We can then can 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 Additional regression results

Table 10: Household fuel consumption and urban form (without Diversity): OLS estimations

Dependent Variable: Fuel consumption (gallons)	Urban households		Motorized urban households	
	(1)	(2)	(3)	(4)
HOUSEHOLD CHARACTERISTICS				
Log(Total income/CU)	70.5***	71.8***	62.0***	64.3***
	(4.13)	(4.34)	(5.15)	(5.22)
Number of working adults	113.2***	112.8***	104.3***	103.1***
	(13.45)	(13.55)	(13.78)	(13.70)
Number of non-working adults	70.0***	70.0***	69.8***	69.4***
	(7.91)	(8.10)	(8.69)	(8.82)
Number of young children (<16 years)	8.0***	7.5***	3.4	3.0
	(2.77)	(2.85)	(3.05)	(3.15)
Age (Head of household)	3.7***	3.6***	4.3***	4.2***
	(0.69)	(0.75)	(0.92)	(0.97)
Age-squared (Head of household) / 100	-5.5***	-5.4***	-6.7***	-6.5***
	(0.54)	(0.55)	(0.84)	(0.87)
Female (Head of household)	-39.1***	-37.1***	-32.2***	-30.2***
	(7.98)	(8.50)	(10.63)	(11.28)
DENSITY				
Log(Density of pop. in residence)	-13.8***	-12.4**	-11.8***	-11.1*
	(4.26)	(5.06)	(4.41)	(5.68)
DESIGN				
Log(Distance from residence to CBD)	12.7***	14.4**	10.7**	13.2*
	(4.16)	(5.65)	(4.47)	(6.91)
Log(Density of pub. transit in residence)	-9.8***	-9.6**	-8.4**	-6.2
	(3.06)	(4.21)	(3.39)	(4.69)
Fractal dimension in residence	-88.3**	-106.7**	-90.0**	-99.6**
	(37.54)	(46.62)	(36.21)	(48.59)
Log(Road potential in the rest of the MA)	20.3***	38.0	19.3**	16.6
	(7.38)	(33.10)	(7.62)	(33.87)
Log(Rail potential in the rest of the MA)	-60.2***	-95.1***	-51.1***	-80.0***
	(10.26)	(24.29)	(11.36)	(24.71)
Education dummies (Head of household)	✓	✓	✓	✓
Occupation dummies (Head of household)	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓
MA fixed effects		✓		✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.250	0.156	0.177

Notes: (i) OLS estimates from Dquation (4); (ii) Robust standard errors in parentheses (at the MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) For the sake of clarity, neither the constant nor the education or occupation 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).

Table 11: Household fuel consumption and urban form (with average distance): OLS estimations

Dependent Variable: Fuel consumption (gallons)	Urban households	Motorized urban households
	(1)	(2)
HOUSEHOLD CHARACTERISTICS		
Log(Total income/CU)	68.3***	59.6***
	(4.26)	(5.47)
Number of working adults	111.7***	102.5***
	(14.16)	(14.59)
Number of non-working adults	68.1***	67.9***
	(8.13)	(9.03)
Number of young children (<16 years)	8.6***	3.9
	(2.84)	(3.08)
Age (Head of household)	3.4***	4.0***
	(0.68)	(0.92)
Age-squared (Head of household) / 100	-5.2***	-6.3***
	(0.53)	(0.85)
Female (Head of household)	-40.7***	-33.6***
	(8.00)	(10.52)
DENSITY		
Log(Density of pop. in residence)	-12.4***	-8.6**
	(4.01)	(4.33)
DESIGN		
Log(Average distance from residence to jobs)	42.1***	43.9***
	(11.23)	(12.84)
Log(Density of pub. transit in residence)	-9.5***	-8.2**
	(3.00)	(3.38)
Fractal dimension in residence	-100.8***	-95.4***
	(37.28)	(35.39)
Log(Road potential in the rest of the MA)	20.9***	17.8***
	(6.86)	(6.76)
Log(Rail potential in the rest of the MA)	-50.4***	-40.8***
	(9.04)	(9.90)
DIVERSITY		
Herfindahl index in residence	24.9	32.7**
	(15.29)	(15.67)
Education dummies (Head of household)	✓	✓
Occupation dummies (Head of household)	✓	✓
Year fixed effects	✓	✓
Observations	14,801	12,132
R-squared	0.240	0.160

Notes: (i) OLS estimates from equation (4); (ii) Robust standard errors in parentheses (at the MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) For the sake of clarity, neither the constant nor the education or occupation 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).

Table 12: Household fuel consumption and urban form: First-stage regressions

Endogenous variable	Population density	Distance to CBD
	(1)	(2)
Log(Density of deaths in 1962)	0.49***	-0.07**
	(0.03)	(0.03)
Log(Distance to the largest municipality of the MA in 1806)	0.02	0.54***
	(0.01)	(0.04)
Log(Road potential in the rest of the MA)	0.24***	0.05
	(0.03)	(0.10)
Log(Rail potential in the rest of the MA)	-0.08^{+}	0.19*
	(0.05)	(0.10)
Log(Density of pub. transit in the residence)	0.16***	0.03
	(0.02)	(0.04)
Fractal dimension in the residence	1.70***	-0.40**
	(0.23)	(0.18)
Herfindahl index in the residence	-1.09***	-0.10^{+}
	(0.14)	(0.06)
Household characteristics	✓	✓
Year fixed effects	✓	✓
Observations	14,801	14,801
F-stat	173	430

Notes: (i) Robust standard errors in parentheses (at the 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 the constant nor their 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), DADS (2001 and 2006), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

Table 13: Household fuel consumption and urban form: further 2SLS estimations

Dependent Variable: Fuel consumption (gallons)	Urban households		
	(1)	(2)	(3)
	OLS	2SLS	2SLS
DENSITY			
Log(Density of pop. in residence)	-11.3**	-11.4**	-12.6**
	(4.53)	(5.72)	(5.76)
DESIGN			
Log(Distance from residence to CBD)	14.7***	25.1***	23.8***
	(3.88)	(5.47)	(4.83)
Log(Density of pub. transit in residence)	-9.7***	-8.1***	-7.9***
	(3.03)	(2.87)	(2.92)
Fractal dimension in residence	-89.6**	-52.9	-51.4
	(39.67)	(44.46)	(45.28)
Log(Road potential in the rest of the MA)	17.6**	11.4^{+}	12.3*
	(7.57)	(7.46)	(7.12)
Log(Rail potential in the rest of the MA)	-59.4***	-59.7***	-59.3***
	(10.14)	(8.89)	(9.06)
DIVERSITY			
Herfindahl index of leisure in residence	28.5*	29.3*	27.5*
	(15.33)	(15.37)	(15.09)
Household characteristics	✓	✓	✓
Year fixed effects	✓	✓	✓
INSTRUMENTS			
Density of deaths in 1962		✓	✓
Distance to the largest municipality in the 1806 MA		✓	✓
Market Potential in 1936			✓
Observations	14,801	14,801	14,801
R-squared	0.234	0.165	0.165
Cragg-Donald F-Stat		5,777	4,935
Shea Partial R-squared (log density)		0.46	0.50
Shea Partial R-squared (log distance to CBD)		0.53	0.61
Hansen J Statistic (p-value)			0.34 (0.56)

Notes: (i) Robust standard errors in parentheses (at the 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 the constant nor these 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), DADS (2001 and 2006), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

Table 14: Household fuel consumption and urban form (without Diversity): Causal estimations

Dependent Variable: Fuel consumption (gallons)	Urban households		Heckman two-step	
	OLS	2SLS	Heckit	dx/dy Probit
	(1)	(2)	(3)	(4)
DENSITY				
Log(Density of pop. in residence)	-13.8***	-12.5***	-13.3***	-0.014***
	(4.26)	(5.14)	(4.07)	(0.004)
DESIGN				
Log(Distance from residence to CBD)	12.7***	23.3***	15.0***	0.014***
	(3.88)	(5.47)	(4.51)	(0.004)
Log(Density of pub. transit in residence)	-9.8***	-8.5***	-12.1***	-0.011***
	(3.06)	(2.86)	(3.64)	(0.003)
Fractal dimension in residence	-88.3**	-62.2^{+}	-106.8***	-0.105***
	(37.54)	(41.42)	(31.10)	(0.028)
Log(Road potential in the rest of the MA)	20.3***	14.3*	23.0***	0.020***
	(7.38)	(7.42)	(6.44)	(0.006)
Log(Rail potential in the rest of the MA)	-60.2***	-61.2***	-70.3***	-0.076***
	(10.26)	(9.21)	(10.52)	(0.008)
Household characteristics	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609
R-squared	0.234	0.165		
Cragg-Donald F-Stat		5,731		ρ : 0.46
Shea Partial R-squared (log density)		0.44		σ : 298
Shea Partial R-squared (log distance to CBD)		0.54		λ : 138

Notes: (i) Robust standard errors in parentheses (at the 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, 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 constant nor these coefficients are shown; (iv) The instruments are mortality density in 1962 (in log) and the distance to the largest municipality in the MA in 1806 (in log).
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), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

Table 15: Greenest MAs: CO_2 'carprint' of the mean household with Corrected Income (kg/year)

Name	OLS pred.	Rank	2SLS pred.	Rank	Heckit pred.	Rank	MA pop.
Paris	2,195	1	2,199	1	2,123	1	11,769,424
Lille	2,521	3	2,537	4	2,436	2	1,164,717
Caudry	2,523	4	2,511	3	2,449	3	14,322
Fourmies	2,376	2	2,361	2	2,304	4	16,324
Saint-Etienne	2,685	7	2,709	10	2,607	5	318,993
Nancy	2,748	8	2,717	7	2,679	6	415,765
Montereau-Fault-Yonne	2,694	6	2,667	6	2,624	7	26,109
Bolbec	2,580	5	2,546	5	2,494	8	15,750
Noyon	2,640	10	2,584	8	2,566	9	22,553
Lunéville	2,672	11	2,624	9	2,597	10	27,549
Le Havre	2,675	9	2,686	15	2,615	11	290,826
Tergnier	2,770	13	2,750	12	2,706	12	23,383
Lyon	2,831	14	2,832	19	2,760	13	1,748,274
Villerupt	2,565	17	2,518	14	2,467	14	19,019
Saint-Quentin	2,750	12	2,717	11	2,703	15	101,438
Hendaye	2,792	25	2,774	25	2,689	16	14,993
Fécamp	2,754	16	2,712	13	2,689	17	30,233
Strasbourg	2,839	19	2,853	24	2,786	18	638,672
Reims	2,843	18	2,837	20	2,795	19	293,316
Boulogne-sur-Mer	2,779	15	2,751	16	2735	20	133,195
Sète	2,780	22	2,839	38	2,705	21	73,674
Provins	2,725	24	2,693	22	2,631	22	22,320
Chauny	2,608	23	2,569	18	2,519	23	22,117
Calais	2,709	20	2,705	23	2,646	24	125,525
Grenoble	2,891	26	2,889	31	2,824	25	531,439

Table 16: Dirtiest MAs: CO_2 'carprint' of the mean household with Corrected Income (kg/year)

Name	OLS pred.	Rank	2SLS pred.	Rank	Heckit pred.	Rank	MA pop.
Bourg-Saint-Maurice	3,732	352	3,681	352	3,743	352	10,357
Sarlat-la-Canéda	3,700	351	3,651	350	3,674	351	18,022
Annemasse	3,683	350	3,666	351	3,660	350	244,178
La Bresse	3,495	347	3,481	346	3,446	349	12,851
Ancenis	3,690	349	3,648	348	3,650	348	19,308
Lannion	3,665	346	3,642	344	3,660	347	63,425
Chamonix-Mont-Blanc	3,599	344	3,600	345	3,575	346	13,127
Les Herbiers	3,687	348	3,669	347	3,650	345	14,833
La Roche-sur-Yon	3,621	345	3,635	349	3,592	344	107,584
Bressuire	3,577	343	3,566	343	3,548	343	18,225
Sablé-sur-Sarthe	3,502	342	3,465	341	3,457	342	30,193
Aubenas	3,560	341	3,493	336	3,541	341	44,546
Livron-sur-Dromme	3,558	339	3,519	339	3,525	340	16,662
Sallanches	3,585	340	3,594	342	3,547	339	43,413
Loudéac	3,543	337	3,508	337	3,503	338	14,217
Ploërmel	3,550	338	3,497	334	3,507	337	11,450
Tulle	3,537	332	3,469	320	3,521	336	31,693
Cluses	3,585	336	3,571	338	3,555	335	65,442
Privas	3,567	335	3,489	319	3,529	334	21,267
Quimper	3,543	331	3,556	340	3,522	333	129,110
Mayenne	3,478	333	3,431	331	3,420	332	26,361
Louhans	3,552	334	3,519	335	3,494	331	15,598
Saintes	3,517	329	3,485	330	3,480	330	55,834
Châteaubriant	3,487	328	3,456	327	3,446	329	23,562
Saint-Gaudens	3,494	327	3,426	311	3,467	328	27,298

D Complementary results

Figure 7: MA size and the CO_2 'carprint' of the sample mean household (kg/year, Paris and Volmerange excluded)

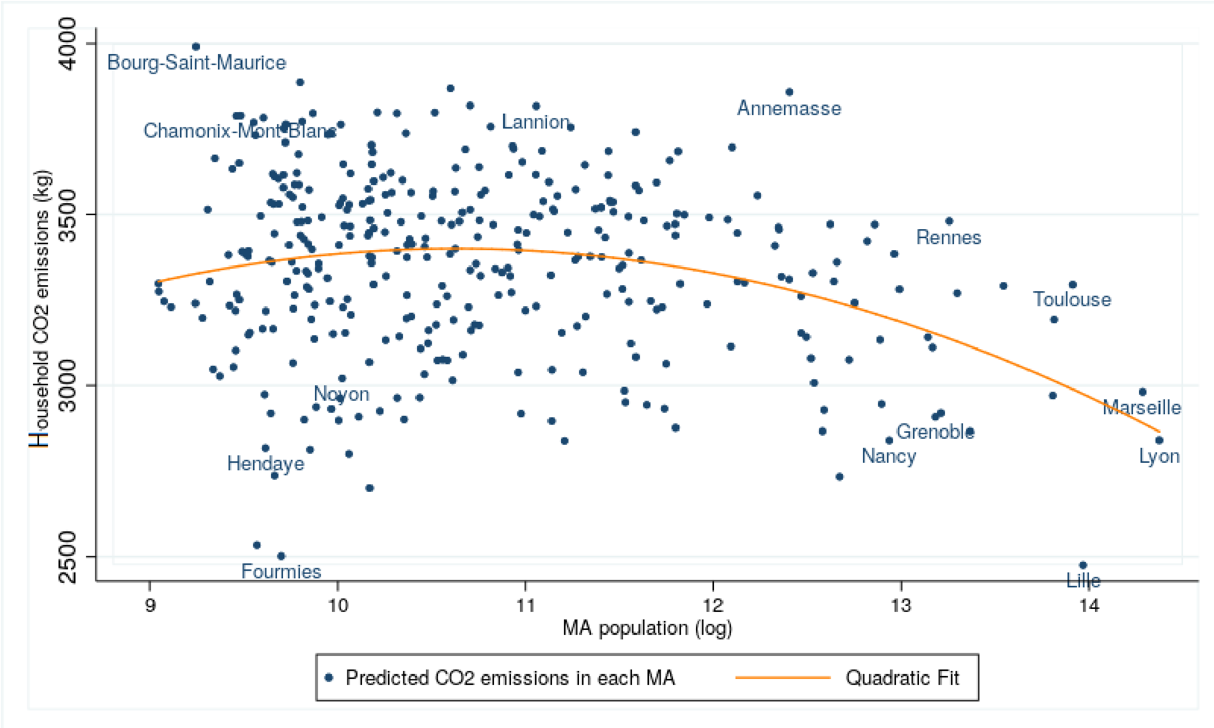


Table 17: MA size and the CO_2 'carprint' of the sample mean household (Paris and Volmerange excluded)

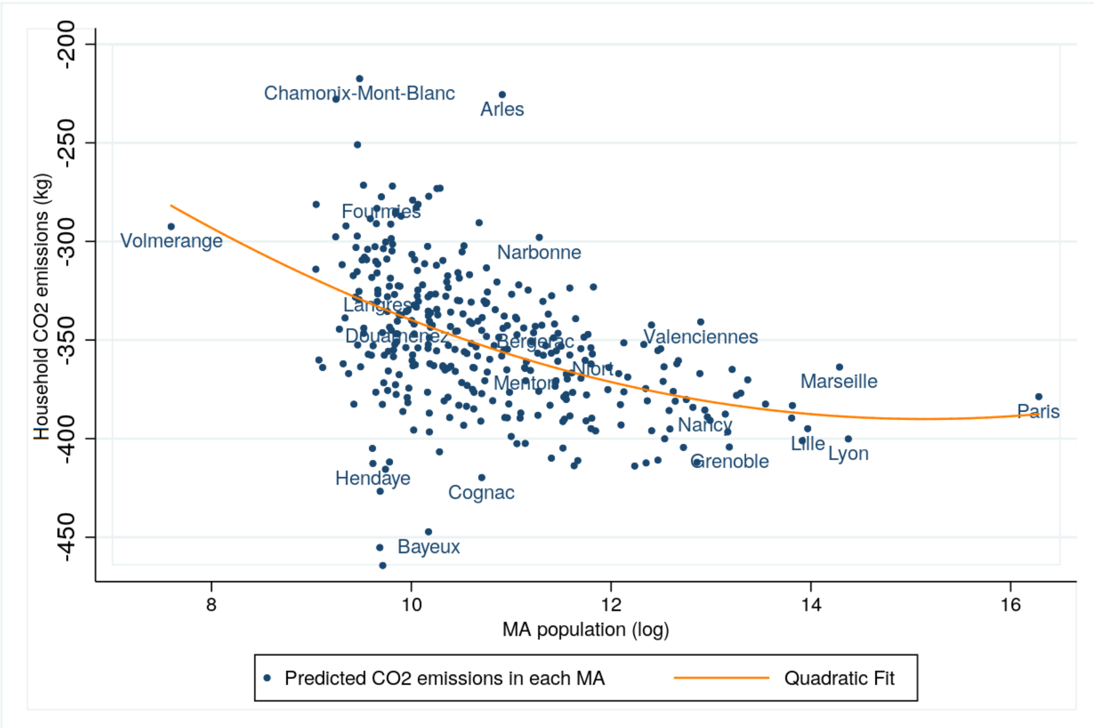
Dependent Variable: Car CO_2 emissions	OLS coefficients	(Std. Dev.)
Log(MA-size)	729.0***	(204.1)
Log(MA-size)^2	-34.1***	(9.1)
Constant	-561.4	(1141.0)
Observations	350	
R-squared	0.06	

Notes: Standard errors in parentheses: ***p<0.01.

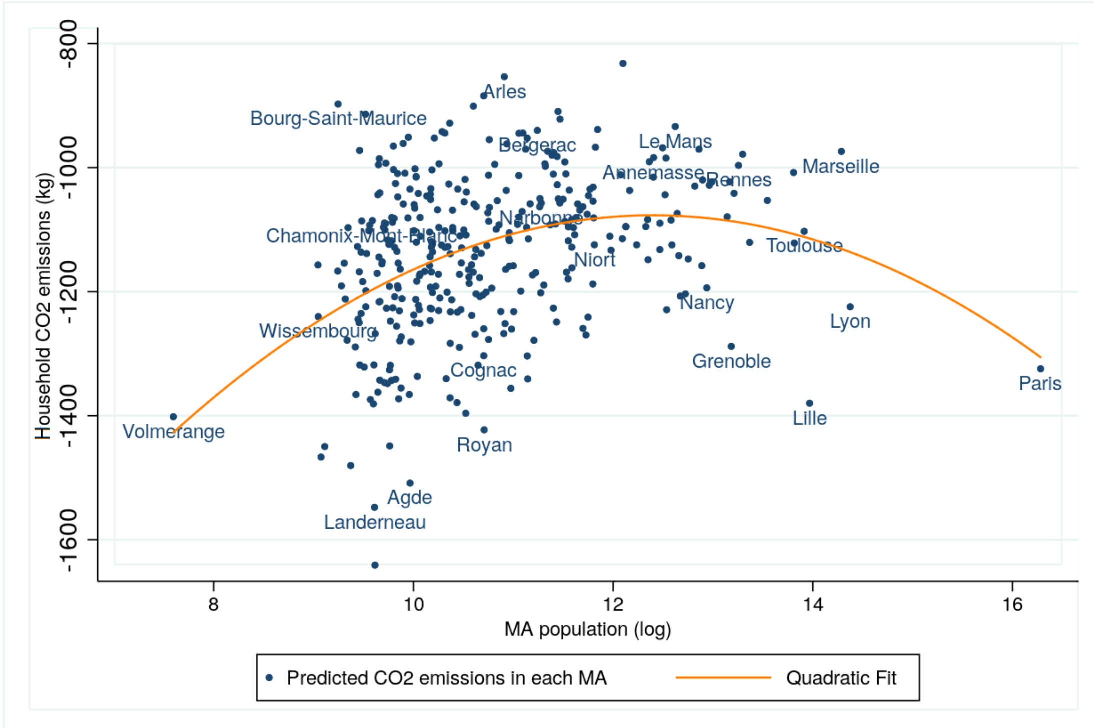
E The car-emission effects of each dimension of urban sprawl

Figure 8: MA size and the car CO_2 emissions associated with each of our 3 D's

The Density channel



The Design channel



The Diversity channel