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

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Abstract

This paper investigates the impact of urban form on households' fuel consumption and car emissions in France. We analyze more particularly three features of cities commonly referred to as the '3 D's' (Cervero & Kockelman 1997): Density, Design and an innovative measure of Diversity. Individual data allow us to circumvent sorting, as some households may live in a location consonant to their socioeconomic characteristics or travel predispositions, while instrumental variables help control for other endogeneity issues. The results suggest that, by choosing to live at the fringe of a metropolitan area instead of its city-center, our sample mean-household would bear an extra-consumption of approximatively six fuel tanks per year. More generally, doubling residential Density would result in an annual saving of approximatively two tanks per household, a gain that would be much larger if compaction were coupled with better Design (stronger jobs centralization, improved rail-routes or buses transiting to job centers and reduced pressure for road construction), and more Diversity (continuous morphology of the built-up environment). Another important finding is that the relationship between metropolitan population and car emissions is bell-shaped in France, contrary to the US, which suggests that small cities do compensate lack of Density by either a better Design or more Diversity.

JEL codes: Q41, R11, R20, R41.

Keywords: Sprawl, car emissions, CO_2 footprint, 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

In the context of global warming, the mitigation of CO_2 emissions is of growing political concern. Carbon reduction policies are generally thought at the macroeconomic level, but Glaeser & Kahn (2010) have advocated that local policies could interestingly complement a global climate policy such as a carbon tax. GreenHouse Gas (GHG hereafter) emissions in developed countries are indeed increasingly driven by private energy consumption, especially car emissions, and less so by industrial activities. In this context, urban planning may help public authorities to curb GHG emissions down and promote a more sustainable development. This paper analyses the interplay between car emissions and urban form in France, with a particular focus on counteracting forces to sprawl conveyed by public transit systems and urban morphology.

Urban economic theory has long underscored the fundamental trade-off whereby households make choices between residential areas by taking into account the price of housing and the price of commuting between workplace and home (Fujita 1991). When population grows, income reaches a certain level and travel costs fall below a certain threshold, people tend to live farther away from city-centers either to save housing costs or to have more spacious houses. As new land developments are more likely to occur in those low-density areas, the urban surface increases at a faster rate than the population is growing, which ultimately fosters sprawl.

Since the mid-1950s, many factors have triggered the decline of travel costs in industrialized countries: decades of low energy prices, enhanced mobility provided by the automobile revolution, massive investments in highway networks... As post-war baby-booms and income-booms were sustaining growth, low-density residential suburbanization became the dominant urban expansion process in many countries.[1] As underlined by Brueckner (2000), urban growth occurring in response to these fundamental forces cannot be faulted as socially undesirable, unless market failures distort the operation. Yet, sprawling cities create harmful impacts in relation to a variety of socioeconomic and environmental issues. The dispersed automobile-dependent development patterns have come at the costs of substantial consumption of non-renewable resources, loss of soil bio-diversity and reductions of carbon sinks, transport congestion or exacerbations of urban segregation and spatial mismatch. More importantly for the purpose of this paper, sprawl has also lengthened the vehicle-miles traveled by suburbanites, which contributes to fuel global warming through a rise in car-related emissions.

Such adverse effects of suburbanization and car dependence have long been evident. But they are currently of particular concerns for several reasons. First, the transport sector, especially

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

the road sector, is a significant and increasing contributor to GHG emissions in most countries, summing up to 24% of CO_2 emissions worldwide in 2015,[2] and for over half of those emissions growth over 1990-2015 (International Energy Agency 2017).[3] Since the urban form affects driving patterns and since driving is an increasing emitter of CO_2, the transport-related energy consumption of cities is of growing concern for urban research.

Newman & Kenworthy (1989) were the first to draw worldwide attention to the relationship between urban form and fuel consumption. In their cross-comparison of 32 cities worldwide, they have shown that per capita gasoline consumption was far higher in US cities than abroad, a fact they attributed to one particular feature of US cities relatively to others: lower density. However, it remains hazardous to extrapolate policy recommendations from their analysis, since there exists substantial socioeconomic differences across countries that may correlate with density, such as income levels, land regulation or 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 host a disproportionate share of low-income residents, elderly or very young people, who are less able to afford owning and operating a car. By way of contrast, US suburban outskirts host a disproportionate share of families or income groups with high levels of car ownership and travel demands for jobs, education or extra-curricular events. Obviously, if fuel consumption is caused by households intrinsic preferences for housing or travel, any attack against urban sprawl could be misguided, with few benefits to expect from compacting cities, since people may not behave differently in denser conurbations.

Over the past thirty years, a large body of empirical research has been conducted to evaluate the causal impact of urban form on travel demand, which we will not try to summarize here.[4] However, we are still left with conflicting policy recommendations, as sprawl is made 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 come 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.[5] Conversely, Brownstone & Golob (2009) argue that, in California, the impact of density would not be large enough to justify a compaction policy, as a slight reduction in fuel consumption would require unrealistic extensions of the housing stock or cramming people in an unthinkable manner. More recently, Duranton & Turner (2018) also assert that densification policies would not be as effec-

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

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

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

[5]Zheng et al. (2011) provide the same kind of analysis for Chinese cities.

tive as gas taxes or congestion charges to decrease aggregate driving in US cities.

If the environmental costs of urban sprawl have been extensively investigated in North-America, this is not the case in Europe. Yet, since the mid-1950s, European cities have expanded their surface area by 80%, whereas the European population grew by only 30%. In France, during the last decade, the surface area of the urban space has increased by an unprecedented rate of 20% (INSEE 2013). Metropolitan areas now cover 50% of the surface of mainland France, against only 30% a decade ago. In this context, a first contribution of our paper is to extend the body of research to Europe, where the impact of sprawl on car emissions has been seldom investigated. Within Europe, a special focus on France is of strong interest for two reasons. First, French cities exhibit two emblematic characteristics that most of their American counterparts lack: (i) they have extended public transit networks offering credible car-alternatives to households, even to suburbanites located very far away from city-centers, (ii) and they vary greatly in their urban morphology, due to strong spatial differences in historical heritage and urban planning. French travel behaviors and modal choices differ thus drastically from US ones.

Second, there is an especially strong social resistance to the implementation of transport-related carbon taxes in France.[6] Nevertheless, France committed to reducing transport emissions by 14% over 2005-2020, under the European energy-climate package. Still, road transport remains excluded from the EU Emissions Trading System, the cornerstone of the European policy to reduce GHG, though external costs associated with burning diesel largely exceed excise taxes levied on this fuel in France.[7] In this context, the urban spatial structure remains a key tenet for policy makers, as it provides them with greater leeway to curb carbon emissions down through spatial policies affecting land, housing and commuting patterns (Borck & Brueckner 2018).

Another important contribution of our paper is to study the impact on driving of a large set of urban form measures, among which an indicator of morphology never used so far, in combination with Heckman and IV strategies that allow us to tackle sorting and other endogeneity issues better than most previous studies. We analyze more particularly the influence of three broad dimensions of the urban form referred to as the '3 D's': 'Density', 'Design' and 'Diversity' (Cervero & Kockelman 1997). The Density of residents or jobs has been the most extensively studied feature of the built-environment, as it is an essential dimension of urban development. The spatial Design of cities has been less investigated, but a subsequent amount of papers consider that job accessibility and transport networks are the cornerstone of this second important urban dimension. Diversity remains by far the less systematically explored determinant of driving behaviors, and a few papers capture this dimension through indicators such as jobs-to-housing ratios, entropy measures of land-use mix or streets density. In this paper, we

[6] The recent attempt of the French government to levy a highway toll on heavy vehicles (the 'eco-tax') has generated violent social turmoil. In October 2013, the 'red caps' movement of the farmers of French Brittany has been the cornerstone of resistance against the willingness to price externalities related to fuel use more adequately. This reluctance spurred French authorities to shelve the 'eco-tax' sine die in October 2014.

[7] For an estimation of how much it is undertaxed, see for instance the OECD Economic Survey on France (2015): https://www.oecd.org/eco/surveys/France-2015-overview.pdf.

resort to an innovative and original measure of Diversity: the fractal dimension of cities, that enables us to capture potentially strong spatial disparities in city morphologies due to either historical heritage or differences in urbanism practices.

Finally, our ultimate contribution regards new policy insights that can be drawn from studying these 3 D's jointly in France. Our results suggest that, by choosing to live at the fringe of a metropolitan area instead of its city-center, the mean household of our data-sample would bear an extra-consumption of approximatively six fuel tanks per year. More generally, doubling residential Density would result in an annual saving of approximatively two tanks per household, a gain that could be much larger if compaction were coupled with a better Design - namely stronger job centralization, improved rail-routes or buses transiting to job centers and reduced pressure for road construction - and increased Diversity conveyed by a more homogeneously built-up environment. Another important finding is that the relationship between metropolitan population and car emissions is not linear in France, contrary to the US. In small French cities, households do not drive much either because of job centralization or because of a relatively low pressure for road construction. Therefore, Design counteracts driving incentives stemming from low densities. As cities grow, trips become longer due to extensive road networks and longer commuting distances, until population is large enough to sustain mass public transit likely to curb car emissions down. The tipping point whereby French cities can or cannot achieve a low-carbon 'carprint' is around 100,000 inhabitants.

The remainder of the paper is structured as follows: Section 1 describes the data used. Section 2 introduces our empirical strategy and outlines our main results. Section 3 computes the car emissions drawn from our estimates, ranks French cities with respect to those emissions, and investigates whether there exists a "sub-optimal" city-size. Section 4 concludes.

1 Data on fuel consumption and urban form

Our empirical work relies upon confidential household micro-data and different indicators of the urban form combining elements of residential density, metropolitan design and morphological diversity.

1.1 Fuel consumption: a household measure

To measure fuel consumption, we resort to the French household survey 'Budget des Familles' (Family Budget, hereafter BdF). This survey has been conducted every five years since 1972 by The French National Statistical Office (hereafter INSEE), and it is aimed at putting together the entire accounts, i.e. expenditures and resources, of a representative sample of households living in French municipalities.[8] We restrict our empirical analysis to the 2001 and 2006 survey issues for two reasons. First, historical topographic data in vectorized format dates back to 1999 in

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

France. It is therefore difficult to characterize precisely the urban environment of French households before this date. Moreover, since 2011, budgetary restrictions led the INSEE to reduce drastically the time coverage of the BdF survey, which resulted in large censoring issues for several 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, on more than 10,000 households (equivalent to 25,000 individuals) per year. The BdF surveys build on two data-collection instruments:

Questionnaire First, a questionnaire using computer-assisted data collection (broken down over 3 visits) records all the household resources over the last twelve months, which include regular resources (wages, independent earned income...), extraordinary revenues (gifts, lottery, inheritance...) and other incomes (such as transfers from relatives). It also records a rich set of household characteristics: municipality of residence,[9] family composition (number of children, workers, job seekers or retired people) and educational attainment,[10] occupation,[11] age and gender of all members of the household.

Self-completed diary Second, all members of the household over 14 years-old are asked to record in a self-completed diary their detailed expenditure over two weeks. They can write the amounts in by hand, or attach cash register receipts. All current expenditure is covered and broken down into 900 budgetary items (food products, beverages, tobacco, clothing and footwear, furnishers...), including expenses that are not associated with the consumption of goods and services (rents, taxes, insurance premiums, loan repayments...).[12] More importantly for this paper, households report their fuel expenditure, broken down into three items: gasoline, diesel and Liquefied Petroleum Gas (hereafter LPG). We use the French average price of each type of fuel in 2001 and 2006 to convert these expenses into volumes.[13]

Table 1 reports descriptive statistics on the main variables drawn from the BdF surveys. To measure income, we sum the resources (whatever they are) of all individuals in the house-

[9] This information is submitted to statistical disclosure. French public authorities waived the rights to confidentiality and gave us access to the geo-coded version of the data.

[10] The classification of diplomas is the following: 1. Doctorate, post-graduate or 'Grande Ecole', 2. University postgraduate degree (Licence or Master), 3. University undergraduate degree (DEUG), 4. University professional degree, 5. Nursing and social training courses, 6. General bachelor degree, 7. Technological bachelor degree, 8. Professional bachelor degree, 9. High-school technician degree, 10. High-school professional degree and apprenticeship, 11. High-school general degree, 12. Primary school, 13. Without diploma.

[11] Occupations are disentangled 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 or non-working people who were never employed.

[12] The BdF survey collects essentially monetary data, but also includes specialized sub-surveys on some items (like transport, housing, leisure, holidays) to produce a more qualitative approach to household behavior.

[13] This will allow us to compute car emissions as it is possible to transform volumes into CO_2 emissions with conversion factors provided by the French Ministry for an Ecological and Solidary Transition (see Section 3). Since spatial variation in fuel prices is very low compared to variations across gas stations of different brands in France, using national instead of local prices to compute car emissions only entails slight measurement error. See for instance https://www.prix-carburants.gouv.fr/.

hold and divide this total by the number of Consumption Units (hereafter CU).[14] In the original BdF surveys, fuel consumption is measured in litres, but for comparisons purposes with North-American studies, we convert these figures in US gallons.[15] One fuel tank being typically 50 litres in France (approximately 13 gallons), yearly mean fuel consumption is about 20 tanks in France.

Table 1: Descriptive statistics on fuel consumption and households' characteristics

Year	2001		2006	
Household variables	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
Gasoline expenditures (€2006)	686 (1024)	11,400	487 (861)	9,634
Diesel expenditures (€2006)	404 (819)	12,556	567 (988)	17,603
LPG expenditures (€2006)	4 (81)	2565	4 (77)	2,820
Volume gasoline (litres)	641 (957)	10,654	390 (689)	7,707
Volume diesel (litres)	505 (1025)	15,695	525 (915)	16,299
Volume LPG (litres)	9 (159)	5,029	5 (109)	3,973
Total fuel volume (litres)	1,167 (1,309)	30,987	920 (1,081)	16,299
Total fuel volume (gallons)	308 (346)	8,180	243 (285)	4,303
Nb. of working adults	1 (0.90)	5	1 (0.88)	5
Nb. of non-working adults	0.87 (0.83)	6	0.84 (0.83)	6
Nb. of young children (< 16 y.o.)	0.54 (0.92)	7	0.55 (0.93)	6
Number of vehicles	1.2 (0.80)	8	1.3 (0.8)	9
Age (head of household)	51 (17)	99	50 (17)	99
Income (€2006)	28,872 (21,458)	464,450	32,246 (22,836)	351,025
Income per CU (€2006)	19,352 (14,195)	511,824	19,880 (12,923)	214,945
Total number of households	10,262		10,208	
Number of urban households	7,814		7,794	

Source: 'Budget des Familles' survey (INSEE, 2001, 2006). We have removed from the initial data a few outliers with huge incomes (top 0.02% percentile of the most affluent households in our sample).

1.2 The metrics of urban sprawl

To supplement the BdF database, we compute different indicators of the urban form at the municipality level. Though municipalities constitute our scale of observation, sprawl is a global phenomenon that affects the entire metropolitan area. Therefore, we build on very local indicators such as residential density or continuity of the local built-up fabric, but also on more global indicators measuring the accessibility or the remoteness of the household residence within the metropolitan area.

In France, a metropolitan area (MA hereafter) is composed of a cluster of urban[16] municipalities hosting a few thousands jobs[17] (forming the "urban pole" of the MA) surrounded by a group

[14]The INSEE computes 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.

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

[16]In France, an urban municipality is characterized by a continuous built-up environment (no cut of more than 200 meters between two constructions) housing 2,000 inhabitants at least. In 2006, mainland France counted 36,571 municipalities, among which 13,808 were urban.

[17]French MAs are periodically redefined. From 1999 to 2010, the minimum threshold was 5,000 jobs. Since 2010, it has reached 10,000 jobs, which has yield substantial modifications in the MA boundaries. In 2001 and 2006, France counted 352 MAs spreading out over 50% of the surface of mainland France, and covering approximatively 85% of its population and employment (see the map provided in Appendix A).

of municipalities having a high degree of social and economic integration with this pole (at least 40% of the MA workforce has to be employed in the pole). Thus, the definition of a French MA hinges on three underlying criteria: morphology (continuity of the built-up environment, which draws the line between urban and rural areas), demography (minimum threshold of inhabitants), and functioning (minimum number of jobs and commuting patterns). As it groups municipalities sharing similar commuting patterns, the MA is a particularly relevant scale to investigate the impact of sprawl on fuel consumption.

To do so, we use two different approaches. The first builds on the monocentric paradigm and considers MAs as a series of concentric rings of municipalities ranging from city-centers to the urban fringe, and even to rural areas under the influence of city-centers. The second is in line with the classification first proposed by Cervero & Kockelman (1997) and characterizes MAs as a collection of municipalities differing along three dimensions of their built environment: Density, Diversity and Design (hereafter referred to by the shorthand of the '3 D's').

1.2.1 A simple monocentric classification of sprawling areas

Our first approach builds on a monocentric classification used by the INSEE, that breaks down municipalities into five different categories.

- The city-center of a MA is either a municipality housing more than 50% of the MA population or, if this condition is unfulfilled, the largest inhabited municipality in the MA and potentially other municipalities housing more than 50% of its population. Small MAs generally have one city-center only, whereas the largest MAs may have several city-centers, as illustrated by Figure 1 for the Paris MA, which has 20 city-centers (the 20 parisian well-known districts composing the dark-red area).

- 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 areas in Figure 1).

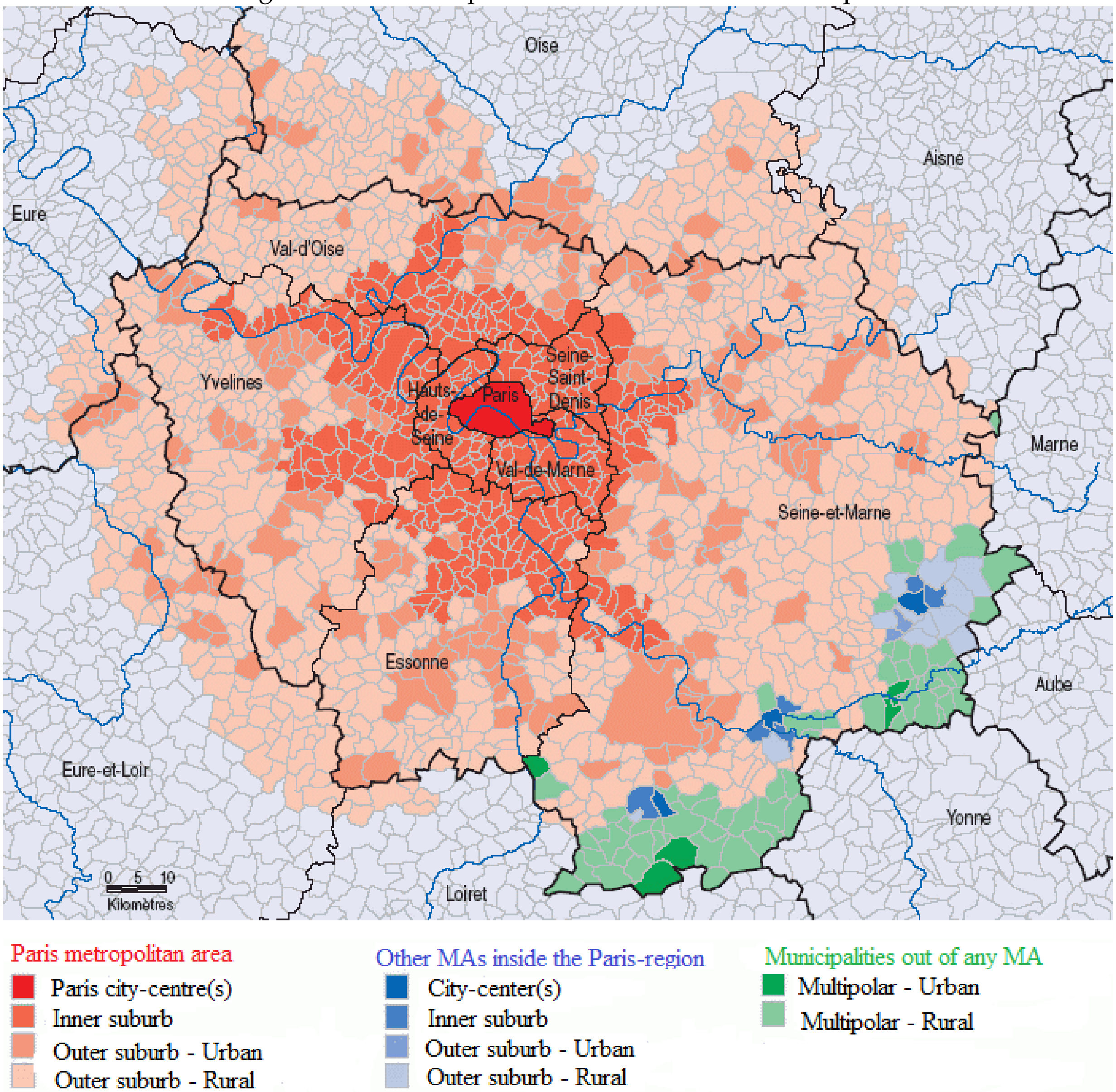
- The outer suburbs of a MA refer to the municipalities outside the urban pole of the MA, but of which 40% of the population work in the pole. They can be either urban or rural (salmon and light-salmon municipalities in Figure 1).[18]

- Multipolar municipalities refer to municipalities out of any MA, but of which 40% of the population work in surrounding MAs, none of which being all alone above this threshold. These municipalities can be either urban or rural (green areas in Figure 1).

- The rural space comprises all rural municipalities outside the predominantly-urban space (grey areas in Figure 1).

[18] 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.

Figure 1: The Metropolitan Area of Paris as an example



Note: 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 areas); Blue lines are rivers (the Seine and its tributaries); Black lines refer to the border of NUTS2 and NUTS3 regions.
Source: French National Geographical Institute (NGI).

This classification relies on functioning and morphological criteria, and is thus well suited to describe urban sprawl, since inner and outer suburbs, multipolar and rural municipalities represent sequential steps of the sprawling process. Therefore, it is very useful to deliver first insights on the impact of sprawl on fuel consumption. However, since it does not provide information on the mechanisms conveying fuel consumption in sprawling areas, we then turn to the analysis of more precise indicators of the urban form.

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

In our second approach, the urban form is modelled by a combination of Density, Design and Diversity indicator, seen as the three main forces driving fuel consumption since Cervero & Kockelman (1997).

Density Most observers agree that density is the first essential feature of urban development, which explains that it has been the most studied land-use dimension. As cities spread, their compactness decreases, which is the most evident characterisation of urban sprawl. However, the effect of higher density gradients on travel demand is not entirely straightforward, making it difficult to determine the net impact in fuel consumption arising from dense cities. Indeed, the compactness of a city reduces the length of commuting trips, but this benefit can be overcome - at least partly - by a larger frequency of trips, as desired destinations have become closer and easier to access. In this paper, density is computed as the number of inhabitants per km^2 of acreage in the residential municipality of the household (Source: 1999 and 2006 Censuses).[19] Table 2, which reports summary statistics on the urban form of French municipalities, 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 downtown Paris.

Table 2: Descriptive statistics on the urban form of sampled French municipalities

YEAR	2001		2006	
Urban Form Variables	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
DENSITY				
Population Density	2,976 (4,534)	23,395	3,419 (5,286)	25,971
DESIGN				
Distance from residence to CBD (km)	8.53 (11.27)	71.20	9.02 (10.75)	58.37
Weighted road access in the rest of the MA	14.47 (20.23)	69.01	16.05 (21.51)	69.01
Access to rail stations in the rest of the MA	1.26 (2.19)	8.46	1.44 (2.35)	8.45
Density of public transport stops (per km^2)	4.89 (7.75)	34.13	5.20 (8.06)	34.13
DIVERSITY				
Fractal dimension of the built environment	1.50 (0.18)	1.82	1.50 (0.19)	1.84
Nb of MAs	156		181	
Nb of urban municipalities	1,379		1,674	

Sources: Censuses (INSEE, 1999, 2006), BD-TOPO (NGI, 2001, 2006), OpenStreetMap (2017), and authors' own computations.

[19] This measure might not necessarily well capture 'true' density, since some municipalities contain large amounts of undeveloped land, while others are nearly completely built. 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. However, since using either the former or the later measure does not change our empirical results, standard density will be used hereafter.

Design The concentration of urban development in one or more high-density business centers may have potential adverse effects on commuting patterns, especially if those centers are located far away from dense residential places. Increased 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 homeplace and the 'Central Business District' (CBD) of the MA[20] to measure the level of centrality or remoteness of the household residence.[21] Table 2 shows that the average distance to CBD is around 9 km in France, but can reach up large numbers, such as more than 70 km in large MAs such as Paris.

The effect of distance to CBD can be mitigated by the design of transport infrastructure, however. The spatial coverage of road and public transit networks determines households' convenience to travel within the MA with or without their car, and this variable is known to have an influence on driving behaviours.[22] To measure how well connected is the household residence to the MA, we build 'Transport Potential' indicators[23] based on the 2001 and 2006 versions of a topographical database called BD-TOPO©, developed by the French National Geographical Institute (NGI afterwards). BD-TOPO summarizes all the landscape elements of the French territory, at a metric accuracy, in particular the road and rail transport networks which are very precisely described. The 'Transport Potential' indicators drawn from the BD-TOPO database are computed as follows:

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

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'.[24] Variable x is a measure of the transport services provided in municipality k'. It can be alternatively the number of rail stations (including subway and tram stations) in the municipality, or the length of its road network weighted by the magnitude of traffic documented in the BD-TOPO.[25] Variable $dens_{k',t}(x)$ is thus the density of x per km^2 of acreage in municipality k' at time t.

However, transport does not only matter to circulate within the MA, it is also crucial at the very local level where daily-life mobility mostly takes place. Typically, small municipalities generally exhibit low modal substitutability, leaving the use of automobile as the only local transport solution, whereas a large modal choice is the rule rather than the exception for house-

[20] For each MA, we define the CBD as the municipality concentrating the highest number of jobs.

[21] Alternative measures would be the effective average distance to jobs computed from either population censuses or wage administrative datasets. However, none of theses metrics stands out significantly in our following empirics, which means that they fail to capture fuel consumption arising from either driving to leisure or shopping. We therefore stick to distance to CBD in subsequent sections.

[22] See among others Ewing & Cervero (2010).

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

[24] If the municipality of residence is a CBD, we compute 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 CBD if population were spread uniformly and the municipality were a disk.

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

holds living in larger municipalities. Unfortunately, the BD-TOPO does not provide information on bus lines, which may be crucial at short distances. We thus complete the BD-TOPO dataset with a comprehensive review of bus stops through OpenStreetMap in 2017, retropolated to 2001 and 2006 using line openings dates published in the French Official Journal or by local transport authorities such as RATP SILOE for Paris. To account for local transport intermodality and accessibility, we then compute the density of all public transport stops (heavy-rail, subway, tramway and bus) in the municipality of residence.[26]

Diversity The Diversity of the built-up environment constitutes our last 'D'. The way Diversity impacts fuel consumption is not straightforward however. Urban planners generally believe that a mixed fabric of attached buildings reduces driving because it enhances functional diversity (Jacobs 1961) and makes destinations (home, shops, jobs) more accessible and conveniently reached by pedestrians (Cervero & Kockelman 1997), whereas large, mono-functional isolated housing complexes foster car use. But several empirical studies indicate that people actually drive more when the land-mix increases (Stevens 2017), presumably because closer destinations also increase the frequency of trips. Investigating the effect of morphological diversity is of large interest in our case, due to the contrasted history of French urban planning. While towns with historical heritage dispaly high morphological diversity, many French municipalities exhibit morphologies reminiscent of the typical 1960's urban planning policy, such as large and regular monofunctional housing complexes inspired by Le Corbusier, emblematic of a low morphological diversity. By contrast, morphological diversity became the guiding principle of French urban planning after the 1980's following Portzamparc's 'Open Block' vision of the urban structure. Therefore, two close municipalities within the same MA can actually exhibit very different urban morphologies, reflecting tiny variations in their local history.

To measure Diversity, previous studies have used many different indicators such as street width, number of ways in crossroads, number of building blocks, block length, parkings, dead-ends per acre, or several entropy measures of land-use mix.[27] We prefer to rely on a morphological synthetic index used by a large corpus of quantitative geographers for two decades: the fractal dimension of the local built-up area. This index, common in natural sciences to characterize irregular geometries, has been used since Frankhauser (1998) as an efficient tool to classify urban morphologies. For instance, Keersmaecker, Frankhauser & Thomas (2003) capture the morphology of Brussels' suburbs with this index, and find that sprawling areas have a small fractal dimension. In a similar approach, Tannier et al. (2011) identify the urban fringe by significant drops in the fractal dimension.

[26] In the BD-TOPO, rail and subway stations are counted as many times as there are lines transiting through it. For instance, the node '*Denfert-Rochereau*' in Paris counts as three stations, as there are three different rail lines connecting 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 (more than 34 public transport stops per km^2).

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

To compute the fractal dimension of the French urban fabric, we use the footprint of buildings of all types available in the BD-TOPO.[28] The indicator we obtain ranges between 0 and 2, and measures how discontinuous and fragmented the French built-up environment is. As seen in Table 2, the average fractal dimension of French municipalities is 1.5. Typically, rural municipalities have a much lower fractal dimension (under 1), while urban municipalities usually range between 1 and 2. Low fractal dimensions (1 to 1.3) are typically associated with leapfrogging urban developments and semi-detached housing leading to large discontinuities in the urban fabric. Medium dimensions (1.3 to 1.5) refer to more continuous urban patterns such as those found in inner suburbs, but where buildings are separated and scarcely dispatched.[29] Higher dimensions (1.7 to 2) embody highly rationalized built-up environments, such as municipalities covered with terraced buildings organized in blocks. Among these, the highest fractal dimensions correspond to the most complex built-up patterns, where blocks contain mixed buildings separated by narrow streets and courtyards, so that the urban fabric is well connected at every scale. Typical 'Haussmanian' 19$^{\text{th}}$ century built-up patterns of central Paris add-up to a fractal dimension of 1.8.

The fractal metric is obviously correlated with density. However, it captures the way density is distributed in space rather than the influence of density *per se*. Two municipalities of similar densities can indeed have very different urban morphologies. For instance, scarce high-rise housing complexes separated by large parkings can be as dense as low-rise terraced housing connected by narrow roads. However these two morphologies induce very different driving behaviours. To fix ideas, let us consider two inner suburbs of the MAs of Paris and Lille, Créteil and Roubaix municipalities. Bot municipalities display similar densities ($7,939$ inhab./km^2 and $7,262$ inhab/km^2 respectively in 2006), distances to CBD and transport potentials, but they strongly differ in their urban morphologies, as illustrated by Figure 2. Créteil has large housing complexes separated by parkings and highways, built from the mid 1950's to the early 1970's by a disciple of Le Corbusier, whereas Roubaix exhibits low-rise attached dwellings organised along narrow streets and squares, built in the end of the 19$^{\text{th}}$ century. These differences translate into a fractal dimension of 1.65 for Créteil and 1.81 for Roubaix, which is close to the maximum fractal dimension computed for the municipalities sampled in the BdF surveys.

2 Empirical strategy and results

A first assessment of the impact of urban sprawl on fuel consumption can be grasped with a parsimonious econometric model breaking down the residence-place of households along our simple monocentric classification of municipalities.

[28]The computation of the fractal dimension is detailed in Appendix B.

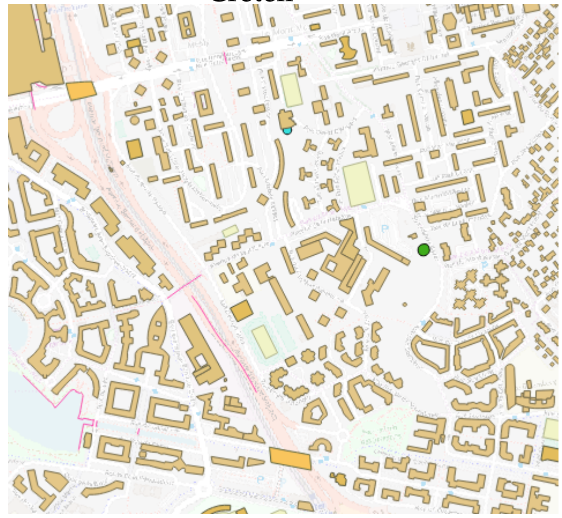
[29]Typically, suburban municipalities with detached housing have a fractal dimension of about 1.5, whereas municipalities with large housing complexes such as French '*Grands Ensembles*' lie at about 1.6.

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

Roubaix

Fractal Dimension 1.81

Créteil



Fractal Dimension 1.65

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

To understand which factors drive the relationship between fuel consumption and the urban form, we then turn exclusively to urban municipalities and analyse how our 3 D's dimensions interact with the urban residence-type. Finally, we tackle sorting and other endogeneity issues to assess the real causal impact of the urban form on fuel consumption.

2.1 Suburbanization and fuel consumption: baseline estimations

The baseline econometric specification we estimate is the following:

$$Fuel_{i(k,t)} = \alpha_0 + \alpha_1 PCC_k + \alpha_2 PIS_k + \alpha_3 IS_k + \alpha_4 OS_k + \alpha_5 M_k + \alpha_6 R_k + X_{i(t)}\theta + u_t + \epsilon_{i(k,t)}, \quad (2)$$

where $Fuel_{i(k,t)}$ is fuel consumption (in gallons) of household i living in municipality k at time t, and $X_{i(t)}$ a vector of household characteristics including income per consumption unit (in log), number of working and non-working adults, presence of children under 16 years-old,[30] as well as age, age-square, sex, diploma and occupation of the household-head. To capture the impact of sprawl on households living respectively in and out a MA, we include six dummies in the regression. PCC_k, PIS_k, IS_k, OS_k, M_k and R_k indicate whether the municipality of residence k is respectively a Parisian City-Center, a Parisian Inner Suburb, a non-parisian Inner Suburb, an Outer Suburb, a Multipolar or a Rural municipality outside the urban space. Finally, u_t is a year-dummy and $\varepsilon_{i(k,t)}$ the error term. Coefficients $\alpha_{j=1,\ldots,6}$ give the incremental effect of residence-type j on fuel consumption, in comparison with the reference-type that we choose

[30] We consider this threshold because the legal age for driving in France is 16 years, as long as an adult is also present in the car. We thus measure the impact on fuel of having underage children, but not the extra consumption associated with their first vehicle.

to be a non-Parisian city-center. Columns 1 and 2 in Table 3 report the results of this first set of linear regressions for the sample of respectively all households and urban households only, once controlled for households' characteristics and year fixed effects.

To further deepen our understanding of urban sprawl, we turn to a semi-log specification including our different measures of the 3 D's, restricting the sample to urban households only:

$$Fuel_{i(k,t)} = \alpha + \beta Density_{k,t} + Design_{k,t}\delta + \gamma Diversity_{k,t} + X_{i(t)}\theta + u_t + \varepsilon_{i(k,t)}, \tag{3}$$

where $Density_{k,t}$ is population density (in log) in the municipality of residence k at time t, $Design_{k,t}$, the vector of log-variables capturing the centrality/remoteness of this municipality within the MA (distance to CBD, road/rail transport potentials, and local density of public transport stops), and $Diversity_{k,t}$, the fractal dimension capturing its local morphology. The coefficients β, δ and γ measure the impact of each dimension of the urban form on fuel consumption, every other dimensions equal. They are thus our main parameters of interest. With a semi-log specification, the magnitude of these coefficients have to be interpreted in the following way. If residential density doubles, annual fuel consumption is expected to vary by $\log 2 \times \beta = 0.7 \times \delta$ gallons. If the decrease in commuting length is not offset by the increase in the frequency of trips, this variation should be negative. The same kind of interpretations hold for the other log-variables capturing the urban form. Columns 3 to 8 in Table 3 add successively each variable capturing our three Dimensions to see how they interact with a particular residence-type, as a first attempt to identify the mechanisms conveying the impact of the urban form.

Fuel consumption and residence-type There are strong disparities in fuel consumption across municipalities, depending on their geographic position in the urban and rural spaces, as shown by the first two columns of Table 3. For instance, a household living in the city-center of Paris would save approximatively 150 gallons per year (column 1) over an observationally-equivalent household living in a non-Parisian city-center, which represents an economy of 10 fuel tanks per year, or half the mean annual fuel consumption in France. Living in a Parisian inner suburb would generate a smaller economy of 47 gallons per year (3.5 fuel tanks), whereas living in a non-Parisian inner suburb would yield an extra consumption of approximatively 41 gallons per year (3 fuel tanks). The diseconomy associated with the next rings of suburbs would be even larger: 84, 106 and 85 further annual gallons (6.5, 8 and 6.5 fuel tanks), for respectively an outer suburb, a multipolar or a rural municipality. An interesting feature is that there is a significant difference between outer suburbs and multipolar municipalities. In other words, living in the influence of two 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 the benefits of an urban location fade away when living at the urban fringe. The large discrepancy found between city-centers and suburbs suggests that those urban areas experience very different spatial organizations that may be due to differentials in their urban form.

Table 3: Household fuel consumption and residence-type: Pooled OLS estimations

Variable explained: Fuel consumption (gallons)	All households (1)	Urban households only (2)	(3)	(4)	(5)	(6)	(7)	(8)
Non-parisian city-center	Reference							
City-center of Paris	-150.4***	-147.4***	-81.7***	-153.2***	-22.1	-82.6***	-99.4***	-105.1***
	(9.65)	(5.96)	(14.1)	(6.71)	(16.5)	(9.57)	(9.82)	(11.8)
Inner suburb of Paris	-47.0***	-44.2***	-15.9*	-68.7***	68.6***	19.3**	-30.6***	-34.7***
	(6.97)	(5.87)	(8.38)	(13.8)	(15.0)	(9.44)	(6.11)	(6.61)
Inner suburb out of Paris	41.2***	43.0***	22.2***	27.6**	51.1***	52.4***	37.4***	20.4 ***
	(5.52)	(7.09)	(6.90)	(11.5)	(7.07)	(6.98)	(6.33)	(7.66)
Outer suburb	83.5***	86.7***	16.3	60.9***	97.8***	96.4***	64.4***	31.3**
	(6.64)	(9.13)	(13.2)	(22.8)	(11.2)	(9.03)	(9.49)	(12.4)
Multipolar municipality	105.9***							
	(10.3)							
Rural municipality	85.3***							
	(5.79)							
DENSITY								
log(residential population density)			-27.9***					
			(4.75)					
DESIGN								
log(distance from residence to CBD)				14.5*				
				(8.21)				
log(access to rail stations in the rest of the MA)					-66.6***			
					(7.41)			
log(weighted road access in the rest of the MA)						-24.1***		
						(2.73)		
log(density of public transport stops)							-23.6***	
							(3.38)	
DIVERSITY								
Fractal dimension of the built-up environment								-202.6***
								(40.29)
Household characteristics	✓	✓	✓	✓	✓	✓	✓	✓
Year fixed-effets	✓	✓	✓	✓	✓	✓	✓	✓
Observations	20,470	15,608	15,608	15,608	15,608	15,608	15,608	15,608
R-squared	0.238	0.225	0.233	0.226	0.228	0.229	0.230	0.231

Notes: (i) OLS estimates drawn from equation (2); (ii) Standard errors in brackets, clustered at the MA level (227 clusters) for the sample of urban households; ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (iii) Household characteristics include income per consumption unit (in log), number of working and non-working adults, presence of children under 16, as well as age, age-square, sex, diploma and occupation of the household-head; For the sake of clarity, the related coefficients are not reported, nor the constant.
Source: 'Budget des Familles' survey (INSEE, 2001 and 2006), Census data (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017) and authors' own computations.

What mechanisms drive these spatial differences? Actually, we do find a very significant impact of our 3 D's on fuel consumption. Their interaction with our monocentric classification helps to understand what drives the observed differences. Including residential density along with all residence-type induces a 45% reduction in the effect of living in a Parisian city-center (column 3), the impact of which remains nevertheless significant, and a three-fold reduction of the impact of living in a Parisian inner suburb (which looses most of its significance), whereas it halves the effect of living in a non-Parisian inner suburb. Therefore, high density explains a large part of the (but not the whole) Parisian effect. In contrast, residential density totally washes out the effect of living in an outer suburb. In other terms, the high fuel consumption of households living at the urban fringe of French MAs is totally explained by low residential density there, whereas density may not be the only mechanism at play in more central municipalities. This calls for extending our investigation to the other 'D's.

When we assess the impact of our Design variables, we find contrasted effects. Distance from residence to CBD magnifies the influence of living in an inner suburb (column 4). The extra consumption of households living in a non-Parisian inner suburb comes thus partly from the remoteness of these areas. Distance to CBD has little impact in other zones. More significant is the effect of rail access to the rest of the MA: it washes out all the effect of living in downtown Paris (column 5). In addition, it twists the sign of the Parisian inner suburb dummy, and brings it close in magnitude to its non-Parisian counterpart. Therefore, it seems that the largest part of the Paris exception transits thought its rail transit network. By contrast, rail access has very low impact on non-parisian inner suburbs and outer suburbs in general: those municipalities obviously benefit less from public transport connectivity, since transit networks in France are concentrated in large cities and mostly radial. Road access has similar but smaller effects than rail access (column 6): it halves the downtown-Paris effect and brings the Paris inner-suburb effect closer - but still smaller - to that of other inner-suburbs. The surprising negative coefficient of road access is due to the strong multi-collinearity of this variable with the Parisian dummies. When the latter are left out of the regression, a better road access does increase fuel consumption, as expected, and this positive impact is robust to the inclusion of all the other D's (see Table 4 below).

Finally, the density of public transport stops in the residence (column 7) and our Diversity indicator (column 8) partly alleviate the impact of all residence-types, without taking out their significance, which indicates that local public transit and morphology are important further channels conveying the impact of urban form on fuel consumption. Including Diversity especially reduces the coefficient of the outer suburb dummy, which indicates that an important part of the effect of living at the urban fringe comes from the leapfrogging morphology of outer suburbs.

The interactions of concentric dummies with our 3 D's indicate first that Density, Design and

Diversity are crucial determinants of fuel consumption *per se*. Moreover, local public transport is a particularly important factor dampening fuel consumption in dense municipalities such as downtown Paris, which cannot be captured by a simple monocentric classification.

It is therefore important to dig further into the analysis of the urban form. Table 4 depicts the results of regressing household fuel consumption on our 3 D's alone, as in equation (3) which constitutes our most comprehensive specification. Column 1 reports the estimates drawn from the sample of all urban households, while column 2 controls for a set of MA fixed-effects as a robustness check. Columns 3 and 4 report the coefficients estimated on the restricted sample of households owning a car, as a preliminary attempt to test for household selection across the urban space.

Fuel consumption and urban household characteristics Household characteristics have a stable impact across all specifications.[31] Quite straightforwardly, the revenue influences positively fuel consumption: affluent households drive more, because they can afford that, and may prefer driving to other travel modes. Doubling the income per CU increases the annual fuel consumption by $0.7 \times 70.3 = 49$ gallons (column 1), a roughly 20% of the average yearly fuel consumption of households in France. The family composition also matters: any additional working adult in the household is associated with an increase in annual fuel consumption of 113.5 gallons. This contrasts with the +70.6 gallons associated with an additional non-working adult, and the +17.4 gallons induced by having more than one young child. The impact of a working-adult is then approximatively 1.5-fold that of a non-working adult, and 7-fold that of two underage children. Households headed by elderly people tend to consume less fuel, as seniors have less occasions to drive and for some of them avoid to drive. The impact of age is not linear, however: the coefficient of the non-quadratic term is significantly positive, and the coefficient of the quadratic term significantly negative. In the same vein, female-headed households represent a net annual saving of 39.2 gallons in comparison with man-headed households.[32] Interestingly, when the sample is restricted to car owners only, the presence of young children does not affect significantly fuel consumption anymore. This suggests that having a second kid requires a vehicle purchase to do the same trips the household may have done before otherwise. In other words, having more than one child conditions car ownership, but not fuel consumption *per se*.

Fuel consumption and urban form Moving to our 3 D's, the negative impact of **Density** is comforted, with a significant semi-elasticity ranging from -13.8 (column 1) to -11.1 (column 4). Doubling population in a municipality would thus yield an annual fuel saving of at most $0.7 \times 13.8 = 10$ gallons for its residents. Put it differently, this suggests that a typical household living in Toulouse consumes 10 more gallons per year than an observationally-equivalent house-

[31] This is the reason why we do not report nor discuss their influence in subsequent sections.

[32] Even though the coefficients are not reported for the sake of clarity, occupation and diploma dummies are generally also highly significant.

Table 4: Household fuel consumption and urban form: Pooled OLS estimations

Variable explained: Fuel consumption (gallons)	Urban households (1)	(2)	Motorized households (3)	(4)
HOUSEHOLD CHARACTERISTICS				
log(total income/CU)	70.3***	71.8***	62.1***	64.6***
	(4.15)	(4.39)	(5.24)	(5.32)
Number of working adults	113.5***	113.0***	104.3***	103.1***
	(13.46)	(13.56)	(13.84)	(13.75)
Number of non-working adults	70.6***	70.5***	70.0***	69.7***
	(7.82)	(8.00)	(8.67)	(8.79)
Presence of young children	17.4***	16.9***	6.51	5.81
	(6.26)	(6.35)	(6.27)	(6.43)
Age (Head of household)	3.70***	3.56***	4.39***	4.26***
	(0.69)	(0.76)	(0.93)	(0.98)
Age square (Head of household) x 1,000	-55.5***	-54.2***	-67.6***	-66.0***
	(5.40)	(5.75)	(8.44)	(8.73)
Woman (Head of household)	-39.2***	-37.1***	-32.5***	-30.4***
	(7.95)	(8.48)	(10.66)	(11.31)
DENSITY				
log(residential population density)	-13.8***	-12.4**	-11.9***	-11.1**
	(4.31)	(5.14)	(4.44)	(5.71)
DESIGN				
log(distance from residence to CBD)	12.4***	14.2**	10.3**	12.8*
	(4.18)	(5.65)	(4.46)	(6.86)
log(weighted road access in the rest of the MA)	20.0***	39.4	19.0***	16.5
	(7.49)	(33.2)	(7.70)	(34.00)
log(access to rail in the rest of the MA)	-59.2***	-96.7***	-50.1***	-80.0***
	(10.68)	(24.48)	(11.76)	(25.06)
log(density of public transport stops)	-9.63***	-9.57**	-8.28**	-6.13
	(3.19)	(4.24)	(3.48)	(4.73)
DIVERSITY				
Fractal dimension of the built-up environment	-89.6***	-107.6**	-91.2**	-100.7**
	(37.79)	(47.32)	(36.17)	(48.95)
Diploma dummies (Head of household)	✓	✓	✓	✓
Occupation dummies (Head of household)	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓
MA fixed effects		✓		✓
Observations	15,608	15,608	12,888	12,888
R-squared	0.234	0.250	0.156	0.177

Notes: (i) OLS estimates drawn from equation (3); (ii) Standard errors in brackets, clustered at the MA level (227 clusters); ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (iii) For the sake of clarity, the constant and coefficients associated with control dummies are not reported.
Source: 'Budget des Familles' survey (INSEE, 2001 and 2006), Census data (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017), and authors' own computations.

hold living in Lyon (the density of which is twice that of Toulouse) only through the density channel. Effects can be larger since density typically varies along several orders of magnitude: a household living in the most scarcely populated French urban municipality (Chézy, which houses 6 inhabitants per km^2) consumes $\log(25,971/6) \times 13.8 = 50$ more gallons (approximatively 4 fuel tanks) per year than an observationally-equivalent household residing in Paris (the densest municipality in France, with 25,971 inhabitants per km^2), everything else equal.

Design metrics have differentiated effects. Halving distance from residence to the CBD would save $0.7 \times 12.4 = 9$ gallons (column 1). Improving heavy-rail access would result in an economy of an order of magnitude far above the distance effect: doubling the rail station access of a municipality would enable its residents to save approximatively 4 fuel tanks per year (a rough 20% of the yearly average fuel consumption of households in France). Conversely, road improvements would raise fuel consumption, but by a lower magnitude. This suggests that a public rail network with a large urban coverage can be a very effective substitute to urban road transport. Finally, local public transit systems convey further significant environmental gains, though their impact is lower than the global rail coverage of the MA.

By way of comparison, Glaeser & Kahn (2010) report 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 more fuel per km than French ones.[33] Once accounted for this difference, the US density coefficient is around 4-fold the French coefficient, and the distance coefficient 2-fold. Second, if we restrict urban form variables to those used by Glaeser & Kahn (2010) (i.e. density and distance to CBD only), this leaves us with a density coefficient for France at 28 gallons, which would halve again the US-French discrepancy. Moreover, the average distance to CBD is approximatively 23 km in the US, that is twice the French average, which also mitigates the distance discrepancy. The remainder of the French-US gap may be explained by the inclusion of our other D's and the fact that we account for many more household characteristics than Glaeser & Kahn (2010). More generally, the impact of density is less marked in France than in many other countries, since the estimated elasticity ($-\frac{13.8}{275.5} = -0.05$ at the mean of our sample) is twice lower than the average reported in the most recent meta-analysis of Stevens (2017).

Diversity has also a very significant negative impact on fuel consumption in France. A 10% difference in the fractal dimension, such as the Roubaix-Créteil gap reported above, would translate into a reduction of $\log(1.1) \times 89.6 = 4$ gallons per year approximatively (column 1), over and beyond the Density and Design channels.[34] Including Diversity in the regression greatly

[33] US cars produced in 2006 were consuming 9.8 litres for 100km, against 4.7 litres for French cars.

[34] Moreover, this impact is robust to the inclusion of many simpler morphological variables such as the share of built-up surface, or the density of crossroads. These additional regressions are available upon request.

reduces the estimated impact of Density, actually. If we exclude the fractal dimension from the urban form variables, the density coefficient roughly doubles, leading to a density elasticity in line with the literature.[35]

As a final robustness check, we include MA fixed effects to control for any unobservable time-invariant urban characteristic that could potentially affect fuel consumption (column 2 of Table 4). Logically, in this highly demanding specification, certain design variables become insignificant, because of their low intra-MA spatial variability. Nevertheless, distance to CBD, rail access and our Density and Diversity variables remain highly significant, despite loss of degrees of freedom, which makes us confident in the identification power of our 3 D's.

2.2 Urban form and fuel consumption: Causal estimations

There are two econometric issues associated with our baseline OLS estimates, however. The first is the sorting of households across municipalities and the second is endogeneity arising from potentially omitted variables correlated with households settlements and therefore, with Density and Distance to the CBD.

Sorting As underlined by Brownstone & Golob (2009) and Grazi, van den Bergh & van Ommeren (2008), lifestyle and individual preferences are known to influence residential choices. For instance, some people do not mind driving and even do like it. One can expect these individuals to locate away from job centers, in low density areas with remote public transport services that they do not value anyway. Conversely, if people who dislike driving and prefer walking, cycling or rolling through public transit self-select into dense places where these options are available, the effect of density on fuel consumption is also likely to be overestimated. Therefore, motorized households may differ in important unmeasured ways from households who do not own a car. It is worth noting that this self-selection bias could be mitigated in our case by the fact that we have included al lot of individual controls in our baseline regressions. Nevertheless, as the complete list of variables influencing residence choice cannot be measured, the error term in the outcome equation (3) is likely to remain correlated with the explanatory variables, which may produce inconsistent estimates.[36]

To deal with household sorting across places, we run two sets of additional regressions. First, as mentionned previously, we perform an OLS regression on the subset of urban households owning a car, and we compare the related results (columns 3 and 4 in Table 4) to those drawn from the whole sample of urban households (columns 1 and 2 in Table 4). We find very similar

[35] Corresponding tables are available upon request.

[36] Note that there is also a censoring issue arising from the fact that several households do own a car, but have not reported positive fuel consumption during the survey period when they were asked to self-complete their expenditure diary. The measure of fuel consumption is therefore exposed to classic storage behaviour: some households may have entered the surveyed period of diary completion with an already filled tank, thus reporting zero fuel expenses afterwards. We cannot do much about this issue, except providing robustness checks on the restricted sample of households owning a car.

results, the only difference being that the effect of public transport reduces by 10 to 30%, which is consistent with the fact that car ownership is negatively correlated with the presence of public transit. In other words, the latter seems to be more a cause of non-motorization than a cause of fuel economies *per se*.

Second, we also use a Heckman (1979) two-step procedure with a selection rule defined according to car ownership. The first step of the 'Heckit' consists in estimating 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 for household i residing in municipality k to own at least one car at time t, $X_{i(t)}$ being the same vector of household characteristics determining participation (i.e. car ownership) as in equation (3).

In a second step, we estimate the outcome equation (3) except that we add to the regressors the inverse of the Mills ratio[37] drawn from the Probit regression and exclude the young children dummy from the vector $X_{i(t)}$. Note that, technically, the Heckman model is identified when the same independent variables are used in both the selection and outcome equations. However, in this case, identification only occurs on the basis of distributional assumptions about the residuals alone, and is not due to variation in the explanatory variables. In other words, identification is essentially possible due to non-linearities, and there is a risk to have more imprecise estimates. Because of these identification issues, it is preferable to have at least one independent variable in the selection equation that is not included in the outcome equation. As observed above, the presence of children under 16 years determines car ownership but not fuel consumption. Therefore, we build our estimation on this exclusion restriction.

Endogeneity To address remainder endogeneity concerns, we instrument the urban form variables that more likely correlate with unobserved determinants of residential choices, that is density and distance to CBD. To this end, we require instruments that affect fuel consumption only through the distribution of population settlements. Long-lagged variables are *a priori* good candidates because they are prone to remove any simultaneity bias caused by contemporaneous local shocks on fuel consumptions. The first historical instrument we use is mortality density in each municipality before the automobile widely expanded in France, that is in the early 1960's (Source: French Census, 1962).[38] Mortality is indeed highly correlated with total population (with a correlation at 0.93 for the sample of municipalities available in the BdF survey), and at the same time very orthogonal to the error term, which encompasses the modern taste for

[37]Computed as $Mills(x) = \frac{\bar{F(x)}}{f(x)}$, where x is the probability of car ownership predicted by the Probit step, f and F the density and cumulative distribution function of the normal distribution.

[38]This is the oldest Census for which mortality is measured at the level of municipalities.

driving.[39] To instrument distance to CBD, we compute the number of kilometers separating the municipality of residence from the most populated municipality of the actual MA in 1806 (Source: 'Dictionnaire d'histoire administrative' of the French National Institute of Demographic Studies; INED, 2003).[40]

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

$$MP_{k,1936} = \sum_{k' \neq k} \frac{dens_{k',1936}}{dist_{kk'}}, \tag{4}$$

where $dens_{k',1936}$ is density in municipality k' in 1936, drawn from a historical dataset reporting population for the 5,198 French municipalities housing more than 5,000 inhabitants at least once between 1831 and 1982 (Source: 'Fichiers Urbanisation de la France', French National Institute of Demographic Studies; INED, 1986). We select 1936 because this is the year for which the data coverage is the largest.[41]

Table 5 provides the results of both our IV (colum 2) and Heckman (colum 3) identification strategies. In comparison with column 1, which replicates our baseline estimates, endogeneity leads to an overestimation of the density effect of approximately 10%, while the distance effect is underestimated by approximately 40%. The coefficients of the other D's are also affected by instrumentation: for instance, instrumentation reduces the impacts of road access and fractality by respectively 30% and 40%. The Shea's partial R-squared show that our two preferred instruments explain a non-negligible share of the endogenous variables, once potential inter-correlations among instruments have been accounted for.[42] However, we have to check that this is not done at the expense of their strength. To make a more formal assessment of our instruments, we turn to the weak instrument tests developed by Stock & Yogo (2005). Instruments are not weak, as the Cragg-Donald F-statistics are above the critical value reported for a 5% maximum IV bias (that is 13.43). Table 9 in Appendix C shows that results remain qualitatively and quantitatively similar if we use market potential in 1936 as an extra instrument. In addition, if we run a Hansen J-Statistic test for overidentifying restrictions, the null of the validity of instruments is not rejected as the p-value is far above 5%.

The second panel of Table 5 reports the coefficients of our 'Heckit' (column 3) and Probit (column 4) regressions.[43] There is no evidence of a selection bias associated with Density.

[39]The correlation between fuel consumption and our instrument is at -0.23.

[40]The first French census dates back to 1801, but we prefer to use the 1806 issue because at that time, Napoléon's French Empire covers all current French municipalities (and even extended outside the current French territory).

[41]Using another year does not change the magnitude of our estimates, but induces a loss of precision.

[42]First-stage regressions are reported in Table 10-Appendix C.

[43]Regarding the Probit, only marginal effects are reported. Therefore, reported coefficients measure how much the (conditional) probability of car ownership changes when the value of a regressor changes, holding all other regressors constant.

Table 5: Urban form and household fuel consumption: Pooled causal estimations

Variable: Fuel consumption (gallons)	All urban households		Heckman two-step	
	(1) OLS	(2) 2SLS	(3) Heckit	(4) dx/dy Probit
DENSITY				
log(residential population density)	-13.8***	-12.3**	-13.4***	-0.014***
	(4.31)	(5.21)	(4.07)	(0.004)
DESIGN				
log(distance from residence to CBD)	12.4***	23.5***	14.5***	0.014***
	(4.18)	(5.46)	(4.48)	(0.004)
log(weighted road access in the rest of the MA)	19.9***	13.5*	22.5***	0.019***
	(7.49)	(7.64)	(6.43)	(0.006)
log(access to rail in the rest of the MA)	-59.2***	-60.3***	-68.8***	-0.075***
	(10.68)	(9.52)	(10.49)	(0.008)
log(density of public transport stops)	-9.63***	-8.28***	-11.8***	-0.010***
	(3.19)	(3.00)	(3.64)	(0.003)
DIVERSITY				
fractal dimension of the built-up environment	-89.6**	-63.4^{+}	-107.2***	-0.11***
	(37.79)	(41.45)	(31.1)	(0.028)
Household characteristics	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓
Observations	15,608	15,608	15,608	15,608
R-squared	0.234	0.165		
Cragg-Donald F-Stat		5,687	ρ : 0.46	
Shea Partial R-squared (log density)		0.44	σ : 298	
Shea Partial R-squared (log distance to CBD)		0.54	λ : 136	

Notes: (i) Standard errors in brackets, clustered at the MA level (227 clusters); ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (ii) The sigma term is the root of the variance of the disturbances and rho, the correlation between the disturbances of the model and selection equations; (iii) List of instruments: mortality density in 1962 (in log), distance to the largest municipality of the MA in 1806 (in log); (iv) For the sake of clarity, the coefficients associated with household characteristics, time dummies and the constant are not reported.
Source: 'Budget des Familles' survey and Census data (INSEE, 1999, 2001, 2006), BD-TOPO (NGI, 2001, 2006), 'Fichiers Urbanisation de la France' (INED, 1986), 'Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative' (INED, 2003).

By way of contrast, the impact of distance to CBD increases when selection is accounted for, which is perfectly in line with previous findings (Stevens 2017). The coefficients of the other variables capturing the urban form exhibit a slight increase (in absolute value): from 3% for the local public transport density to 20% for the fractal dimension. Therefore, selection leads to a general underestimation of the 3 D's impact on fuel consumption, the bias being slightly larger for Design and Diversity than for Density.

As shown in column 4, the probit regression produces a significant and positively signed lambda term, which suggests that the error terms in the selection and outcome equations are positively correlated (since the coefficient on λ is $\rho \times \sigma$). Therefore, unobserved factors that make participation more likely tend to be associated with higher fuel consumption. As for the magnitude of the marginal effects (column 4), doubling density (respectively distance to CBD or road access) decreases (respectively increases) car ownership by a small order of magnitude, around 1%, whereas the marginal impacts of rail access and morphological diversity are five to ten times larger.

All of these checks support the conclusion that our 3 D's exert a robust influence on fuel consumption, beyond any selection or other endogeneity bias.

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

In the same spirit as in Glaeser & Kahn (2010), we use our causal estimates to predict the CO_2 car emissions produced by a standardized household in each French MA. We then identify the greenest and dirtiest cities according to this 'carprint', and investigate the relationship between city-size and this ranking.

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

To compute the driving footprint of a standardized household in each MA, we proceed as follows. We first estimate how much fuel the mean household of the 2006 BdF survey[44] would consume in each of the $j = 1, ..., 13, 808$ French urban municipalities, based on either the 2SLS (equation 5) or the Heckman (equation 6) estimates drawn from Table 5:

$$\widehat{Fuel}_{m(j)} = \widehat{\alpha} + \widehat{\beta} \log Density_j + \log Design_j \widehat{\delta} + \widehat{\gamma} \log Diversity_j + \overline{X_i}\widehat{\theta}, \forall j, \tag{5}$$

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

where $\overline{Y_i}$ is the vector of the mean-household characteristics in 2006 except the dummy for young children (since this is our exclusion restriction).

[44] That is a household composed on 1.03 working adult, 0.83 non-working adult, 0.55 young children, with a mean income of 28,872 euros, headed by a man who is 49 years-old, whose occupation is an intermediate profession, and who has a high-school professional degree or apprenticeship.

As French municipalities display drastic variations in wealth, we find interesting to compute a second set of projections, by letting the average income earned in each municipality vary along with its geographical characteristics. To estimate the average income in each urban municipality, we use an exhaustive French administrative dataset called 'DADS', which reports the earnings of the universe of salaries in France. We first run an OLS regression of the average municipal income per CU drawn from the 2006 BdF survey on the average municipal earnings computed from the DADS in 2006.[45] We then use the related estimates to compute car emissions as before, except that we assign to the mean-household the Corrected Income estimated for each urban municipality (CI afterwards), instead of the BdF mean-income in 2006:

$$\widehat{Fuel}_{m(j)CI} = \widehat{\alpha} + \widehat{\beta} \log Density_j + \log Design_j \widehat{\delta} + \widehat{\gamma} \log Diversity_j + \overline{Z_i}\widehat{\eta}, \forall j, \tag{7}$$

where $\overline{Z_i}$ is the vector of the mean-household characteristics in 2006, except income per CU, that is replaced by the Corrected Income estimated above.

With these two different sets of projections 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 motorized households in each municipality:

$$\widehat{Fuel}_{m(MA)} = \sum_{j \in MA} \left(\widehat{Fuel}_{m(j)} \times \text{Nb of motorized households}_j / \text{Nb of households}_{MA} \right). \tag{8}$$

Finally, we draw carbon emissions from those volumes using conversion factors provided by the French Ministry for an Ecological and Solidary Transition. To account for the mix of fuels in the French vehicle fleet, we use a specific conversion factor for each type of energy: 10.6 kg of CO_2 per gallon of gasoline, 12.0 kg of CO_2 per gallon of diesel, and 7.0 kg of CO_2 per gallon of LPG. By prorating each type of energy with its share in total fuel consumption drawn from the 2006 BdF survey, we obtain a global conversion factor of 11.96 kg of CO_2 per gallon of fuel.[46]

Tables 6 and 7 report the car emissions obtained for our standardized household in the 25 greenest and dirtiest French MAs.[47] Each panel of the table presents driving emissions computed from either the OLS, 2SLS or Heckit estimates provided in Table 5, and the rank of each MA with respect to those emissions. The last column reports the number of inhabitants per MA in 2006, to fix ideas.

It is important to note that, regardless of the estimation strategy, car emissions vary drastically across French MAs, from approximatively 2.2 tons in Paris up to 3.9 tons in MAs such as Bourg-Saint-Maurice, Annemasse or Chamonix, which are all located - somehow paradoxically

[45] More precisely, we perform the following regression for all municipalities available in the 2006 BdF sample: $\log \overline{(income/CU)}_{j,2006} = \Phi_1 + \Phi_2 \log \overline{wage_{j,2006}} + \xi_{j,2006}$.

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

[47] Tables 11 and 12 in Appendix C replicate the same exercise with emissions computed with Corrected Incomes, as in equation (7).

Table 6: Greenest French MAs: CO_2 'carprint' of the sample mean-household (kg / year)

Name	OLS	Rank	2SLS	Rank	Heckit	Rank	MA pop.
Paris	2,294	1	2,297	1	2,241	1	11,769,424
Fourmies	2,607	3	2,584	2	2,502	2	16,324
Lille	2,598	2	2,605	3	2,502	3	1,164,717
Caudry	2,672	4	2,642	4	2,567	4	14,322
Saint-Etienne	2,856	5	2,885	6	2,739	5	31,8993
Montereau-Fault-Yonne	2,863	6	2,830	5	2,749	6	26,109
Bolbec	2,923	7	2,885	7	2,804	7	15,750
Tergnier	2,963	10	2,930	8	2,847	8	23,383
Lyon	2,962	9	2,968	12	2,850	9	1,748,274
Sète	2,962	8	3,023	23	2,851	10	73,674
Menton	2,965	11	2,977	13	2,856	11	68,826
Hendaye	2,982	12	2,951	10	2,860	12	14,993
Villerupt	3,008	15	2,950	9	2,882	13	19,019
Nancy	3,003	14	2,961	11	2,892	14	415,765
Le Havre	2,992	13	3,007	20	2,898	15	290,826
Yvetot	3,051	24	2,987	14	2,907	16	15,432
Strasbourg	3,016	16	3,029	24	2,914	17	638,672
Armentières	3,036	20	3,012	21	2,918	18	58,458
Grenoble	3,032	18	3,030	25	2,918	19	531,439
Douai	3,032	19	3,063	29	2,919	20	546,721
Nemours	3,047	23	3,012	22	2,922	21	18,429
Berck	3,039	21	3,004	18	2,928	22	24,648
Boulogne-sur-Mer	3,025	17	2,997	16	2,928	23	133,195
Aulnoye-Aymeries	3,063	30	3,007	19	2,937	24	19,649
Lunéville	3,054	26	2,990	15	2,940	25	27,549

- in the French Alps.[48] In other words, the decision for a French standardized household to live in Bourg-Saint-Maurice (respectively in Chamonix) would generate a driving footprint twice (respectively 65%) larger than the decision to live in Paris.

Car emissions of a standardized household remain much lower in French MAs than in American MSAs, however. According to 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. Hence, a typical French driver would produce around one fifth of the carbon emissions of a typical US driver.

The CO_2 ranking of French MAs is rather stable across estimates, though Heckman emissions are slightly lower, and significant differences may occur for several coastal or border MAs. For instance, MAs such as Fourmies, Caudry, Hendaye or Boulogne-sur-Mer have lower emissions when those are computed with 2SLS estimates, whereas larger emissions are the most frequent case. However, differences remain marginal as these cities have low driving footprints anyway, presumably because their development has been constrained by lack of surrounding space.

[48]Note that, since we computed the standard errors associated with these predictions, we can state that differences between high and low emissions are actually very significant. Moreover, we have checked that the peculiarity of mountainous MAs is not due to altitude by controlling for different measures of elevation.

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

Name	OLS pred.	Rank	2SLS pred.	Rank	Heckit pred.	Rank	MA pop.
Bourg-Saint-Maurice	4,004	352	3,952	352	3,880	352	10,357
Sarlat-la-Canéda	3,940	351	3,886	350	3,809	351	18,022
Annemasse	3,909	350	3,902	351	3,798	350	244,178
Cahors	3,896	348	3,834	345	3,786	349	40,175
Les Herbiers	3,906	349	3,879	349	3,757	348	14,833
Bressuire	3,890	347	3,873	348	3,756	347	18,225
Lannion	3,868	344	3,848	346	3,749	346	63,425
La Bresse	3,869	345	3,855	347	3,746	345	12,851
Saint-Lô	3,864	343	3,794	337	3,746	344	49,761
Ancenis	3,883	346	3,833	344	3,746	343	19,308
Sablé-sur-Sarthe	3,858	342	3,814	342	3,739	342	30,193
Aubenas	3,853	341	3,785	335	3,735	341	44,546
Saint-Gaudens	3,849	340	3,762	333	3,734	340	27,175
Auch	3,847	339	3,808	341	3,729	339	36,934
Saint-Louis	3,832	337	3,806	340	3,713	338	89,549
Ussel	3,837	338	3,761	332	3,710	337	14,074
Oloron-Sainte-Marie	3,822	336	3,748	328	3,696	336	22,382
La Roche-sur-Yon	3,812	333	3,823	343	3,694	335	107,584
Bergerac	3,805	331	3,790	336	3,692	334	76,179
Chamonix-Mont-Blanc	3,817	335	3,798	339	3,692	333	13,127
Belley	3,817	334	3,728	324	3,689	332	16,547
Figeac	3,809	332	3,735	325	3,681	331	16,711
Montbéliard	3,775	324	3,739	326	3,672	330	179,761
Loudéac	3,802	329	3,756	331	3,671	329	14,217
Livron-sur-Drôme	3,804	330	3,767	334	3,666	328	16,662

As shown by Tables 11 and 12 in Appendix C, rankings change more drastically when we let vary the income across municipalities (as in equation 7). MAs poorer than expected from the BdF survey, such as Valenciennes or Boulogne-sur-Mer, greatly improve their rankings, whereas richer cities, such as Lyon or Grenoble, move down on the carbon ladder.

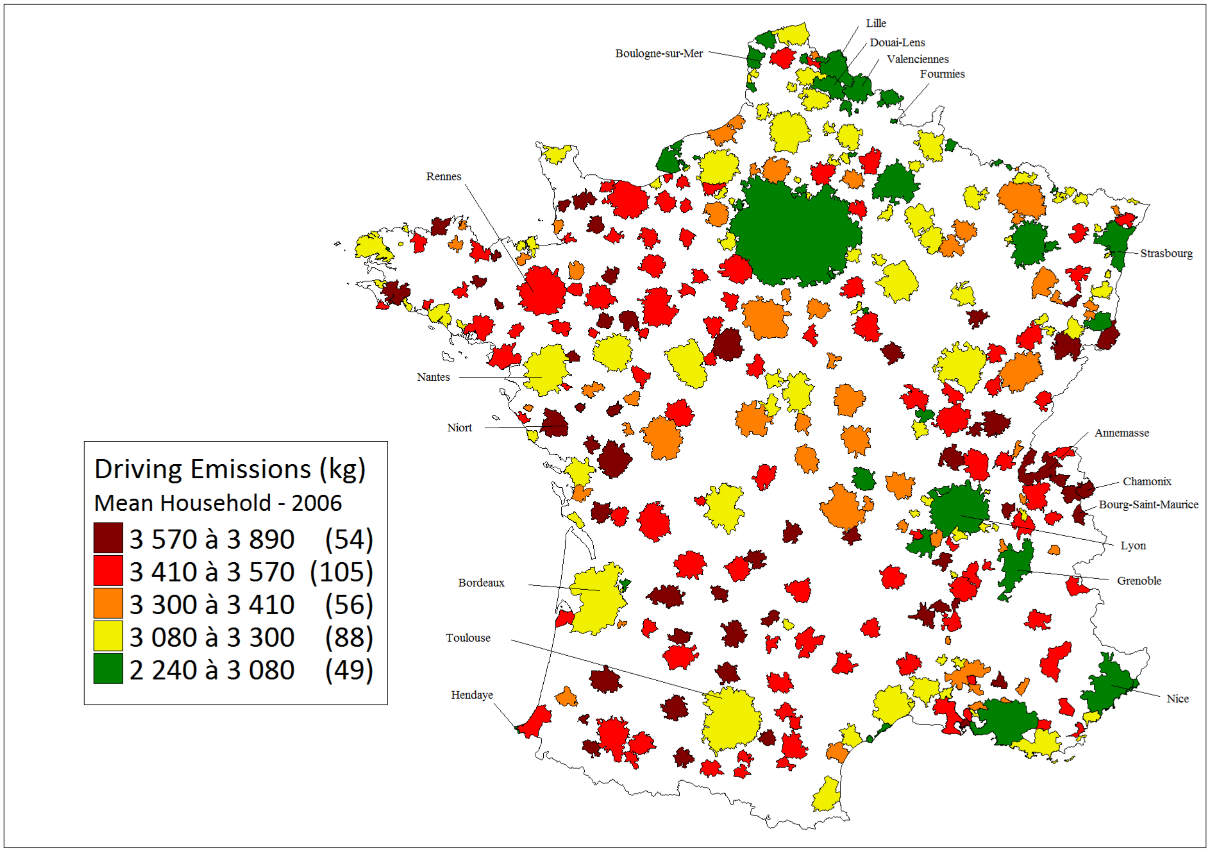
3.2 Carbon 'carprint' and city-size: A bell-shaped curve

Figure 3 depicts the car emissions produced by our standardized household for the whole set of French MAs, using the Heckman estimates provided in Table 5 (column 5).[49]

A salient geographic divide The spatial heterogeneity of household emissions across French MAs is very salient. Very large MAs such as Paris, Lyon, Nice, Strasbourg or Lille exhibit low-carbon footprints (less than 3 tons of CO_2 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 suburbanites to commute easily to city-centers. The MAs of Nantes, Bordeaux and Toulouse are noticeable exceptions, suggesting that they are more concerned with urban

[49] Results are qualitatively very similar for the OLS and 2SLS estimates and we thus do not report them here.

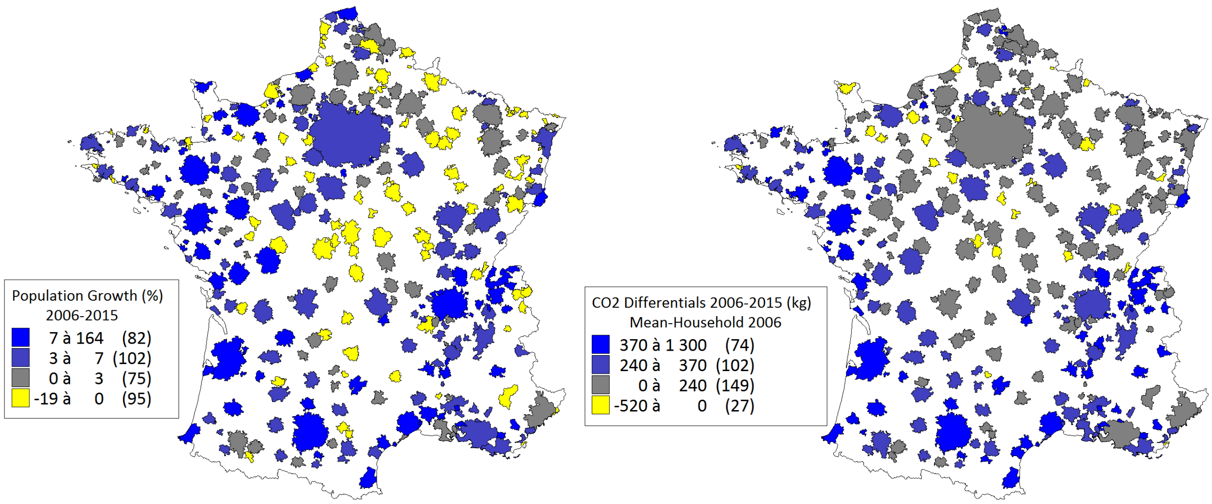
Figure 3: Estimates of the CO_2 'carprint' of the sample mean-household (kg/year)



sprawling than other big French cities. Small MAs such as Hendaye (southwestern tip of France) or Fourmies (northeastern border of France) are also environmentally-friendly, due to a compact design partly driven by their border nature, a natural limit to sprawl. By way of contrast, small MAs located in the Alps (such as Bourg-Saint-Maurice or Annemasse), as well as Western medium cities (such as Rennes or Niort), exhibit very high-carbon 'carprints' due to the large dispersion of population in a geographically scattered urban fabric, whereas eastern medium-cities (such as Grenoble or Valenciennes) have lower car emissions conveyed by the political determination to develop light-rail transit systems. A geographical East-West divide then emerges, with eastern cities having somehow better transport networks (Lille, Grenoble, Nancy, Douai exhibit the largest emissions reductions due to public transport, after Paris and Lyon), but also a more compact urban form. Note that differences across low-carbon cities are not negligible: a French standardized household living in Paris consumes 25% less than an observationally-equivalent resident of Lyon, a gap that is similar to the effect of moving a US standardized household from Atlanta to Boston (Bento et al. 2005).

These figures are of crucial importance for policy makers, since Atlantic and Mediterranean cities experienced the strongest urban growth over the past decade. As shown by Figure 4, that plots population growth in each MA over 2006-2015 (left map) against differentials in carbon emissions computed from our projections over the same period (right map), the two patterns are very similar, with a correlation coefficient above 0.5. In addition, as urban growth mostly occured at the city-fringe of Atlantic and Mediterranean cities, this participated to further deteriorate their environmental performance. In Rennes for instance, according to our estimates, our standardized household emits 550 kg more CO_2 in 2015 than in 2006, wheras the city of Strasbourg experienced much less sprawl, with an increase of only 250 kg of CO_2.

Figure 4: Population growth (left) and car emissions differentials (right) over 2006-2015



A bell-shaped curve Therefore, our estimates suggest that Density, Diversity and Design affect all together significantly households' car emissions in France. Densely populated MAs have lower driving footprints, as well as MAs with good rail transit networks. As it is easier for large cities to afford mass transit infrastructure, Density and Design feed on each other to self-sustain the low-carbon 'carprint' of large metropolitan areas. By contrast, job-housing centrality and the high fractal dimension of historical city centers (where there is one) might compensate poor transit and low density in small cities. This balance cannot be achieved in the midstream medium-cities, which are either sprawling (low density suburbs and extensive road networks), or not large enough to sustain mass public transport networks, or leapfrogging in their built-up fabric (low fractal dimension).

As such, Table 8 and Figure 5 depict an inverted U-shaped relationship between MA-size and the mean-household car emissions.[50] To precise the rationale of this bell-shaped pattern, we can separate the effects of the 3 D's in our projections.[51] We find that Density has a strong homogeneous linear effect on fuel consumption: a larger MA population translates into a higher density and large car emissions savings. The effect of Design is much more differentiated. Since commuting distance and road stock increase with MA size, driving increases first as city population expands.

[50] Computed from the Heckman estimates drawn from Table 5. Results are qualitatively similar for OLS and 2SLS.
[51] Figure 7 in Appendix D summarizes these findings.

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

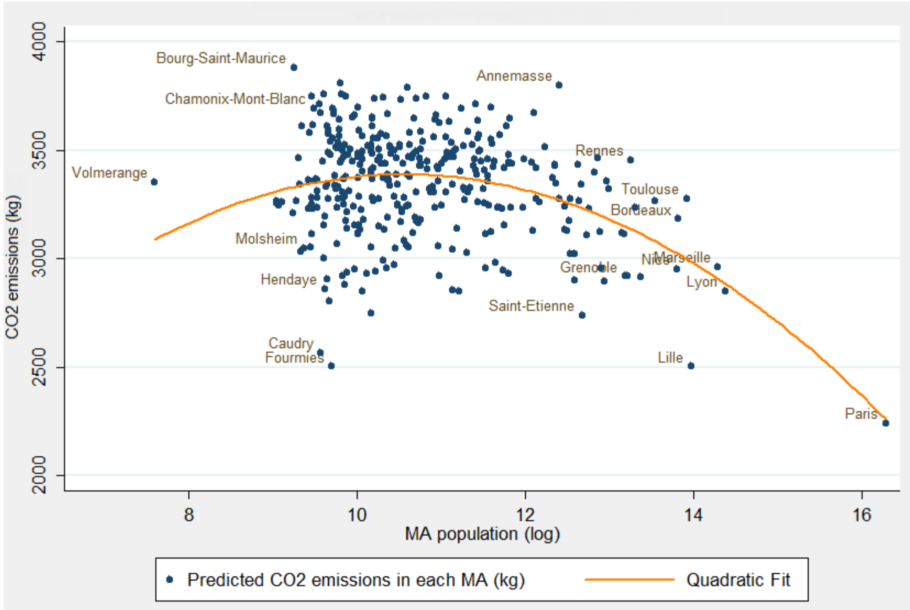


Table 8: MA-size and the CO_2 'carprint' of the sample mean-household: estimations

CO_2 car emissions	OLS coefficients	(Std. Dev.)
log(MA-size)	725.8***	(135.6)
log(MA-size)^2	-34.4***	(5.9)
Constant	-440.4	(766.5)
Observations	352	
R-squared	0.149	

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

But above the threshold of 400,000 inhabitants, public transit systems largely compensate the other effects and generate drastic savings in car emissions. These gains are even more exacerbated that large cities are more fractal. The impact of Diversity is indeed very heterogeneous across small and medium cities: those can exhibit very low-carbon as well as very high-carbon urban morphologies, depending on their local history.

This confirms that, in small cities, households do not drive much either because of the good job-housing balance or because of the relatively low road stock. Design therefore compensates the driving incentives stemming from low densities. As city grows, trips become longer because of road networks expansion and longer commuting distances, until public transit becomes strong enough to curb car emissions down. All in all, the turning point below and above which French MAs can achieve a low-carbon 'carprint' is around 100,000 inhabitants.[52] From an urban

[52] As shown in Table 13 and Figure 8 provided in Appendix E, this bell-shaped form is not triggered by the two tails of the distribution of MAs, as it still holds when Paris and Volmerange-les-Mines are excluded from the sample.

planning perspective, it should be emphasized that the existence of what seems to be a sub-optimal population size could call for specific policy actions designed to address more specifically medium-sized MAs, so that they can develop in a more sustainable manner.

4 Conclusion

While personal driving contributes to an increasing percentage of GHG emissions, this paper shows that there exists exciting opportunities for urban policies to curb those emissions down. It shows that low density, neighborhoods far-flung from job centers, poor public transit and morphological homogeneity increase car-related emissions.

Therefore, increasing the Density of new residential developments, in inner cities or at the urban fringe of metropolitan areas where most new developments take place, might help reducing significantly the carbon 'carprint' of households, and operating cities more efficiently. We estimate that doubling residential density would result in an annual saving for its residents of approximatively two tanks per year, over and above any difference attributable to changes in earnings, employment status, occupation, education, family composition or more generally, to residence selection. Even though these savings are small, it can be considerably magnified if coupled with better access to job-centers, improved public transit systems, reduced pressure for road construction and a strategic infill of vacuous places (more 'fractal' development), that play a prominent role in car emissions reductions. Therefore, even though compaction alone might not reduce emissions as much as other mitigating policies such as carbon taxes, a package of urban policies combining Densification with better Design and more Diversity can provide an excellent foundation for a low-carbon city in France. In this respect, this paper brings quantitative arguments to support the "Smart City" ideals of an integrated sustainable urban development.

Due to strong spatial disparities in those 3 D's across the urban space in France, we find notable geographic differences in GHG emissions across French cities, even for observationally-equivalent households. For instance, a motorized resident of inner Chamonix, the Alps' largest ski resort, produces around 65% more CO_2 emissions - about $1,450$ more kg of CO_2 - per year, than an observationally-equivalent household of inner Paris.

Disparities across French cities actually reveal a spatial environmental bell-shaped curve, as it provides evidence of an inverted U-shape relationship between city-size and CO_2 car emissions, that contradicts the linear pattern exhibited in most previous US studies. Therefore, beyond the introductory slogan for promoting the ecological advantages of big compact cities, this paper shows that there is also great potential of energy savings in small cities with low densities, which may be spontaneously as 'smart' as their large, heavily-engineered counterparts. Conversely, medium cities - around 100,000 inhabitants - could deserve more specific attention from policy makers.

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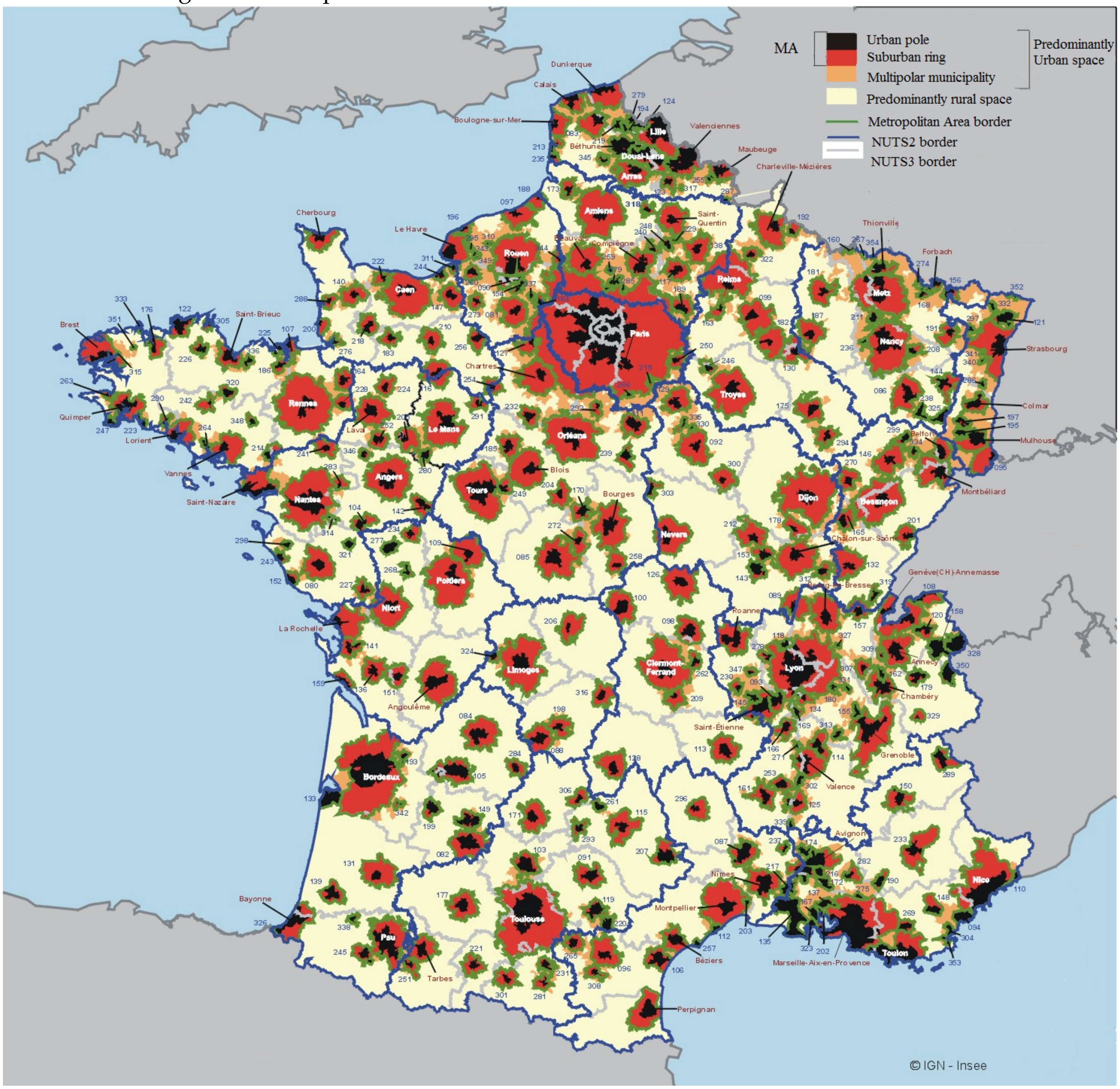
APPENDIX

A French Metropolitan Areas

Figure 6: Metropolitan Areas of 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 described by a mean value. This is arguable, a typical counterexample being a leapfrogging city, where the mean density at the municipal level does not reflect well the irregularities of the distribution of density in the municipality itself. However, finding a good metric to characterise such irregular geometries if difficult. How can we characterize the 'leapfrogging-ness' of a city? Mandelbrot (1982) coined the term 'fractal' to qualify such intrinsically irregular objects. Fractals are objects in which mass is not homogeneously distributed, but concentrated in nested clusters at different scales. This description fits well with the clusters of buildings of a leapfrogging city that arrange themselves into neighbourhoods, municipalities and cities in an irregular way at each scale. Mandelbrot (1982) uses a powerful metaphor to explain why geometric measures such as length, surface or density loose most of their descriptive power for these objects. For instance, it is difficult to compute the length of the Britanny coast, as it is crawling with small irregular creeks. The contour one can compute with a pen and a ruler from maps of Brittany printed at two different scales would definitely strongly differ, since the tiniest creeks would only appear when we zoom enough on the map. Any measure of the length of this coast would thus describe very imperfectly its real morphology. In the same spirit, the 'density' of a leapfrogging city does not reflect the complexity of its urban form.

Mandelbrot (1982) proposed a new metric independent of scale to classify these objects: the 'fractal dimension', which is a 'degree of inhomogeneity' of an object across scales. The most common and robust way to compute this dimension, which is also known as the Minkowski-Bouligand definition,[53] 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 $D = \lim\limits_{a_n \to 0} \frac{log(N(a_n))}{log(1/a_n)}$.

The rationale of this calculus resorts to limit cases of classical geometries. The surface area of a classical geometric object is $Area = A \cdot a^D$ where A is a factor of form,[54] D the classical dimension, and a the typical scale of the object. The fractal dimension represents the same D for non regular objects that do not exhibit typical scale a.[55]

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

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

[55] If we cover a line of length L (geometric object of classical dimension 1) with the lattice of squares of size a_n, we find that $N(a_n) = \frac{L}{a_n}$. Thus, $\frac{log(N(a_n))}{log(1/a_n)} = \frac{log(L)+log(1/a_n)}{log(1/a_n)} \underset{n\to+\infty}{\to} 1$. 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, $\frac{log(N(a_n))}{log(1/a_n)} = \frac{2\cdot log(L)+2\cdot log(1/a_n)}{log(1/a_n)} \underset{n\to+\infty}{\to} 2$. This limit coincides systematically with the classical dimension for classical objects.

The fractal dimension can vary continuously from 0 to 2.

- If $D < 1$, we have a collection of unconnected points: mass is concentrated in punctual, 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 close to 1.4, we have a collection of sparse clusters (typically a leapfrogging residential city);
- If D is close to 1.6, we face a continuous fabric of large buildings separated by large spaces (typically large housing complexes such as French 1960's 'Grands Ensembles';
- If D is close to 1.8, we have attached housing separated by large streets (Haussmannian style in Paris, for instance);
- If D is close to 2, the object covers the geographic map with more and more detail (buildings of mixed size separated by tiny streets and courtyards, such as Paris inner historical center).

B.2 Box counting algorithm

The best numerical computation of the Minkowski-Bouligand fractal dimension is given by the box-counting algorithm exposed in (Liebovitch & Toth 1989). After counting for 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:

$$N(a_n) \approx A \cdot (a_n)^D.$$

Thus, with a log-log specification we can write:

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

Therefore, one can recover D through a log-log OLS regression over the number of boxes covering the fractal at different scales. We follow Thomas et al. (2010) and use the R-squared of this regression is an indicator of the fractal behaviour (or not) of the geometric object. If the lower limit $R^2 = 0.999$ is not matched, the object may not be fractal or may exhibit multifractal behaviour, which means that two different morphologies coexist in it. This is likely to occur for municipalities with very different neighborhoods. In France, contrary to many other countries, municipalities are small enough to have rather homogeneous morphologies, which advocates for the existence of a maximum one-slope break. All French municipalities are found to be fractal actually, with a small part (28% of the total) exhibiting multifractality.

Note that all the results presented in this paper are robust to changes in the limit scale and fractal computational method.

C Additional regression results

Table 9: Household fuel consumption and urban form: further 2SLS estimations

Variable: Fuel consumption (gallons)	All urban households		
	(1) OLS	(2) 2SLS	(3) 2SLS
DENSITY			
log(residential population density)	-13.8***	-12.3 **	-14.9***
	(4.31)	(5.21)	(5.53)
DESIGN			
log(distance from residence to CBD)	12.4***	23.5 ***	20.9***
	(4.18)	(5.46)	(5.08)
log(weighted road access in the rest of the MA)	19.9***	13.5*	14.9**
	(7.49)	(7.64)	(7.32)
log(access to rail in the rest of the MA)	-59.2***	-60.3***	-59.2***
	(10.7)	(9.52)	(9.91)
log(density of public transport stops)	-9.63***	-8.28***	-7.81**
	(3.19)	(3.00)	(3.08)
DIVERSITY			
Fractal dimension of the built-up environment	-89.6**	-63.4^{+}	-56.1
	(37.8)	(41.5)	(44.0)
Household characteristics	✓	✓	✓
Year fixed effects	✓	✓	✓
INSTRUMENTS			
Mortality density in 1962		✓	✓
Distance to largest MA municipality in 1806		✓	✓
Market Potential in 1936			✓
Observations	15,608	15,608	15,608
R-squared	0.234	0.165	0.165
Cragg-Donald F-Stat		5,687	5,191
Shea Partial R-squared (log density)		0.44	0.50
Shea Partial R-squared (log distance to CBD)		0.54	0.62
Hansen J Statistic (p-value)			1.20 (0.27)

Notes: (i) Standard errors in brackets, clustered at the MA level (227 clusters); ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (ii) For the sake of clarity, the coefficients associated with household charactaristics and the constant are not reported.
Source: 'Budget des Familles' survey and Census data (INSEE, 1999, 2001, 2006), BD-TOPO (NGI, 2001, 2006), 'Fichiers Urbanisation de la France' (INED, 1986), 'Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative' (INED, 2003).

Table 10: Household fuel consumption and urban form: First-stage regressions

Variable	Population density	Distance to CBD
	(1)	(2)
log(mortality density in 1962)	0.68***	-0.08***
	(0.04)	(0.03)
log(distance to largest MA municipality in 1806)	-0.025	0.55***
	(0.03)	(0.04)
log(weighted road access in the rest of the MA)	0.31***	0.035
	(0.05)	(0.09)
log(access to rail in the rest of the MA)	-0.17**	0.19**
	(0.0651)	(0.0949)
log(density of public transport stops)	0.18***	0.02
	(0.03)	(0.04)
Fractal dimension of the built-up environment	0.13***	-0.56
	(0.23)	(0.38)
Household characteristics	✓	✓
Year fixed effects	✓	✓
Observations	15,608	15,608
R-squared	0.905	0.826
F-stat	499	229

Notes: (i) Standard errors in brackets, clustered at the MA level (227 clusters); ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (ii) For the sake of clarity, coefficients associated with household characteritics or time dummies and the constant are not reported.
Source: 'Budget des Familles' survey and Censuses (INSEE, 1999, 2001, 2006), BD-TOPO (NGI, 2001, 2006), 'Fichiers Urbanisation de la France' (INED, 1986) and 'Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative' (INED, 2003).

Table 11: Greenest MAs: CO_2 'carprint' of the mean-household with Corrected Income (kg/year)

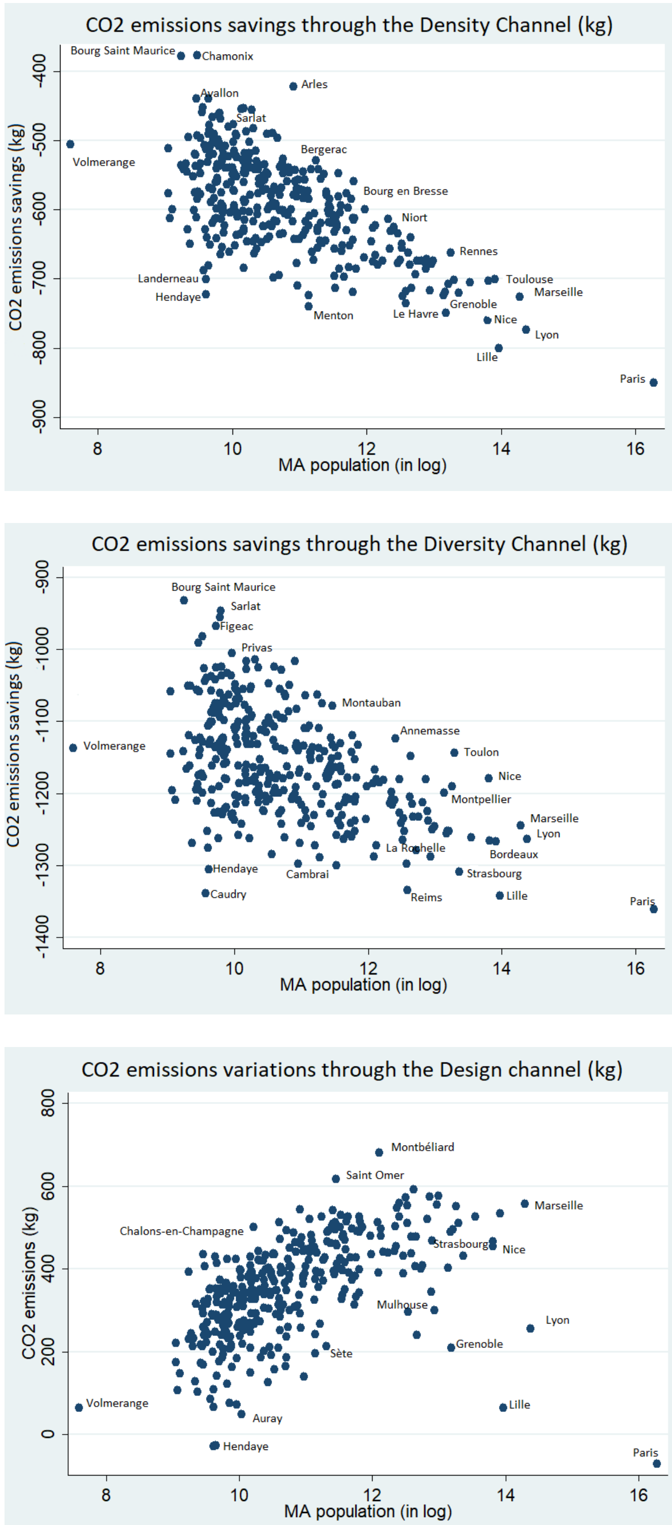
Name	OLS pred.	Rank	2SLS pred.	Rank	Heckit pred.	Rank	MA pop.
Paris	2,284	1	2,287	1	2,237	1	11,769,424
Fourmies	2,479	2	2,456	2	2,367	2	16,324
Lille	2,499	3	2,505	4	2,420	3	1,164,717
Caudry	2,532	4	2,501	3	2,428	4	14,322
Montereau-Fault-Yonne	2,719	5	2,685	5	2,605	5	26,109
Saint-Étienne	2,731	6	2,760	8	2,618	6	318,993
Menton	2,750	7	2,761	10	2,635	7	68,826
Villerupt	2,777	8	2,718	6	2,650	8	19,019
Bolbec	2,799	11	2,761	9	2,676	9	15,750
Sète	2,791	10	2,852	15	2,677	10	73,674
Hendaye	2,789	9	2,758	7	2,680	11	14,993
Tergnier	2,829	12	2,796	11	2,706	12	23,383
Agde	2,871	13	2,865	16	2,720	13	21,293
Boulogne-sur-Mer	2,871	14	2,842	13	2,770	14	133,195
Douai	2,896	17	2,925	28	2,777	15	546,721
Nancy	2,890	15	2,847	14	2,781	16	415,765
Lunéville	2,903	18	2,838	12	2,782	17	27,549
Lyon	2,891	16	2,897	23	2,785	18	1,748,274
Aulnoye-Aymeries	2,924	25	2,866	17	2,791	19	19,649
Berck	2,908	20	2,873	19	2,791	20	24,648
Armentières	2,905	19	2,880	20	2,792	21	58,458
Nemours	2,918	23	2,883	22	2,793	22	18,429
Valenciennes	2,921	24	2,917	27	2,804	23	398,813
Yvetot	2,947	30	2,883	21	2,804	24	15,432
Calais	2,916	22	2,915	26	2,808	25	125,525

Table 12: 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	3,789	352	3,736	352	3,622	352	10,357
Sarlat-la-Canéda	3,768	351	3,713	351	3,607	351	18,022
Cahors	3,728	347	3,665	342	3,588	350	40,175
Annemasse	3,712	345	3,704	349	3,583	349	244,178
Mâcon	3,701	343	3,645	340	3,582	348	93,073
Ancenis	3,739	350	3,688	346	3,582	347	19,308
Lannion	3,720	346	3,700	347	3,577	346	63,425
Niort	3,691	339	3,681	344	3,568	345	134,927
Bressuire	3,728	348	3,710	350	3,566	344	18,225
Montbéliard	3,682	336	3,644	339	3,564	343	179,761
Ussel	3,709	344	3,632	335	3,559	342	14,074
Saint-Lô	3,701	342	3,630	334	3,559	341	49,761
Les Herbiers	3,728	349	3,701	348	3,557	340	14,833
Sablé-sur-Sarthe	3,692	340	3,647	341	3,547	339	30,193
Saint-Gaudens	3,686	338	3,599	329	3,545	338	27,175
La Bresse	3,697	341	3,682	345	3,543	337	12,851
Auch	3,682	337	3,642	338	3,538	336	36,934
Lons-le-Saunier	3,652	328	3,565	319	3,527	335	56,134
Belley	3,676	335	3586	326	3,526	334	16,547
Oloron-Sainte-Marie	3,674	334	3,599	330	3,523	333	22,382
Saint-Louis	3,660	333	3,633	336	3,521	332	89,549
La Roche-sur-Yon	3,660	332	3,670	343	3,521	331	107,584
Aubenas	3,653	329	3,585	325	3,504	330	44,546
Tulle	3,644	326	3,571	320	3,503	329	31,693
Mayenne	3,645	327	3,584	324	3,500	328	26,361

D Car emissions effects of each dimension of urban sprawl

Figure 7: MA-size and the CO_2 emissions associated with each of our 3 D's



E Complementary results

Figure 8: MA-size and the CO_2 'carprint' of the sample mean-household (kg/year, Paris and Volmerange excluded)

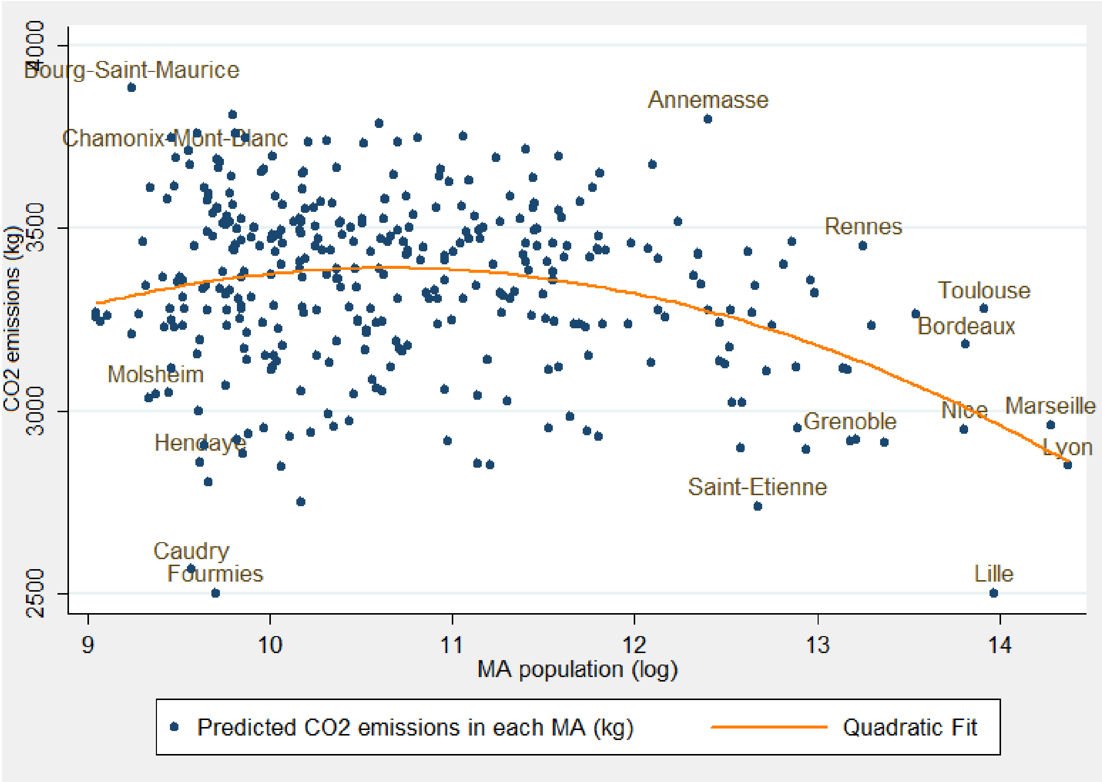


Table 13: MA-size and the CO_2 'carprint' of the sample mean-household (Paris and Volmerange excluded)

Variable explained: CO_2 car emissions	OLS coefficients	(Std. Dev.)
log(MA-size)	811.8***	(186.8)
log(MA-size)^2	-38.1***	(8.3)
Constant	-931.1	(1044.1)
Observations	350	
R-squared	0.10	

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