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 Diversity. Individual data allow us to sort out emission disparities triggered by the urban form and the spatial sorting of households. We also use instrumental variables to control for other endogeneity issues. Our results suggest that, by choosing to live at the fringe of a metropolitan area instead of its city-center, a representative household would bear an extra-consumption of approximately six fuel tanks per year. More generally, doubling residential Density would result in an annual saving of approximately two tanks per household, a gain that would be much larger if compaction were coupled with a better urban Design (job-housing centralization, improved rail/bus routes to central business districts, reduced pressure for road construction and less fragmented built-up environment in urban areas), and more Diversity (concentration of various local amenities such as shops and public facilities). 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/Diversity by a better Design.

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

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

Urban planning may be a cornerstone case for local carbon policies. Actually, GHG emissions in developed countries are increasingly driven by private energy consumption, and especially car emissions that prove difficult to tax. Urban planning offers an alternative way to reduce those emissions. Moreover, a more sustainable urban form can contribute to reduce car dependence and therefore, political and social oppositions to a possible carbon tax. This paper analyses the interplay between car emissions and urban form in France, with a particular focus on sprawl-counteracting forces conveyed by job-housing centralization, public transit systems and building morphology.

Urban economic theory has long underscored the fundamental trade-off between real estate prices and transport costs (Wilson 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 live in more spacious homes. 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, and gave birth to automobile-dependent urban forms at

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

the urban fringe.[2] As underlined by Brueckner (2000) and Brueckner & Helsley (2011), 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. Sprawl has come at the costs of substantial consumption of non-renewable resources, loss of soil bio-diversity and reductions of carbon sinks, transport congestion or air pollution. More importantly for the purpose of this paper, the dispersed automobile-dependent development pattern has also increased urban segregation and lengthened the vehicle-miles traveled by suburbanites, which contributes to fuel global warming through a rise in automobile externalities (Parry, Walls & Harrington 2007).

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

Newman & Kenworthy (1989) were the first to draw worldwide attention to the urban form - fuel consumption nexus. 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, we cannot extrapolate strong policy recommendations from this seminal analysis, since there exists substantial 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, elderly or young residents, who are less able to afford owning and operating a car. By 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 activities. Obviously, if fuel consumption is caused by households intrinsic preferences for housing or travel, any attack against sprawl could be misguided, with few benefits to expect from compacting cities, since people may not behave differently in denser

[2] Empirical evidence of this decentralization process is provided by Baum-Snow (2019) and Baum-Snow & Turner (2017) for the US, by Baum-Snow et al. (2017) for China, and by Mayer & Trevien (2017) and Garcia-López, Hémet & Viladecans-Marsal (2017) for France.

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

[4] In France, CO_2 emissions 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 -approximately 95% of transport-related emissions, and a very large share -more than 55%- of road emissions is generated by cars in France.

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

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 in the US.[6] 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.[7] 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 compaction policies would not be as effective as gasoline taxes or congestion charges to decrease 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.[8] 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 fuel consumption has been seldom investigated and currently dampens the acceptability of a fuel carbon tax.

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 exhibit large variations in their morphology, due to strong spatial differences in historical heritage and urban planning. Therefore, French travel behaviors and modal choices differ drastically from US ones. Second, as stated above, there is an especially strong social resistance to the implementation of carbon taxes in France. Nevertheless, France committed to reducing transport emissions by 14% over 2005-2020, under the European energy-climate package and to carbon neutrality by 2050 under the National Low-Carbon Strategy. Still, external costs associated with burning fuel largely exceed excise taxes levied on it in France,[9] and road transport remains excluded from the EU Emissions Trading System, the cornerstone of the European policy to reduce GHG emissions.

[6] 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), Handy (2005), as well as the meta-analyses of Ewing & Cervero (2010) and Stevens (2017).

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

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

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

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.

Another important contribution of our paper is to study the impact on driving patterns of a large set of urban form measures, among which an indicator of morphology never used so far, in combination with both 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). Density has been the most extensively studied feature of the urban form, as it is an essential dimension of the built-environment. The spatial Design of cities has been less investigated, but a subsequent amount of papers consider that access to jobs and to 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 or entropy measures of land-use mix. In this paper, we examine the joint impact of these 3 D's on car emissions in France, and we also resort to an innovative measure of city-Design, the fractal dimension, that enables us to capture spatial disparities in urban morphology due to historical legacy.

Our ultimate contribution regards new policy insights that can be drawn from studying 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 approximately six fuel tanks per year. More generally, doubling residential Density would result in an annual saving of approximately 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 business districts, reduced pressure for road construction and a more pedestrian built-up environment - and more Diverse local amenities. Another important finding is that the relationship between metropolitan population and car emissions is not linear in France, contrary to the US (Borck & Pflüger 2019). In small French cities, households do not drive much because of either a good job-housing balance or a lower 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.

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

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

1 Data on fuel consumption and urban form

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

1.1 Fuel consumption: a household measure

To measure fuel consumption, we resort to the French household survey 'Family Budget' (*Budget des Familles*, 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.[10] 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 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 (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,[11] family composition (number of children, workers, job seekers

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

[11] 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.

or retired people) and educational attainment,[12] occupation,[13] 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, among which fuel expenditure, broken down into gasoline, diesel and Liquefied Petroleum Gas (hereafter LPG) expenses.[14] We use the French average price of each type of fuel in 2001 and 2006 to convert these expenses into volumes.[15]

Table 1 reports descriptive statistics on the main variables drawn from the BdF surveys. To measure income, we sum the resources (living aside extraordinary revenues) of all individuals in the household and divide this total by the number of Consumption Units (hereafter CU).[16] 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.[17] One fuel tank being typically 50 litres in France (approximately 13 gallons), yearly mean fuel consumption is about 20 tanks in France.

1.2 The metrics of urban sprawl

We supplement the BdF database with several metrics of urban form at the municipality and metropolitan area levels. Though municipalities constitute our scale of observation for Density and Diversity, the Design of the entire metropolitan area actually affects car usage. In France, a metropolitan area (MA hereafter) is composed of a cluster of urban municipalities[18] hosting a

[12]The classification of diplomas is the following: 1. Doctorate, post-graduate or *Grande Ecole*, 2. University post-graduate 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.

[13]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.

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

[15]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 of Ecological and Solidarity 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/.

[16]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.

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

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

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

Year	2001		2006	
Household variables	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
Fuel consumption (gallons)	308 (346)	8,180	243 (286)	4,303
Nb. of working adults	1.02 (0.90)	5	1.02 (0.88)	5
Nb. of non-working adults	0.87 (0.83)	6	0.84 (0.84)	6
Nb. of young children (< 16 y.o.)	0.54 (0.92)	7	0.55 (0.93)	6
Number of vehicles	1.24 (0.80)	8	1.31 (0.84)	9
Age (head of household)	51 (16.7)	99	50 (16.9)	99
Income (€)	28,871 (21,458)	464,450	32,416 (24,907)	688,617
Income per CU (€)	17,562 (12,883)	464,450	19,969 (14,026)	459,078
Total number of households	10,260		10,211	
Number of urban households	7,812		7,797	

Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006). A few outliers with huge incomes (top 0.02% percentile of the most affluent households) have been removed from the raw data.

minimum number of jobs[19] (the "urban pole" of the MA) surrounded by a group 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). Thereby, 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 the urban design on fuel consumption.

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

1.2.1 A simple monocentric classification of municipalities

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

- The city-center of a MA would either be 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

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

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 (aggregated in the dark-red area depicting downtown Paris).

- The inner suburbs of a MA refer to all municipalities of an urban pole that are not city-centers (illustrated for Paris by the dark-salmon 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).[20]
- Multipolar municipalities refer to non-urban municipalities under the influence of several MAs without being part of a particular MA: 40% of their population work in surrounding MAs, none of which being all alone above this threshold (green municipalities in Figure 1).
- The rural space comprises all municipalities outside the predominantly-urban space and outside the influence of any MA (see Figure 6 in Appendix A).

This classification relies on functional and morphological criteria, and it is thereby particularly relevant to describe urban sprawl as inner/ outer suburbs, multipolar and rural municipalities actually represent sequential steps of land development. However, since it does not provide information on the mechanisms conveying fuel consumption in sprawling areas, we then turn to more precise indicators of the urban form.

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

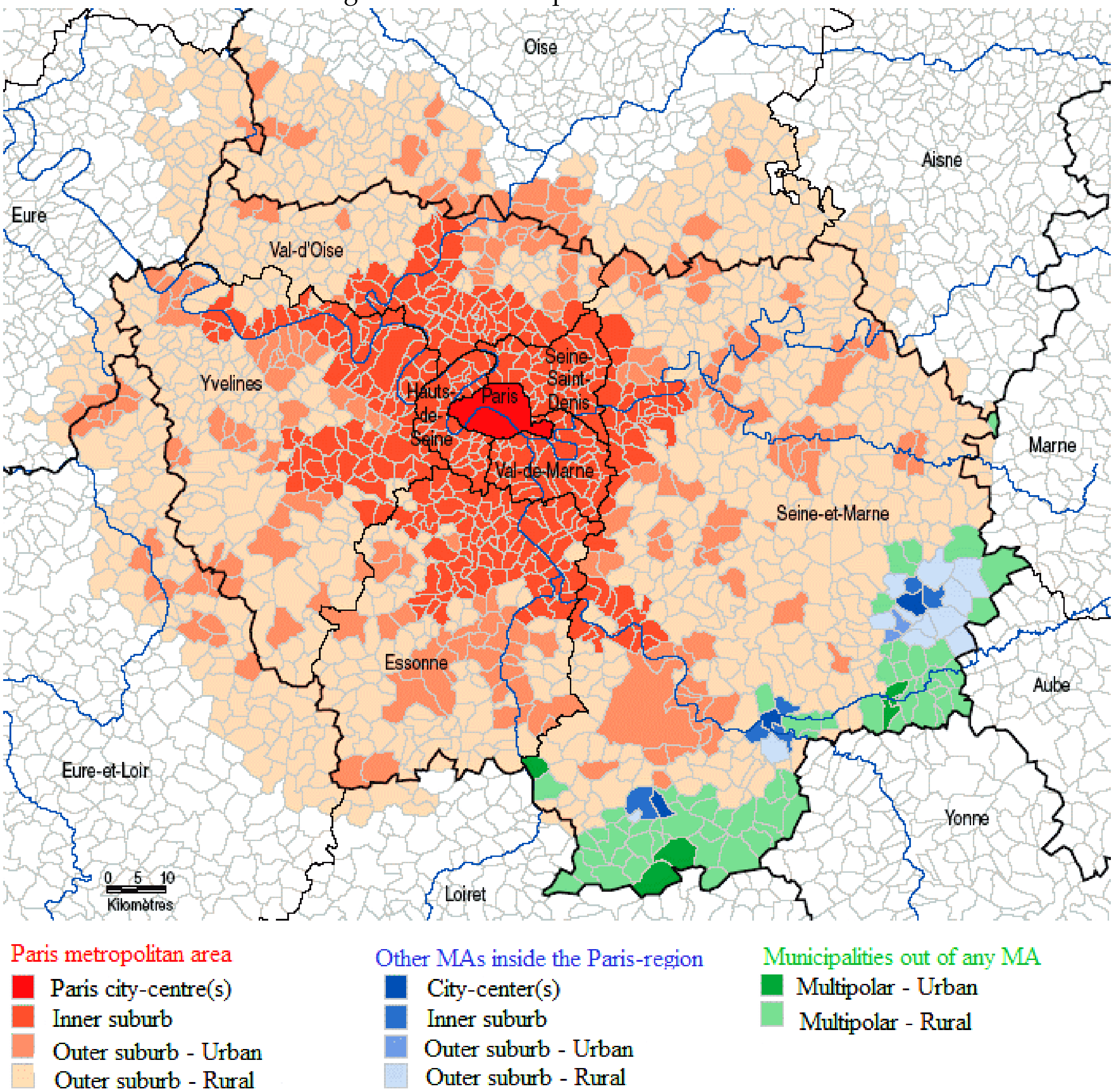
In our second approach, urban form is apprehended by several indices of Density, Design and Diversity.

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 every trip, but this benefit can be overcome - at least partly - by a larger frequency of trips, as desired destinations have become closer. 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).[21] Table 2, which reports summary statistics on the urban form of French municipalities, shows that the average population

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

[21] This measure might not necessarily 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.

Figure 1: The Metropolitan Area of Paris



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

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

YEAR	2001		2006	
Urban Form Variables	Average (Std. Dev.)	Max	Average (Std. Dev.)	Max
DENSITY				
Density of population	2,959 (4,519)	23,396	3,410 (5,282)	25,971
DESIGN				
Distance from residence to CBD (km)	8.55 (11.27)	71.20	9.02 (10.75)	58.37
Density of pub. transit in residence (stops/km^2)	4.64 (7.32)	33.47	4.96 (7.61)	33.57
Fractal dimension in residence	1.50 (0.18)	1.82	1.50 (0.19)	1.84
Road potential in the rest of the MA	14.46 (20.22)	69.01	16.06 (21.52)	69.01
Rail potential in the rest of the MA	1.26 (2.19)	8.46	1.44 (2.35)	8.46
DIVERSITY				
Herfindahl index of leisure activities	0.11 (0.17)	1	0.13 (0.20)	1
Nb of MAs	156		181	
Nb of urban municipalities	1,379		1,674	

Note: Urban municipalities sampled in the BdF surveys (INSEE, 2001 and 2006).
Sources: Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap(2017), DADS (2001 and 2006), and authors' own computations.

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

Home-Business distance The existence of business centers may have potential adverse effects on commuting patterns, especially if they 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 home-municipality and the 'Central Business District' (CBD) of the home-MA[22] to measure the level of centrality or remoteness of the household's residence.[23] Table 2 shows that the average distance to CBD is around 9 km in France, but can exceed 70 km in large MAs such as Paris.

Transport accessibility The effect of distance to CBD can be mitigated by the design of transport infrastructure. The spatial extension of road and public transit networks determines households' convenience to travel within the MA without their car.[24] To measure how well connected

However, since using either the former or the later measure does not change our empirical results, standard density will be used hereafter.

[22]The CBD is the municipality concentrating the highest number of jobs in the MA.

[23]Alternate metrics would be the effective average distance from residence to all municipal jobs in the MA, computed from population censuses. We are able to reproduce our key findings with these metrics, as will be shown afterwards.

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

is the household residence to the MA, we build 'Transport Potential' indicators[25] based on the 2001 and 2006 versions of the BD-TOPO© topographical database, developed by the French National Geographical Institute (NGI afterwards). BD-TOPO summarizes all landscape elements of the French territory, at a metric accuracy, in particular road and rail transport networks. The 'Transport Potential' indicators drawn from the BD-TOPO database are computed as follows:

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

where k is the municipality of residence, $k' = 1, ..., K$ are the other municipalities in the MA and $dist_{kk'}$ the distance between the centroids of municipalities k and k'.[26] 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.[27] 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 a MA. For shorter trips, modal substitutability depends strongly on transit systems (bus, tram, rail) accessible in the close-vicinity of the residence. Unfortunately, the BD-TOPO does not provide information on bus lines. Thereby, we complete our dataset with a comprehensive review of bus stops through OpenStreetMap in 2017, that we retropolate to 2001 and 2006 using line openings dates published either by French Official Journals or by local transport authorities. We then compute the density of all public transport stops (heavy-rail, subway, tramway and bus) in the municipality of residence.[28]

Fractal dimension as a walkability measure However, if buses and trains are car substitutes for long trips, walking may be the most influential mode for everyday trips. To account for the walkability of the local urban fabric, previous studies have used indicators such as street width, number of ways in crossroads, number of building blocks, blocks length, parkings or dead-ends per acre.[29] We prefer to rely on a morphological synthetic index used by a large corpus of quantitative geographers for two decades, but neglected so far by economists: 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.

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

[26] 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.

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

[28] 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).

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

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.

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

To compute the fractal dimension of the French urban fabric, we use the building footprint available in the BD-TOPO.[30] Our index of fractality ranges from 0 to 2, the highest values being associated to municipalities having the highest number of interlocked buildings of different scales. The average fractal dimension of French municipalities is 1.5 (see Table 2). Typically, rural municipalities have a much lower fractal dimension (below 1), while urban municipalities usually range between 1 and 2. Fractal dimensions ranging from 1 to 1.3 are emblematic of outer suburbs with detached-housing developments (leapfrogging). Medium dimensions (1.3 to 1.6) refer to large housing complexes typical of French inner suburbs.[31] Higher dimensions (1.7 to 2) embody more complex built-up environments typical of ancient city centers: buildings blocks of different sizes arranged around squares, avenues or narrow streets.[32]

The fractal metric is obviously correlated with density. However, it captures the way buildings are distributed in space rather than density *per se*. Two municipalities of similar density can indeed exhibit very different urban morphological legacy. 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 Paris and Lille MAs: *Créteil* and *Roubaix*. Both municipalities display similar densities ($7,939$ inhab./km^2 and $7,262$ inhab/km^2 respectively in 2006), as well as similar distances to CBD and transport potentials,[33] but they strongly differ in their fractal dimensions, as illustrated by Figure 2. *Créteil* hosts regular housing complexes crossed by motorways, built from the mid 1950's to the early 1970's by a disciple of *Le Corbusier*, whereas *Roubaix* exhibits low-rise attached dwellings located along narrow streets dating back to the 19$^{\text{th}}$ century. These differences in urban morphology result in a fractal dimension of 1.65

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

[31] Suburban municipalities with '*Grands Ensembles*' have an average fractal dimension at 1.6.

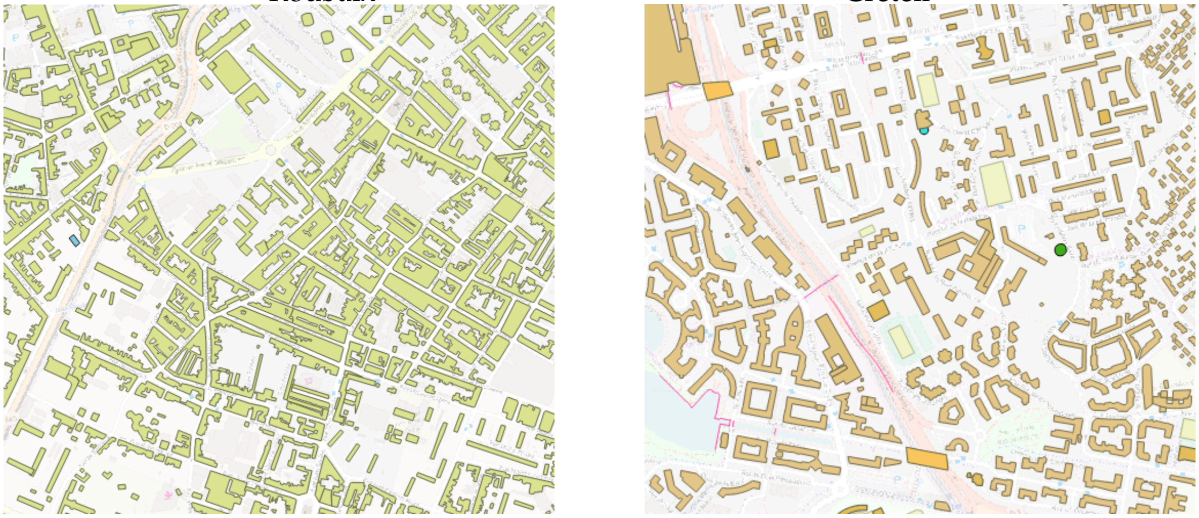
[32] *Haussmanian* patterns typical of the 19$^{\text{th}}$ century can exceed 1.8, for instance in downtown Paris.

[33] For instance, they both enjoy a subway line that connects them to the city center in less than 30 minutes.

for *Créteil* and 1.81 for *Roubaix*, which is close to the maximum value found for downtown Paris.

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

Roubaix | Créteil



Fractal Dimension: 1.81 | Fractal Dimension: 1.65

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

Diversity The Diversity of local amenities constitutes our last 'D'. Indeed, if households value local amenities, transport demand will strongly depend on the scope of leisure activities enjoyable in the municipality of residence. The way Diversity impacts fuel consumption is not straightforward, however. The more diverse the recreation opportunities, the shorter the distances covered to enjoy these amenities. Nevertheless, the frequency of trips may also increase with the number of activities one can enjoy.

To measure Diversity, we compute a Herfindahl index of leisure activities in the municipality of residence, using the matched employer-employee dataset DADS (*Déclaration Annuelles de Données Sociales*) constructed by the INSEE from compulsory declarations made annually by all legal employer entities settled in France. These declarations provide longitudinal information about each employer (identifier, sector and location municipality) and each employee (start and end date of each job spell, earnings, occupation, part-time/full time, permanent/temporary contract, occupation and working time).[34] We use the three-digit level of the 'Economic Nomenclature Synthesis' (NES) to precisely identify the market shares of the following activities in the municipality of residence: restaurants (NES 553), bars or nightclubs (NES 554), cinemas (NES 991), museums, theaters, sport facilities (NES 923 to 927), and shops (NES 521 to 527). The Herfindhal index is then computed as follows:

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

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

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

There are some very small rural municipalities for which a Herfindahl index cannot be computed, since they have no salaries working in the leisure sector.[36] Since we loose 808 observations (5% of total) when we include our index of Diversity in the regression, we provide two sets of estimates afterwards (with and without this metrics).

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. To understand which factors drive the nexus between fuel consumption and 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:

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

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, number of children under 16 years,[37] as well as the age, age-square, sex, diploma and occupation of the household-head. To capture the impact of sprawl on households, 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 to be a non-Parisian city-center. Columns

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

[36] One half of the 36,000 French municipalities has less than 500 inhabitants, one tenth less than 100 inhabitants.

[37] 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 thereby measure the impact on fuel of having underage children, but not the extra consumption associated with their first vehicle.

1 and 2 in Table 2.1 display the results of this first set of linear regressions for the sample of all households and urban households respectively, once controlled for households' characteristics and year fixed effects.

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

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

where $Density_{k,t}$ is the log of population density in the municipality of residence k at time t, $Design_{k,t}$, the vector of log-variables capturing the design of the residential environment (distance to CBD, road/rail transport potentials, local density of public transport stops, local morphology), and $Diversity_{k,t}$, the Herfindahl index capturing the diversity of local amenities. The coefficients β, δ and γ measure the impact of each dimension of the urban form on fuel consumption, every other dimensions equal. They are 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 increases by 1%, annual fuel consumption is expected to vary by $\beta \div 100$ 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 2.1 add successively each variable capturing our three D's 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 2.1. For instance, a household living in the city-center of Paris would save 150 gallons per year (column 1) over an observationally-equivalent household living in a non-Parisian city-center, which represents an economy of about 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 approximately 41 gallons per year (3 fuel tanks). The diseconomy associated with the next rings of suburbs would be even larger: approximately 84, 106 and 85 further annual gallons (or 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 several MAs does seem to increase travel demand. By way of contrast, there is no significant difference between outer suburbs and rural areas, which suggests that all 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 (2)
Log(Total income/CU)	69.4***	70.3***
	(4.705)	(4.218)
Number of working adults	126.5***	116.3***
	(4.688)	(12.531)
Number of non-working adults	74.0***	70.3***
	(3.977)	(7.776)
Number of young children (<16 years)	9.3***	8.7***
	(2.670)	(3.067)
Age (Head of household)	5.2***	4.2***
	(0.651)	(0.727)
Age square (Head of household) / 100	-6.8***	-5.9***
	(0.568)	(0.546)
Woman (Head of household)	-37.2***	-40.8***
	(4.566)	(8.548)
Non-Parisian city-centre	Reference	
City-centre(s) of Paris	-150.0***	-147.0***
	(9.643)	(5.959)
Inner suburb of Paris	-47.1***	-44.2***
	(6.973)	(5.873)
Inner suburb out of Paris	41.3***	43.1***
	(5.520)	(7.080)
Outer suburb	83.7***	86.9***
	(6.641)	(9.102)
Multipolar municipality	105.9***	-
	(10.285)	
Rural municipality	85.3***	-
	(5.795)	
Household characteristics	✓	✓
Year fixed-effects	✓	✓
Observations	20,471	15,609
R-squared	0.238	0.225

Notes: (i) OLS estimates drawn from equation (3); (ii) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

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

Variable explained: Fuel consumption (gallons)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Urban households							
Non-Parisian city-centre	Reference							
City-centre(s) of Paris	-147.0***	-80.9***	-152.7***	-19.7	-82.3***	-98.7***	-104.7***	-148.4***
	(5.96)	(14.26)	(6.63)	(15.36)	(9.57)	(9.99)	(11.88)	(6.02)
Inner suburb of Paris	-44.2***	-15.7*	-68.3***	70.4***	19.2**	-30.5***	-34.7***	-45.5***
	(5.87)	(8.45)	(13.81)	(14.03)	(9.44)	(6.17)	(6.64)	(5.79)
Inner suburb outside Paris	43.1***	22.4***	28.0**	51.4***	52.5***	37.6***	20.5***	37.8***
	(7.08)	(6.91)	(11.58)	(7.07)	(6.97)	(6.34)	(7.65)	(7.33)
Outer suburb	86.9***	16.4	61.6***	98.2***	96.6***	64.6***	31.5**	57.4***
	(9.10)	(13.16)	(22.78)	(11.32)	(9.04)	(9.48)	(12.34)	(12.29)
DENSITY								
Log(Density of pop. in residence)		-27.9***						
		(4.78)						
DESIGN								
Log(Distance from residence to CBD)			14.3*					
			(8.29)					
Log(Rail potential in the rest of the MA)				-67.6***				
				(6.83)				
Log(Road potential in the rest of the MA)					-24.0***			
					(2.73)			
Log(Density of pub. transit in residence)						-23.7***		
						(3.44)		
Fractal dimension in residence							-202.6***	
							(40.38)	
DIVERSITY								
Herfindahl index of leisure in residence								86.5***
								(20.50)
Household characteristics	✓	✓	✓	✓	✓	✓	✓	✓
Year fixed-effects	✓	✓	✓	✓	✓	✓	✓	✓
Observations	15,609	15,609	15,609	15,609	15,609	15,609	15,609	14,801
R-squared	0.225	0.233	0.225	0.228	0.228	0.230	0.231	0.232

Notes: (i) OLS estimates; (ii) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) Household characteristics include income per consumption unit (in log), number of working and non-working adults, number of children under 16, as well as age, age-square, sex, diploma and occupation of the household-head; For the sake of clarity, their coefficients are not reported, nor the constant.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

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 is shown in Table 4 and helps to understand what drives the disparities observed between municipalities of different rings. Including residential density alone with residence-type induces a 45% reduction in the effect of living in a Parisian city-center (column 2), 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.[38] 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 pro-ecological effect of living in Paris and the counter-ecological effect of living outside Paris (column 3). The extra consumption of non-Parisian households comes thereby partly from the remoteness of these non-Parisian suburbs. 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 4). 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 pro-ecological effect of living in Paris transits thought its rail transit network, which is the most extensive in France. By contrast, rail access has low impact on non-Parisian inner suburbs and outer suburbs in general: those municipalities obviously benefit less from public transport connections, since transit networks in France are concentrated in large cities and mostly radial. Road access has similar but smaller effects than rail access (column 5): it halves the pro-ecological 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 5 below). The density of public transport stops in residence (column 6) and the walkability of its built-up environment (column 7) partly alleviate the impact of all residence-types, without taking out their significance, which indicates that transit systems and morphology are important further channels conveying the impact of urban form on fuel consumption. Including the fractal dimension especially reduces the coefficient of the outer-suburb dummy, which indicates that an impor-

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

tant part of the effect of living at the urban fringe comes from the leapfrogging morphology of outer-suburbs.

Finally, Diversity has a pro-environmental impact, since fuel consumption rises with the Herfindahl index, and most of its influence comes from the functional specialization of 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, morphology and leisure amenities are particularly important factors dampening negative environmental externalities associated with car use in dense areas such as downtown Paris, and they are only partly captured through a simple monocentric classification.

It is therefore important to dig further into the analysis of the urban form. Table 5 displays the results of regressing household fuel consumption against the 3D's embedded in equation (4), which is our most comprehensive specification. Column 1 reports the point estimates drawn from the sample of all urban households, while column 3 restricts to the sample of urban 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.[39] 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. If the income per CU roughly doubles (is multiplied by 2.7) the annual fuel consumption increases by 68.9 gallons (column 1), a roughly 30% 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 111.3 gallons. This contrasts with the +68 gallons associated with an additional non-working adult, and the +8.3 gallons induced by having more than one young child. The impact of a working-adult is then approximately 1.5-fold that of a non-working adult, and 13-fold that of two young 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 40.5 gallons in comparison with man-headed households.[40] Interestingly, when the sample is restricted to car owners only, the number of young children does not affect significantly fuel consumption anymore. This suggests that having young kids requires a vehicle purchase ant thereby car ownership, without changing drastically the travel demand of households.

[39] This is the reason why we do not report nor discuss anymore their influence hereafter.

[40] Though their coefficients are not reported for the sake of clarity, occupation and diploma dummies are generally also highly significant.

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

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

Notes: (i) OLS estimates drawn from equation (4); (ii) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) For the sake of clarity, the constant and coefficients associated with diploma and occupation categories are not reported.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

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 -11.3 (column 1) for urban households on average to -7.9 (column 3) for motorized households only. Doubling population in a municipality would thereby yield an annual fuel saving of at most $\ln(2) \times 11.3 \cong 8$ gallons for urban residents. Put it differently, this suggests that a typical household living in Toulouse consumes 8 more gallons per year than an observationally-equivalent household 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 $\ln(25,971/6) \times 11.3 \cong 95$ more gallons (approximately 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 in 2006), everything else equal. More generally, the impact of density is less marked in France than in other countries, since the estimated elasticity ($-\frac{11.3}{215} = -0.05$ at the mean of our sample in 2006) is twice lower than the average reported in the most recent meta-analysis of Stevens (2017).

Design metrics have differentiated effects. Halving distance from residence to the CBD would save $\ln(2) \times 14.7 \cong 10$ 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 potential of a municipality would enable its residents to save approximately 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 car use. Finally, local public transit systems and fractal morphologies convey further significant and substantial environmental gains.[41]

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.[42] 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 approximately 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).

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

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

Urban morphology has a strong and significant pro-environmental effect. A 10% difference in the fractal dimension, such as the *Roubaix-Créteil* gap reported above, would translate into a reduction of $\ln(1.1) \times 89.6 = 8.5$ gallons per year approximately (column 1), over and beyond the Density and Design channels.[43] Our index of fractality greatly reduces the estimated impact of Density alone. Absent this variable, the density coefficient roughly doubles, leading to a density elasticity in line with the literature.[44]

Diversity has also a positive but less significant impact on fuel consumption in France. Doubling leisure diversity would translate into a reduction of $0.24 \times 28.5 \cong 7$ gallons per year approximately (column 1), comparable to the Density and Design channels. Including Diversity in the regression also greatly reduces the estimated impact of Density. If we exclude Diversity from the urban form variables, the density coefficient increases by 50% approximately.[45]

As a further robustness check, Table 10 in Appendix displays the results of a less conservative specification, from which we exclude Diversity not to loose observations (columns 1 and 3). Logically, the point estimates of density and distance to CBD are slightly magnified, since diversity is one of the channels through which transit the two effects. In columns (2) and (4), we also include MA fixed effects to control for omitted or unobservable time-invariant confounding factors specific to cities. Logically, in this highly demanding specification, certain design variables become insignificant, because of their low intra-MA variability. Nevertheless, most other fuel determinants remain significant, despite loss of degrees of freedom, which makes us confident in the identification power of our first 2 D's.

Finally, Table 11 in Appendix C checks whether results change when we consider the effective average distance from residence to all municipal jobs located in the MA (computed from population censuses), instead of the distance from residence to CBD. Results remain virtually unchanged, except for the Herfindahl index that becomes insignificant. Since it would be really hard to find a good instrument for this second distance metrics, we keep on with the first afterwards.

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 confounders correlated with households settlements and therefore, with Density and Distance to the CBD.

Sorting As underlined by Brownstone & Golob (2009), Grazi, van den Bergh & van Ommeren (2008) or Kahn & Walsh (2015), lifestyle and individual preferences influence residential choices,

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

[44]Corresponding tables are available upon request.

[45]Complementary tables are available upon request.

as households live in locations consonant to their socioeconomic characteristics or travel predispositions. 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 a 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 (4) is likely to remain correlated with the explanatory variables, which may produce inconsistent estimates.[46]

To deal with household sorting across places, we run two sets of additional regressions. First, as mentioned previously, we perform an OLS regression on the subset of urban households owning a car. We find very similar results (see column 2 of Table 5), 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 the one embedded in equation (4).

In a second step, we estimate the outcome equation (4) except that we add to the regressors the inverse of the Mills ratio[47] 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

[46]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, thereby 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.

[47]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.

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 number 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 consumption. 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: Census, 1962).[48] Mortality is indeed highly correlated with total population (with a correlation at 0.94 for the municipalities sampled in the BdF surveys), and at the same time very orthogonal to the error term, which encompasses the modern taste for driving.[49] 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).[50]

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):

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

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.[51]

Table 6 provides the results of both our IV (column 2) and Heckman (column 3) identification strategies. In comparison with column 1, which replicates our baseline estimates, endogeneity leads to an underestimation of the distance effect of approximately 70%, whereas the point estimates of the fractal dimension and the road potential decreases by around 40%. The other

[48] This is the oldest census for which mortality is measured at the level of municipalities.

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

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

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

coefficients are virtually unaffected by instrumentation. 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.[52] 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 far above the critical value reported for a 5% maximum IV bias (that is 13.43).[53] 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 also far above 5%.

The second panel of Table 6 reports the coefficients of our 'Heckit' (column 3) and Probit (column 4) regressions.[54] The selection bias associated with Density is rather small. By way of contrast, the impact of distance to CBD increases when selection is accounted for, which is perfectly in line with the literature (Stevens 2017). The coefficients of the other variables capturing the urban form exhibit a slight increase (in absolute value): from 12% for the road potential to 23% 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 than for Density.[55]

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. 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 2%, 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.

[52]First-stage regressions are reported in Table 12-Appendix C.

[53]Table 13 in Appendix C shows that results remain qualitatively and quantitatively similar if we use market potential in 1936 as an extra instrument.

[54]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.

[55]Table 14 in Appendix C displays the results associated with the first two D's only. As for OLS, the 2SLS point estimates of density and distance to CBD are magnified, since they also convey the effect of diversity.

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

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

Notes: (i) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (ii) The sigma term is the root of the variance of the disturbances and rho, the correlation between the disturbances of the model and selection equations; (iii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, age, age-square, sex, diploma and occupation of the household-head; For the sake of clarity, their coefficients are not reported, nor the constant. (iv) List of instruments: mortality density in 1962 (in log), distance to the largest municipality of the MA in 1806 (in log). *Sources*: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

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[56] would consume in each urban municipality, based on either the 2SLS (equation 6) or the Heckman (equation 7) estimates drawn from Table 6:

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

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

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).

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 exhaustive files of personal income tax and housing tax returns provided to INSEE by the General Tax Directorate. We first run an OLS regression of the average municipal income per CU drawn from the 2006 BdF survey on the average municipal income computed from tax sources.[57] We then use the estimates drawn from this regression to compute car emissions as before, except that we assign to the mean household the income estimated for the home municipality, instead of the BdF mean-income in 2006:

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

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 (CI) 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:

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

Finally, we draw carbon emissions from those volumes using conversion factors provided by the French Ministry for an Ecological and Solidarity Transition. To account for the mix of fuels in the French vehicle fleet, we use a specific conversion factor for each type of energy: 10.8 kg of

[56] 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.

[57] More precisely, we perform the following regression: $\log\left(Inc^{\text{BdF}}_{j,2006}\right) = \Phi_1 + \Phi_2 \log\left(Inc^{\text{tax}}_{j,2006}\right) + \xi_{j,2006}$. We then use $\widehat{\Phi_1}$ and $\widehat{\Phi_2}$ to estimate the real average income of each French municipality so as to compute CO_2 emissions.

CO_2 per gallon of gasoline, 12.2 kg of CO_2 per gallon of diesel, and 7.1 kg of CO_2 per gallon of LPG. 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.[58]

Tables 7 and 8 display the car emissions obtained for our standardized household in the 25 greenest and dirtiest French MAs.[59] Each panel of the table presents driving emissions computed from either the OLS, 2SLS or Heckit estimates provided in Table 6, 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.

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

Name	OLS	Rank	2SLS	Rank	Heckit	Rank	MA pop.
Paris	2,209	1	2,213	1	2,136	1	11,769,424
Lille	2,563	3	2,580	4	2,476	2	1,164,717
Caudry	2,571	4	2,559	3	2,504	3	14,322
Fourmies	2,550	2	2,536	2	2,509	4	16,324
Saint-Etienne	27,98	7	2,823	10	2,736	5	318,993
Nancy	2,800	8	2,770	7	2,738	6	415,765
Montereau-Fault-Yonne	2,794	6	2,767	6	2,739	7	26,109
Bolbec	2,792	5	2,759	5	2,744	8	15,750
Noyon	2,846	10	2,790	8	2,795	9	22,553
Lunéville	2,852	11	2,805	9	2,806	10	27,549
Le Havre	2,845	9	2,856	15	2,808	11	290,826
Tergnier	2,862	13	2,842	12	2,811	12	23,383
Lyon	2,887	14	2,888	19	2,822	13	1,748,274
Villerupt	2,893	17	2,847	14	2,826	14	19,019
Saint-Quentin	2,861	12	2,828	11	2,835	15	101,438
Hendaye	2,932	25	2,914	25	2,844	16	14,993
Fécamp	2,888	16	2,846	13	2,848	17	30,233
Strasbourg	2,897	19	2,912	24	2,851	18	638,672
Reims	2,895	18	2,890	20	2,855	19	293,316
Boulogne-sur-Mer	2,887	15	2,860	16	2,858	20	133,195
Sète	2,921	22	2,980	38	2,869	21	73,674
Provins	2,928	24	2,896	22	2,870	22	22,320
Chauny	2,922	23	2,885	18	2,872	23	22,117
Calais	2,906	20	2,903	23	2,876	24	125,525
Grenoble	2,943	26	2,942	31	2,879	25	531,439

It is important to note that, regardless of the estimation strategy, car emissions vary drastically across French MAs, from approximately 2.2 tons per year in Paris up to 3.8 tons per year in MAs such as Bourg-Saint-Maurice, Annemasse or Chamonix, which are all located in the French Alps.[60] In other words, the decision for a French standardized household to live

[58] 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).

[59] Tables 15 and 16 in Appendix C replicate the same exercise with emissions computed with the Corrected Incomes embedded in equation (8).

[60] Note that, since we computed the standard errors associated with these predictions, we can state that differences

Table 8: Dirtiest French MAs: CO_2 'carprint' of the sample mean-household (kg / year)

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

in Bourg-Saint-Maurice (respectively in Chamonix) would generate a driving footprint nearly twice (respectively 80%) 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, 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.

As shown by Tables 15 and 16 in Appendix C, though rankings do not change when we let

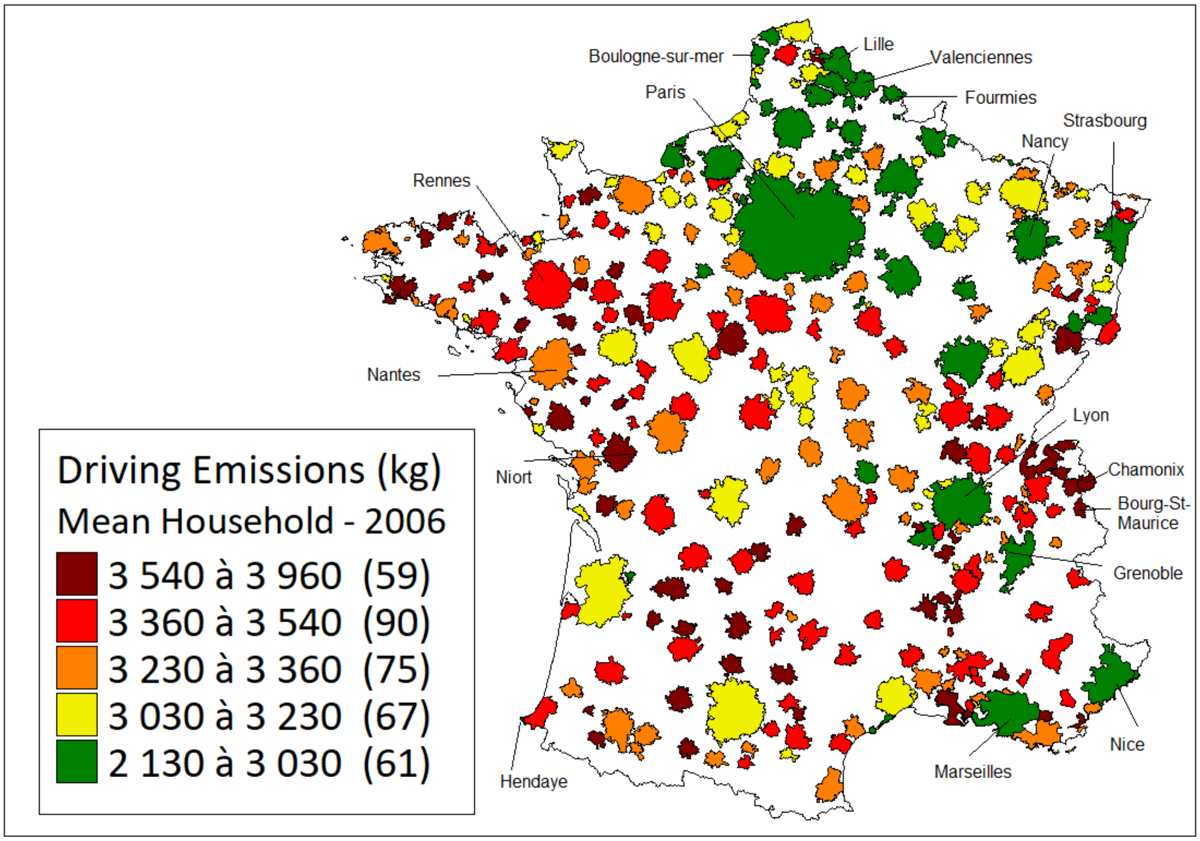
between high and low emissions are actually very significant. Moreover, we have checked that the peculiarity of mountainous MAs is not due to altitude by controlling for different measures of elevation.

vary the income across municipalities (as in equation 8), cities move down on the carbon ladder.

3.2 Driving footprint 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 6 (column 5).[61]

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



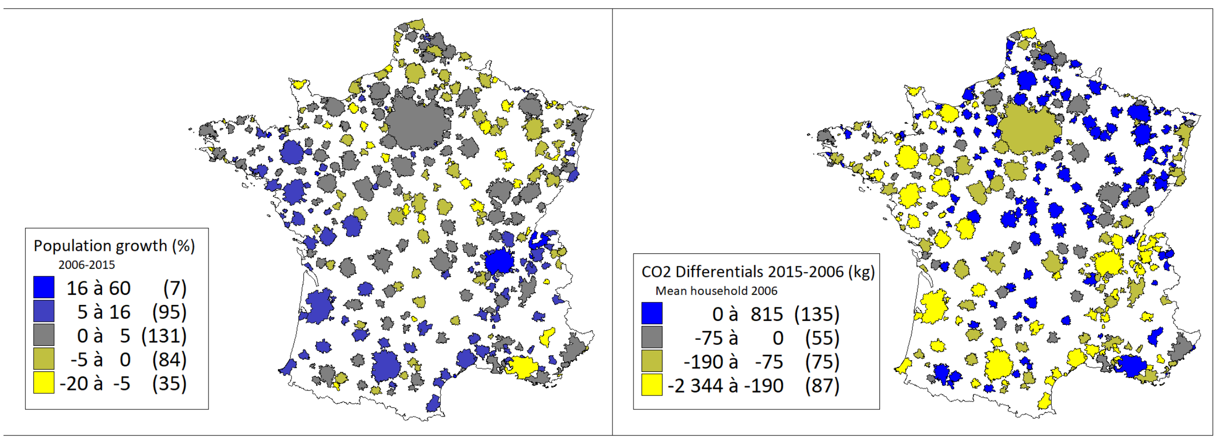
A salient geographic divide The spatial heterogeneity of household emissions across French MAs is very salient. Very large MAs such as Paris, Lyon, Nice, Strasbourg or Lille exhibit low-carbon 'carprints' (less than 3 tons of CO_2 per year and household), due to the combination of high population densities (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 and Rennes are noticeable exceptions, suggesting that they are more concerned with urban sprawl 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

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

Western medium cities (such as 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 and Nancy 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).

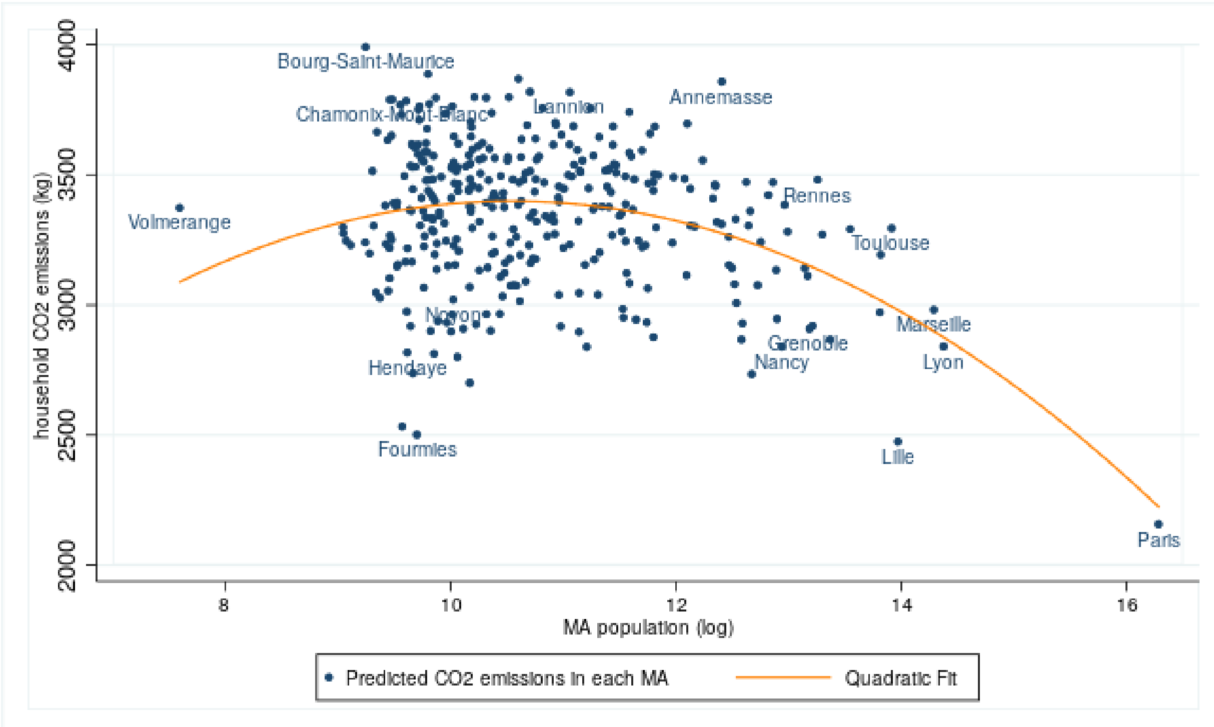
These figures are of crucial importance for policy makers, since Atlantic and Mediterranean cities experienced the strongest urban growth over the past decade. As shown by Figure 4, that plots population growth in each MA over 2006-2015 (left map) against differentials in carbon emissions computed from our projections over the same period (right map), the two patterns are inversely correlated, with a correlation coefficient at -0.8. In addition, as urban growth mostly occurred at the city-fringe of Atlantic and Mediterranean cities, this participated to enhance their environmental performance.

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 significantly all together 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, the absence of leapfrogging suburbs and the high walkability (high fractal dimension) of an historical city center (where there is one) might produce a Design that compensate low Density in small cities. This balance cannot be achieved in the midstream medium-cities, which are either sprawling (low density suburbs), or not large enough to sustain mass public transport networks and experiencing extensive road networks, or leapfrogging in their built-up fabric (low fractal dimension). Moreover, since sectorial diversity is more systematic in large cities, Diversity can also contributes to the reduction of their carbon emissions.

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



As such, Table 9 and Figure 5 depict an inverted U-shaped relationship between MA-size and the mean-household car emissions.[62] To precise the rationale of this bell-shaped pattern, we can separate the effects of the 3 D's in our projections.[63]

We find that Density has a strong negative linear effect on fuel consumption, as strongly established in the economic literature since Newman & Kenworthy (1989) : a larger MA population translates into a higher density and large car emissions savings.

The effect of Design is much more differentiated. The smallest MAs may indeed experience high walkability (fractal dimension) and good job-housing balance. However, since commuting distance and road stock increase with MA size, driving increase first as city population expands. Though, above the 300,000 inhabitants threshold, the development of public transit systems compensate the other effects and generate drastic savings in car emissions, while ultimately an infill of vacuous places provided by the use of urban planning strategies may provide a higher walkability in large cities. Taking Design into account thus introduces a inversed U-shaped behavior in the relationship between emissions and city-size that was absent from previous literature.

The impact of Diversity is quite diverse in small MAs, depending on their sectorial special-

[62]Computed from the Heckman estimates drawn from Table 6. Results are qualitatively similar for OLS and 2SLS.
[63]Figure 8 in Appendix E summarizes these findings.

ization[64], however, large MAs experience a high sectorial diversity that lead to a reduction in carbon emissions.

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

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

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

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 cities grow, 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.[65] From an urban 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, morphological homogeneity and lack of urban diversity 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 roughly two tanks per year, over and above any difference attributable to changes in income, employment status, occupation, education, family composition or more generally, to residence

[64]Even is this is not systematic, though, isolated small MAs often experience a high sectorial diversity. Medium MAs are thus the less diverse from this point of view. This contributes also to the U-shape behavior

[65]As shown in Table 17 and Figure 7 provided in Appendix D, 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.

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 80% more driving emissions - about $1,650$ more kg of CO_2 - per year, than an observationally-equivalent household of inner Paris.

Disparities across French cities exhibit 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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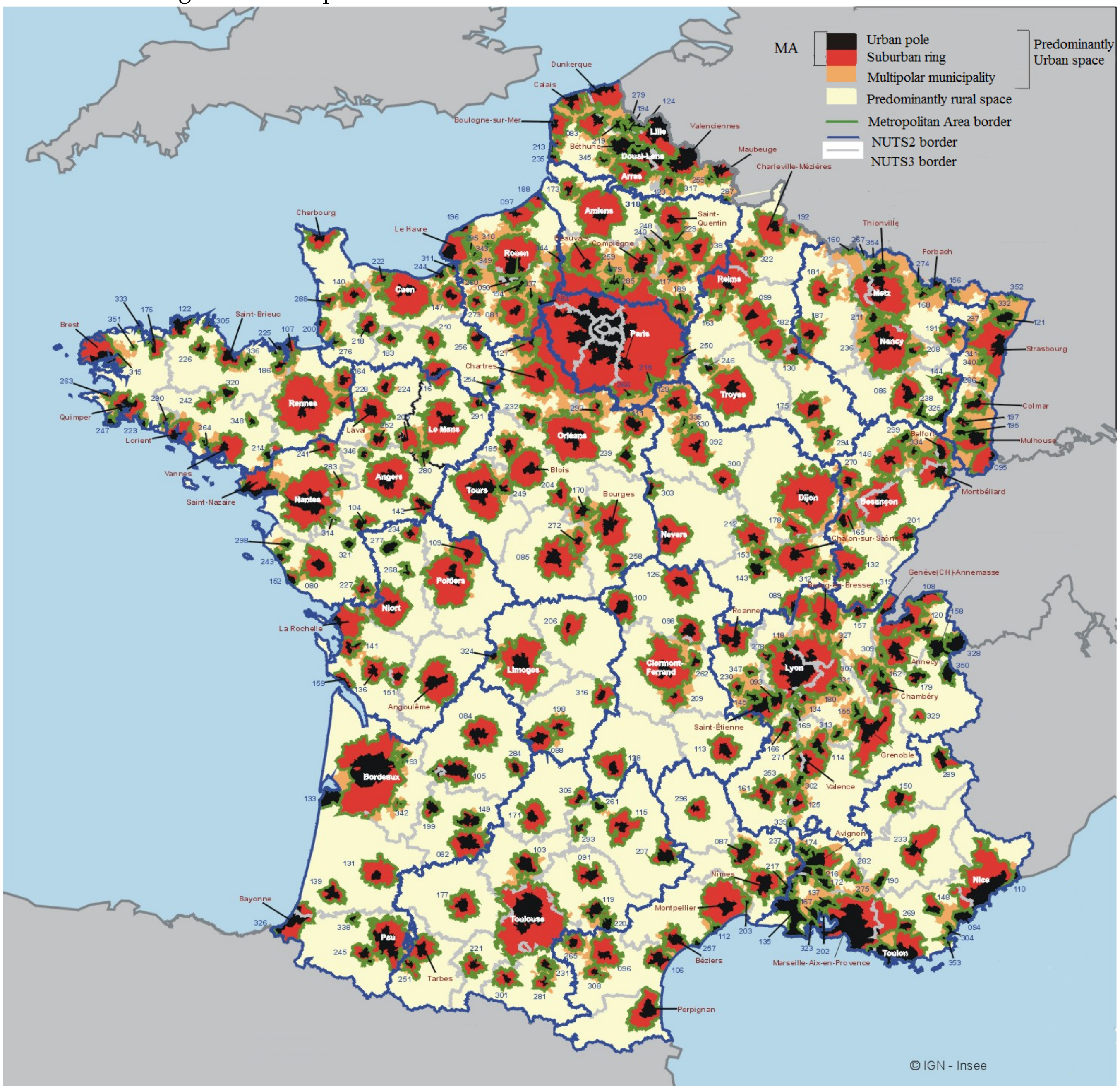
APPENDIX

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 be described by a mean value. This is arguable, a typical counterexample being a leapfrogging city, in which mean density hides huge disparities between built-up areas and bare ground. When it turns to urban geography, such irregularities in the built-up fabric are quite common : some neighborhoods are composed of small detached houses, whereas others are built around large blocks of dwellings. To describe these differences, we need an index that measures the way building cover space, and not the sole density. Mandelbrot (1982) coined the term 'fractal' to qualify intrinsically irregular objects where mass is not evenly distributed.[66] He proposed a new metric to classify these objects: the 'fractal dimension', which is a 'degree of inhomogeneity' of a geometric object. The most common and robust way to compute this dimension, which is also known as the Minkowski-Bouligand definition,[67] is the following:

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

This concept is named "dimension" because of the way it connects to the classical concept of geometrical dimension in the case of a classical object. The surface area of such an object is $Area = A \cdot a^D$ where A is a factor of form,[68] D the dimension, and a the typical scale of the object. The fractal dimension represents the same D for non regular objects that do not exhibit typical scale a.

For instance, if we cover a line of length L (an object of dimension 1) with the lattice of squares of size a_n, we find that $N(a_n) = \frac{L}{a_n}$. Thus, $\frac{log(N(a_n))}{log(1/a_n)} = \frac{log(L)+log(1/a_n)}{log(1/a_n)} \underset{n\to+\infty}{\to} 1$.
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, $\frac{log(N(a_n))}{log(1/a_n)} = \frac{2\cdot log(L)+2\cdot log(1/a_n)}{log(1/a_n)} \underset{n\to+\infty}{\to} 2$.

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

[66] Mandelbrot (1982) uses a powerful metaphor to explain why geometric measures such as length, surface or density loose most of their descriptive power for such irregular objects. For instance, it is difficult to compute the length of the Britanny coast, as it is crawling with small irregular creeks. The contour of maps of Brittany printed at very different scales strongly differ, since the tiniest creeks only appear when we zoom enough on the map. Any simple measure of coastal length describes very imperfectly its real morphology. In the same spirit, the 'density' of a leapfrogging city does not reflect the complexity of its urban form.

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

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

The fractal dimension can vary continuously from 0 to 2.

- If $D < 1$, we have a collection of unconnected points: mass is concentrated in 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 between 1 and 1.3, we have a collection of sparse clusters (typically a leapfrogging residential city);
- If D from 1.3 to 1.6, we face a continuous fabric of buildings separated by large spaces (typically housing complexes such as French 1960's *Grands Ensembles*;
- If D from 1.6 to to 1.8, we have attached housing separated by large streets (for instance, *Haussmannian* style of downtown Paris);
- If D is close to 2, the object covers the geographic map quasi-homogeneously (buildings separated by very tiny streets and courtyards, such as downtown 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:

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

With a log-log specification, we can write:

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

We can then can recover D by regressing the number of boxes on the size of the box, at different scales. We follow Thomas et al. (2010) and use the R-squared of this regression as an indicator of the fractal (or not fractal) behaviour 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 measured actually happen to be fractal, with a small part (28% of the total) exhibiting multifractality.

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

C Additional regression results

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

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

Notes: (i) OLS estimates drawn from equation (4); (ii) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) For the sake of clarity, the constant and coefficients associated with diploma and occupation categories are not reported.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

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

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

Notes: (i) OLS estimates drawn from equation (4); (ii) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10; (iii) For the sake of clarity, the constant and coefficients associated with diploma and occupation categories are not reported.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017) and DADS (2001 and 2006).

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

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

Notes: (i) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10, $^+$p<0.15; (ii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, age, age-square, sex, diploma and occupation of the household-head; For the sake of clarity, their coefficients are not reported, nor the constant.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

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

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

Notes: (i) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (ii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, age, age-square, sex, diploma and occupation of the household-head; For the sake of clarity, their coefficients are not reported, nor the constant.
Sources: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

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

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

Notes: (i) Robust standard errors in brackets (MA level); ***p<0.01, **p<0.05, *p<0.10, $^{+}$p<0.15; (ii) The sigma term is the root of the variance of the disturbances and rho, the correlation between the disturbances of the model and selection equations; (iii) Household characteristics include income per CU (in log), number of working and non-working adults, number of children under 16, age, age-square, sex, diploma and occupation of the household-head; For the sake of clarity, their coefficients are not reported, nor the constant. (iv) List of instruments: mortality density in 1962 (in log), distance to the largest municipality of the MA in 1806 (in log). *Sources*: *Budget des Familles* surveys (INSEE, 2001 and 2006), Census (INSEE, 1999 and 2006), BD-TOPO (NGI, 2001 and 2006), OpenStreetMap (2017), DADS (2001 and 2006), *Fichiers Urbanisation de la France* (INED, 1986) and *Les communes de la France métropolitaine, 1801-2001. Dictionnaire d'histoire administrative* (INED, 2003).

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

Name	OLS pred.	Rank	2SLS pred.	Rank	Heckit pred.	Rank	MA pop.
Paris	2,195	1	2,199	1	2,123	1	11,769,424
Lille	2,521	3	2,537	4	2,436	2	1,164,717
Caudry	2,523	4	2,511	3	2,449	3	14,322
Fourmies	2,376	2	2,361	2	2,304	4	16,324
Saint-Etienne	2,685	7	2,709	10	2,607	5	318,993
Nancy	2,748	8	2,717	7	2,679	6	415765
Montereau-Fault-Yonne	2,694	6	2,667	6	2,624	7	26,109
Bolbec	2,580	5	2,546	5	2,494	8	15,750
Noyon	2,640	10	2,584	8	2,566	9	22,553
Lunéville	2,672	11	2,624	9	2,597	10	27,549
Le Havre	2,675	9	2,686	15	2,615	11	290,826
Tergnier	2,770	13	2,750	12	2,706	12	23,383
Lyon	2,831	14	2,832	19	2,760	13	1,748,274
Villerupt	2,565	17	2,518	14	2,467	14	19,019
Saint-Quentin	2,750	12	2,717	11	2,703	15	101,438
Hendaye	2,792	25	2,774	25	2,689	16	14,993
Fécamp	2,754	16	2,712	13	2,689	17	30,233
Strasbourg	2,839	19	2,853	24	2,786	18	638,672
Reims	2,843	18	2,837	20	2,795	19	293,316
Boulogne-sur-Mer	2,779	15	2,751	16	2735	20	133,195
Sète	2,780	22	2,839	38	2,705	21	73,674
Provins	2,725	24	2,693	22	2,631	22	22,320
Chauny	2,608	23	2,569	18	2,519	23	22,117
Calais	2,709	20	2,705	23	2,646	24	12,5525
Grenoble	2,891	26	2,889	31	2,824	25	531,439

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

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

D Complementary results

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

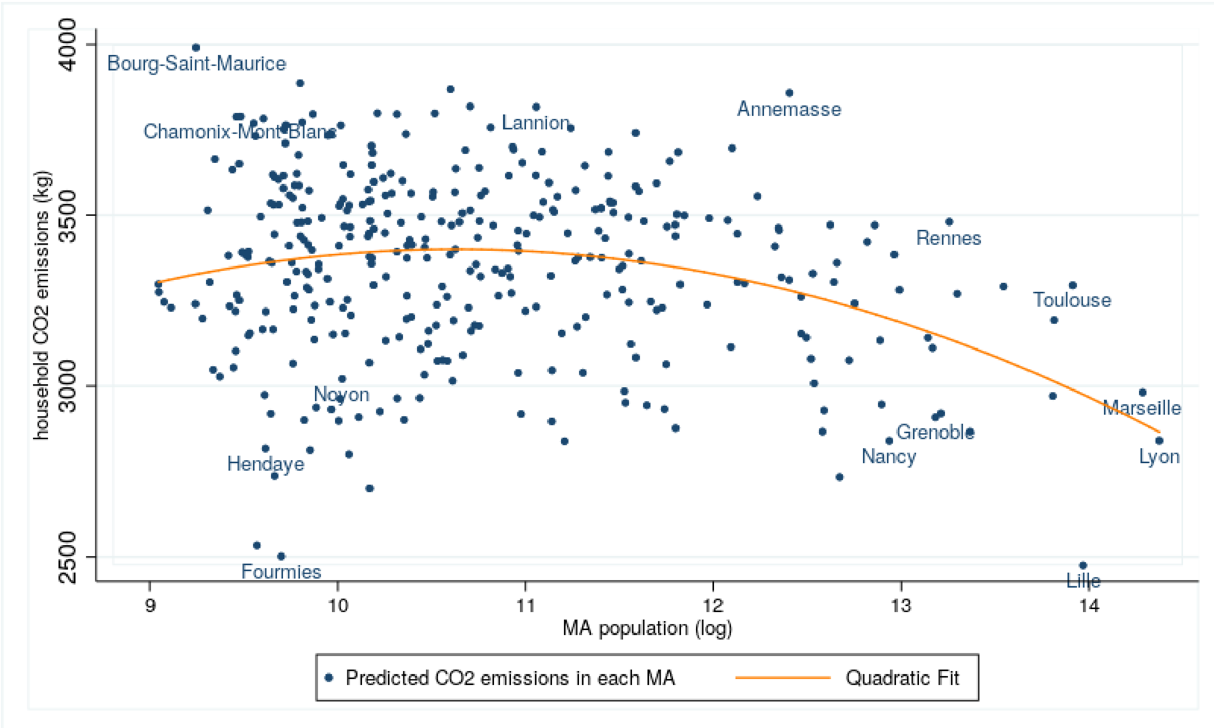


Table 17: MA-size and the CO_2 'carprint' of the sample mean-household (Paris and Volmerange excluded)

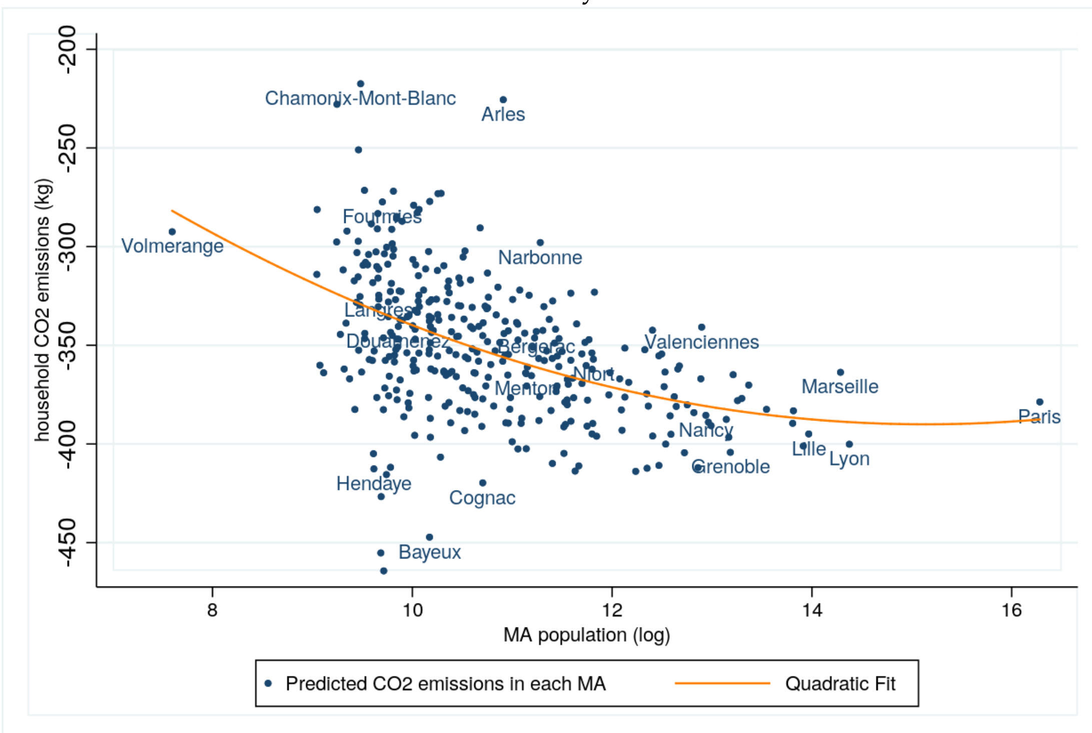
Variable explained: CO_2 car emissions	OLS coefficients	(Std. Dev.)
Log(MA-size)	729.0***	(204.1)
Log(MA-size)^2	-34.1***	(9.1)
Constant	-561.4	(1141.0)
Observations	350	
R-squared	0.060	

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

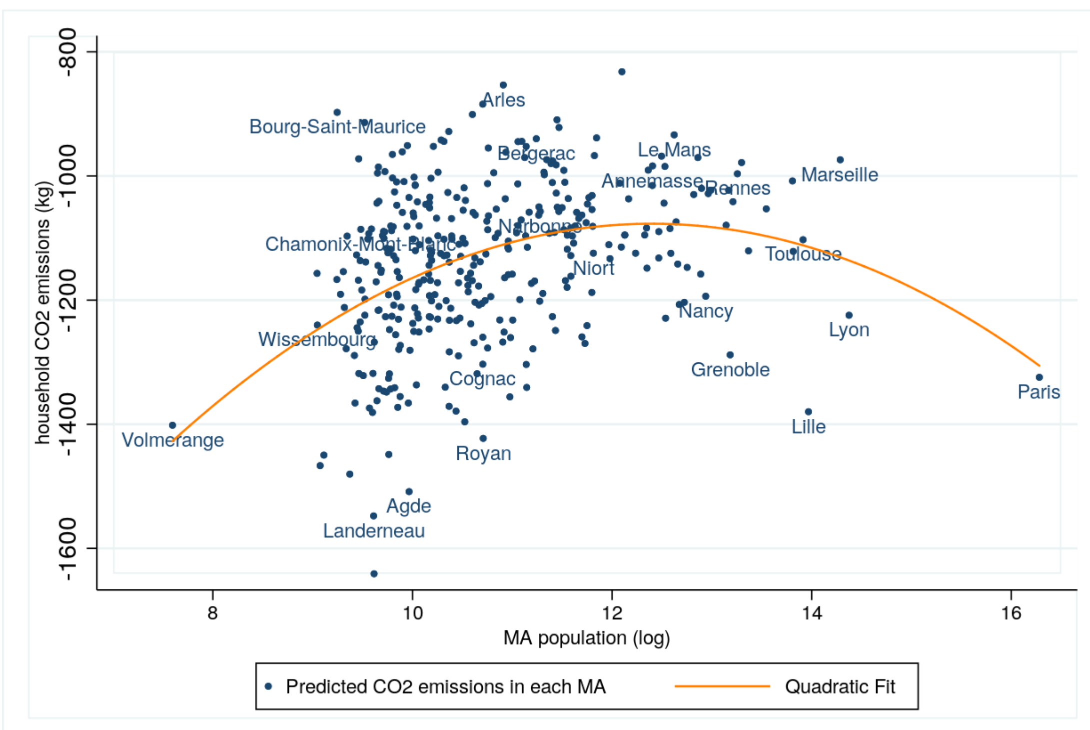
E Car emissions effects of each dimension of urban sprawl

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

Density channel



Design channel



Diversity channel