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The heterogeneous effects of motorways on urban sprawl: causal evidence from Portugal

Abstract

As urban land increased in mainland Portugal by 55.9% between 1990 and 2012 and the country developed an extensive motorway network between the 1980s and the early 2010s, we set out to investigate the effect of motorways on urban sprawl across mainland municipalities. We document the evolution of urban sprawl for these 275 municipalities across several dimensions, including the population density of urban land, its degree of fragmentation and shape irregularity (which we combine in a summary "total interface" indicator), and the differences between the central urban unit and the remaining "peripheral" urban land. Given that the spatial distribution of motorways is likely to be endogenous, we use road itineraries from the 18^{th} century as an instrumental variable. Our results suggest that motorways contributed to the fragmentation of urban land into numerous urban patches. Also, we identify important within-municipality heterogenous effects, in that motorways did not cause the contiguous growth of the central urban unit (typically the largest urban unit in each municipality) but, conversely, appeared to contribute in a significant manner to the development of peripheral urban land. There is also some evidence that motorways contributed to an increase in the shape irregularity of urban areas. Finally, we show that motorways caused a decrease in urban population density, but only in the relatively small group of more urbanised municipalities.

Keywords: Urban sprawl; urban land; urban fragmentation; motorways; transport accessibility; instrumental variables; Portugal.

1 Introduction

Urban sprawl is a global phenomenon, and a challenging policy concern. In the US, Europe, and emerging and developing countries, urban land has often expanded in sprawling and scattered patterns, in which many of the new residential areas are surrounded by non-developed land. This spatial fragmentation increases the costs of developing and maintaining public infrastructure, as well as of providing services such as public transportation and waste collection. Planners in many countries regard the socioeconomic and environmental impacts of urban sprawl as a threat to sustainable development, and are concerned with containing it and promoting more compact urban forms.

The issue has been investigated by geographers and planning scholars, economists, sociologists, and other researchers. While some authors argue that the social and economic consequences of urban sprawl are not particularly serious (Glaeser and Kahn, 2004; Eid et al., 2008), the predominant view emphasises the adverse aspects of the phenomenon. The costs of sprawl involve not only ecological problems, such as impacts on wildlife and ecosystems, the loss of fertile soils, impacts on water quality and quantity, poorer air quality, and increases in greenhouse gas emissions (Tu et al., 2007; Bart, 2010; Bhatta, 2010; Morote and Hernández, 2016; Yang et al., 2021; Wu et al., 2022), but also a reduction in the efficiency of residential energy consumption. This is because detached houses, the most common type of house in sprawling areas, consume more energy than apartments in buildings (Navamuel et al., 2018; Cartone et al., 2021). In addition, urban sprawl generates more spending on infrastructure and public services by local governments (Carruthers and Ulfarsson, 2003; Fernandez Milan and Creutzig, 2016; Fregolent and Tonin, 2016; Ida and Ono, 2019; Sass and Porsse, 2021), which may lead to higher local taxes (Varela-Candamio et al., 2019). The literature also shows impacts on the spatial mismatch between poor populations and employment opportunities (Covington, 2009), as well as on obesity levels – due to the lower walkability in these areas – and other public health issues (Frumkin, 2002; Sturm and Cohen, 2004; Garden and Jalaludin, 2009; Ewing et al., 2014; Yan et al., 2021).

Given that urban sprawl appears to have many negative implications, it is important to have a good understanding of its causes and, in particular, of how the development of transport infrastructure affects the expansion of artificialized land. Glaeser and Kahn (2004) argue that, while many factors may have helped the growth of sprawl, ultimately this has only one root cause, the rise of the automobile. Christiansen and Loftsgarden (2011), Colsaet et al. (2018), OECD (2018, Chapter 4), and Rubiera-Morollón and Garrido-Yserte (2020), among others, provide detailed surveys of the existing literature on the determinants of urban sprawl. They show that sprawl has been associated to a plethora of factors, including: (a) physical constraints on development continuity and other geographical factors (steep-sloped terrain, water bodies, proximity to natural amenities, etc.); (b) population growth and migrations; (c) social problems, e.g., crime rates in inner urban areas; (d) economic growth and economic structure, i.e., the degree at which a given city is specialised in sectors that are more or less susceptible to agglomeration forces; (e) changes in personal income, housing preferences and housing costs; (f) political governance structures and decentralisation; (g) regulatory frameworks, e.g., land use planning, building restrictions, taxes and subsidies, housing policies; (h) and, naturally, transport-related factors, including transport infrastructure (roads and railways, but also airports and ports), the level of public transport service, and the price of fuel and other transport costs.

In particular, some studies show correlations between motorways and measures of urban sprawl. The underlying logic is simple. As a new motorway makes travelling faster, more distant areas become accessible for the same driving time, which, in principle, will induce sprawl to expand to those areas. Oueslati et al. (2015) and Ahrens and Lyons (2019) find evidence for this association across, respectively, 282 European cities and the electoral divisions of Ireland. Deng et al. (2008) for China, Müller et al. (2010) for Switzerland, and Padeiro (2016) for the Lisbon Metropolitan Area provide results that point in the same general direction. Note however that, with the exception of Müller et al. (2010), these studies do not focus specifically on the impact of motorways; they consider a more or less extensive set of explanatory variables for urban sprawl and, in this context, include a variable for motorways in the regressions.

While the relationships found in these studies are interesting, the analyses do not implement quasi-experimental methods to identify the causal effects of motorways on urban sprawl. Yet, it is likely that the former are not exogenous to the latter. Garcia-López (2019) addresses this problem through using roman roads and 19th century roads and railways as instrumental variables for motorways in a sample of 579 metropolitan areas in Europe. The findings are that motorways cause residential sprawl by expanding cities with new, more fragmented, and more isolated land developments. More recently, Pratama et al. (2022) adopted a similar strategy in their study of urban sprawl in the Jakarta Metropolitan Area. The analysis instruments distance to motorway access ramps with distances to 1815 and 1924 roads and colonial train stations, concluding that improvement in highway access results in the development of new built-up areas in the city suburbs.

At a more general level, it should be noted that the use of historical transport networks to identify causal effects of motorways has gained traction since the work of Baum-Snow (2007) on the impact of motorways on suburbanisation in the US. The approach has been applied in other studies on suburbanisation dynamics (Garcia-López et al., 2015; Baum-Snow et al., 2017; Levkovich et al., 2020), as well as in studies on the growth of population and employment at the local or regional level (Duranton and Turner, 2012; Percoco, 2016; Möller and Zierer, 2018).

The main motivation of this study is to investigate the effect of the development of the Portuguese motorway network on urban sprawl across mainland municipalities. That is, while Garcia-López (2019) focuses on metropolitan areas across Europe and Pratama et al. (2022) focus on sprawl within a very large metropolitan area, we study urban sprawl within a whole country. In this sense, our study is close to that of Ahrens and Lyons (2019) on Ireland. A key difference, however, is that we use quasi-experimental methods to account for the potential endogeneity of motorways. More specifically, we use historical dirt roads from the 18th century as an instrumental variable for motorways in two-stage least squares estimations.

We contribute to the literature in the following ways. First, we add a new case to this literature. We see Portugal as a particularly interesting case. On the one hand, the country developed an extensive motorway network between the early 1980s, when motorways were almost non-existent, and the 2010s. Indeed, according to Eurostat data, in 2022 Portugal had the third highest ratio of total length of motorways relative to population in the European Union (EU). On the other hand, urban land expanded very considerably too. According to our GIS measurements based on CORINE Land Cover data, between 1990 and 2012 urban land in mainland Portugal increased by 55.9% (for comparison, total population grew by only 7.2% between 1991 and 2011). Importantly, about 3/4 of this increase occurred in the 250 municipalities (out of 275) that are not "cities" or part of cities according to the Eurostat classification.[1] This fact shows that focusing only on relatively large urban centres would result in an incomplete evaluation of the impact of motorways on urban sprawl in Portugal.

Second, we follow most of the literature in recognising urban sprawl as a multidimensional phenomenon. Accordingly, we document the evolution of urban sprawl in Portugal between 1990 and 2012 across several dimensions, which we organise in two groups. The first group measures the growth of urban land; we also compute the population density in these areas. The second group has to do with the way urban land is distributed within the area of the municipality. We capture the degree of *fragmentation* of urban land by counting the number of separate urban land units or "plots" or "patches" (we use these terms interchangeably). In addition, we measure the *irregularity* of the geometrical shape of the units by calculating a non-compactness index, which is based on the extent of their perimeter relative to the area (that is, the circle is the more compact form). For example, if urban units A and B have the same area but B has a high value for this index, this means the perimeter of B (i.e., its contact line with the surrounding undeveloped land) is longer than that of A, indicating a non-compact pattern of development. Finally, we propose a "total interface indicator" that combines the two dimensions of fragmentation and shape irregularity into a single index.

Third, we divide urban land between the "central" urban unit and the many non-central (or "peripheral") urban units. The former is defined as the urban plot where the Municipal Hall (*Câmara Municipal*) is located, which typically corresponds to the main town or city proper, the main individual urban unit in each municipality. The distinction allows us to examine an important *within*-municipality heterogeneity, that is, we can analyse if the effect of motorways on urban sprawl operates through the contiguous development of the central unit and/or the development of non-central

[1] See https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:City.

areas. Fourth, and lastly, we implement nonlinear specifications to explore the heterogeneity *across* municipalities. This allows us to see if the effects of motorways on the expansion of urban land and, in particular, on urban population density is different for the group of "high-density" municipalities (i.e., where the initial proportion of urban land is higher) vis-à-vis the larger "low-density" group of municipalities. To the best of our knowledge, our study is the first to analyse the impact of motorways on sprawl through these two heterogeneity angles.

To advance the most important findings, our results suggest that 10 km of motorways in a municipality cause an increase of approximately 6.8% in urban land between 1990 and 2012. We also show that motorways cause an increase in the number of urban plots, indicating that they contribute to a significant extent to the fragmentation of urban land. Interestingly, the estimates show that motorways have a strong effect on the growth of non-central urban units, but, in contrast, do not contribute to the contiguous growth of the central urban unit, e.g., the town proper. Also, motorways appear to cause urban land to expand into less compact, more irregular geometric shapes. Finally, when we look at deviations from estimated average effects, we find that, for the group of more urbanised municipalities, motorways induce increases in urban area but have no effect on urban population, causing a reduction in urban population density. That is, motorways appear to contribute to the *redistribution* of population across urban areas. Yet, for the group of low-density municipalities, motorways have an effect on the growth of both urban area and urban population, resulting in a zero effect on urban population density.

The rest of the paper is organised as follows. Section 2 describes the evolution of urban sprawl and the development of the motorway network in the period of analysis. Section 3 describes the empirical methodology and the data, while the following section presents our results. Section 5 concludes, discusses policy implications, and presents some ideas for future research.

2 Urban sprawl and motorways in Portugal

2.1 Definition of urban and residential land

The CORINE Land Cover (CLC) database is our main source to delimit urban land and urban residential land. The database is produced by visual interpretation of high-resolution satellite imagery, resulting in an inventory of land cover and land use of 44 classes grouped in five main groups: "artificial surfaces", "agriculture", "forests and seminatural areas", "wetlands", and "water".[2] We are interested in the artificial surfaces group, which is composed by four sub-groups (and 11 classes): "urban fabric" (2 classes), referring to both continuous and discontinuous areas occupied by residential buildings and buildings used for administrative and public services;

[2] The database covers 39 European countries. See https://land.copernicus.eu/en/products/corine-land-cover for more details.

“industrial, commercial and transport units” (4 classes); “mine, dump, and construction sites” (3 classes); and “artificial, non-agricultural vegetated areas” (2 classes), which refers to recreational land uses, notably green urban areas, leisure urban parks, and sport facilities.

The functional relationship between the “urban fabric” and the remaining classes of artificial surfaces is taken into consideration in our broader definition of urban land. For example, the facilities in the “sport and leisure” class exist to support residential land – typically, residents in the latter use the facilities in the former. Indeed, urban sprawl is not limited to residential sprawl, and should also include the movement of people and goods within an urban area (Schneider and Woodcock, 2008). After a detailed analysis of the 11 classes of “artificial surfaces”, we define urban land as all the land in this group, with three exceptions. We exclude the “mineral extraction sites” class, since mining is a primary sector activity usually located in non-urban or rural environments and often has no direct functional relationship with urban land. We also exclude “road and rail networks and associated land” (in the sub-group “industrial, commercial and transport units”), as this class includes the motorway network, which is our explanatory variable of interest. Finally, the “construction sites” class is not considered because it consists of construction sites *of any kind*, i.e., this class includes the construction of, and interventions in, infrastructure that cannot be considered as urban land. That comprises, for instance, the construction of mineral extraction sites, water reservoirs, motorways and motorway access ramps, new nature areas, etc.

In addition to the CLC, we used the Census spatial database to improve the accuracy of the identification of urban land. This additional step is required as, in some cases, the CLC does not identify relatively small and isolated residential settlements (which may have been classified as agricultural land, for example). To overcome this limitation, we combine the CLC with the Census statistical subsections with a population density equal or larger than 1000 residents per km^2 (this density threshold is often used to consider an area as urban; see, e.g., Lobo et al., 1990).

In summary, our broader definition of urban land includes the urban fabric, industrial or commercial units, port areas, airports, dump sites, green and leisure urban parks, and sport and leisure facilities, all from the CLC, plus the Census statistical subsections with a density ≥ 1000 residents per km^2 that are not identified by the CLC. A stricter definition, which we term “residential land”, is obtained by combining the CLC’s urban fabric (which is by definition dominated by residential buildings) with the aforementioned Census statistical subsections. We use CLC data for 1990 and 2012, which we combine respectively with Census data for 1991 and 2011.

2.2 Urban sprawl in 1990 and 2012

2.2.1 Urban land: size and population density

The first measure of urban sprawl is the expansion of urban land, i.e., a straightforward measure of land take that does not take in consideration the spatial patterns through which urban land sprawls. Figure 1 shows an important increase in urban land between 1990 and 2012. According to our GIS calculations, total urban land in mainland Portugal increased by 55.9%, from 2.92% to 4.55% of Portugal's mainland area (see Panel A in Table 1). Residential land, in particular, increased by 49.3%, from 2.63% to 3.92% of mainland area. These trends are not a mere reflection of population growth in the country, as, according to Census data, mainland population increased by no more than 7.2% between 1991 and 2011. The population that resides in urban land increased by 25.9%, i.e., from 65.2% to 76.6% of total mainland population. However, as urban land increased even more rapidly, population density decreased. More specifically, the *gross* density, i.e., the number of residents per square km of urban land, decreased from 2351.5 to 1899.4 res./km^2. The *net* density, that is, the residents per square km of residential land, decreased from 2611.6 to 2204.7 res./km^2.

Table 1 also displays summary statistics for these variables for the 275 mainland municipalities.[3] For example, in 2012 the average municipality had around 9.5% of urban land (6.5% in 1990). There is, naturally, a large cross-sectional variation in the variables that reflect the size of urban areas, as seen in their large standard deviations. Such heterogeneity is apparent in Figure 1, which shows that the more urbanised municipalities tend to be located in the Lisbon Metropolitan Area, in the Porto Metropolitan Area (plus the nearby region of Braga), and, to a smaller extent, in the coastal strip between these two dominant poles. In 2012, the municipality of Lisbon, the capital of the country, was the one with the highest share of urban land, 98.4% (with a population of around 547 thousand residents). At the other extreme of the distribution, there were 64 municipalities with less than 1% of urban land. The share of population that resides in urban land varies less drastically across the sample, as evidenced by a coefficient of variation that is not very high (0.35 = 21.84/61.67 in 2012). This reflects the fact that the municipalities with small populations, often in interior and/or rural regions, also tend to concentrate their population in urban land.

[3] We use the pre-1998 administrative division to maintain consistency. Three new municipalities were created in 1998 through the detachment of civil parishes (*freguesias*) from five municipalities.

Figure 1. Urban land in mainland Portugal

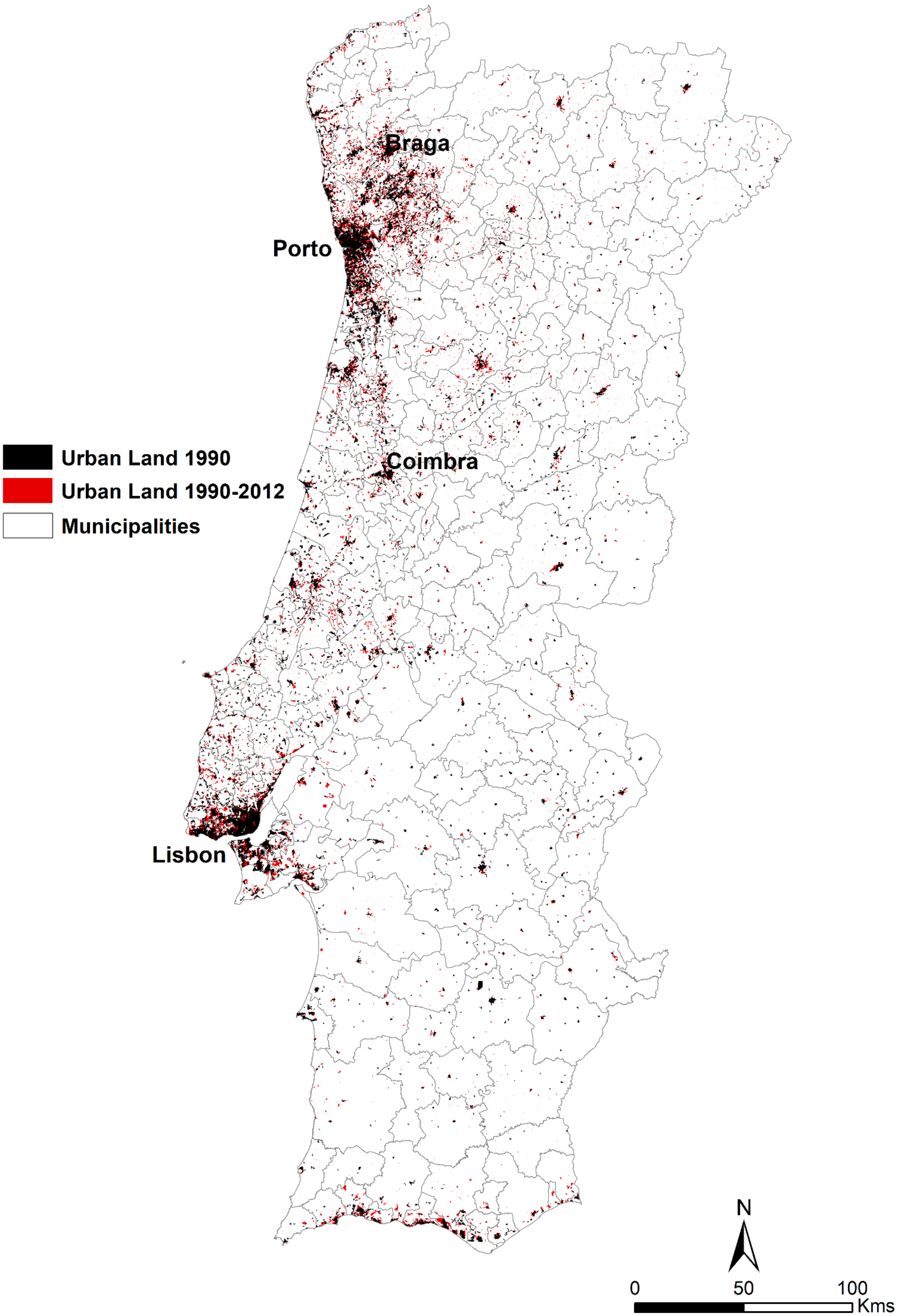

Table 1. Urban land in mainland Portugal

Variable	Aggregate (country)		Municipalities							
			Mean		Standard deviation		Minimum		Maximum	
	1990	2012	1990	2012	1990	2012	1990	2012	1990	2012
Panel A. Size and population density										
Urban land, km^2	2599.5	4053.3	9.453	14.739	12.995	18.363	0.245	0.545	81.268	108.33
Urban land, % of total land	2.92	4.55	6.55	9.54	13.42	16.56	0.08	0.27	92.70	98.38
Residential land, km^2	2338.3	3490.1	8.503	12.691	11.636	16.274	0.245	0.545	79.240	103.76
Residential land, % of total land	2.63	3.92	5.85	8.26	11.77	14.43	0.08	0.27	86.52	89.78
Resident pop. in urban land, 000s	6112.8	7699.0	22.228	27.996	56.282	58.266	0.227	0.864	660.89	547.32
Resident pop. in urban land, % total pop.	65.20	76.63	47.55	61.67	26.37	21.84	2.85	13.00	99.62	99.98
Gross pop. density, residents/km^2	2351.5	1899.4	1799.5	1465.4	1273.6	1001.5	281.62	396.96	12449.4	9509.5
Net pop. density, residents/km^2	2611.6	2204.7	1969.7	1705.4	1506.2	1225.0	281.66	396.98	13435.0	11039.3
Panel B. Fragmentation and irregularity										
Number of urban units	4258	10871	15.484	39.531	17.801	32.507	1	1	125	202
Number of urban units $>$ 0.5 ha	4131	9600	15.022	34.909	17.126	29.330	1	1	121	196
Number of urban units $>$ 1 ha	4022	8244	14.625	29.978	16.719	25.648	1	1	120	175
WIRR (multi-unit shape irregularity indicator)	3.060 a)	3.530 a)	2.176	2.486	0.839	1.069	1.308	1.411	8.420	7.737
TINT (total interface indicator)	100.14 b)	130.45 b)	5.640	7.945	2.951	3.360	1.799	1.870	17.198	19.644

Notes. Variables as defined in the main text. a) is equal to the area-weighted average of the *IRR*s of all the 4258 and 10871 urban units in 1990 and 2012, respectively; b) is calculated using the sum of the perimeters and the sum of the areas of these units. The number of observations used in the calculation of the means and the other descriptive statistics is equal to 275.

2.2.2 Urban land: fragmentation, shape irregularity, and interface

Accounting for the expansion of urban land, as done above, does not capture the degree of urban land fragmentation. Yet, this is a salient dimension of the urban sprawl phenomenon. Urban land may increase by 1 km^2 due to the contiguous expansion of a large well-established urban area or, for example, through the creation of ten new scattered urban patches of, say, 0.1 km^2 each. The two patterns of expansion have very different implications. As in Garcia-López (2019), we measure the degree of fragmentation by counting the number of separate urban land units (or "plots" or "patches"; we use these terms interchangeably). At the aggregate level, the total number of plots grew from 4258 in 1990 to 10871 in 2012 (+155%). If we disregard the very small patches and focus on plots that are larger than 1 ha,[4] the growth in the number of units is still very expressive, from 4022 to 8244 (+105%). As Figure 1 and Table 1 show, there is a large heterogeneity in terms of urban fragmentation patterns. In 2012, for example, there were 3 municipalities with only one urban unit (e.g., the city of Lisbon); at the other extreme, there were 13 municipalities with more than 100 urban plots.

For context, it should be noted that the extent of urban dispersion represents a major policy concern and is a recurrent topic in the Portuguese literature of the past 20-30 years. Urbieta et al. (2019) and Nicolau and Condessa (2022) show that land take between 1990 and 2007 was driven, to a large extent, by the growth of discontinuous urban fabric. Tonini et al. (2018) document an increase of 68% between 1990 and 2012 of the interface zone between artificial surfaces and the CLC classes "forest and semi-natural areas" and "heterogenous agricultural areas",[5] which is an additional indication of scattered land artificialization. According to most authors, the first generation of Municipal Master Plans (PDMs) contributed decisively to this diffuse form of urbanisation. Most municipalities did not have the necessary technical expertise and specialised staff to design and implement the PDMs. Not only the plans tended to delimit unrealistically oversized developable areas, but, in addition, construction outside these areas was common, in a context in which the PDMs were not systematically monitored and evaluated – see, among others, Ferreira and Condessa (2012), Oliveira (2012), Abrantes et al. (2016), Padeiro (2016), and Nicolau and Condessa (2022). The Habitat III National Report for Portugal, prepared by the Directorate-General for Territorial Development of the Portuguese government (DGT, 2016) pointed clearly to "the lack of an urbanisation strategy based on

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[4] The patches ≤ 1 ha represent a very small proportion of total urban land. In 2012, they amounted to a total of 13.9 km^2, i.e., 0.34% of mainland's total urban land.

[5] That is, CLC codes 3 and 24 respectively. Note that the interface zone identified by the authors is only part of a broader interface between artificial surfaces (code 1) and the other classes. As the authors are interested in analysing the relationship between wildfires and land use changes (and, therefore, in identifying a flammable interface zone), they do not calculate the growth in the interface zone between artificial areas and the other agricultural areas (codes 21, 22, and 23).

compact growth" (p.52), which facilitated "decades of uncontrolled urban development" (p.53).[6]

Another important dimension of the urban sprawl phenomenon is the way the shape of the urban units evolves – less compact, i.e., more irregular shapes are indicative of urban sprawl. We measure shape irregularity with the index used, for example, in Frenkel and Ashkenazi (2008) and He et al. (2020). The indicator is defined as the ratio of the perimeter of a given urban unit to the perimeter of a circle with the same area. That is, irregularity *IRR* for urban unit *j* is given by:

$$IRR_j = \frac{P_j}{2\sqrt{\pi A_j}}, \tag{1}$$

where P is the perimeter of j and A is its area. We illustrate this in Figure 2, where b and c represent two urban settlements with the same area but different irregularity, and a is a circle with the same area. Values of *IRR* closer to 1 indicate more compact urban forms.

Figure 2. Illustration of irregularity in urban plots

a. $IRR = 1$ *b.* $IRR = 1.304$ *c.* $IRR = 2.017$

Since almost all municipalities have more than one urban unit, we consider the area-weighted mean *IRR*. That is, for municipality *i*, we calculate:

$$WIRR_i = \sum_j w_j IRR_j, \tag{2}$$

where weight w_j corresponds to the share of urban unit j in the total urban area of municipality i. For descriptive purposes, we also compute *WIRR* and other indicators

[6] As noted in DGT (2016) and Nicolau and Condessa (2022), it was only in the Framework Law of 1998 that the containment of urban expansion and dispersed land take was articulated as an explicit policy concern. These objectives were developed in planning documents in the second half of the 00s and reinforced in the new Framework Law of 2014. Yet, as of 2021, there were still 102 municipalities with the first, i.e., non-revised PDM in effect; see https://observatorioindicadores.dgterritorio.gov.pt for more detailed information.

at the country level. We can see in Table 1 that, in general, urban units became more irregular in their shape. The *WIRR* calculated at aggregate country level increased from 3.060 to 3.530, i.e., +15.4%. At the municipality level, the mean *WIRR* increased from 2.176 to 2.486, i.e., +14.2%. To give more detail, *WIRR* increased in 226 municipalities, and decreased in the other 49.

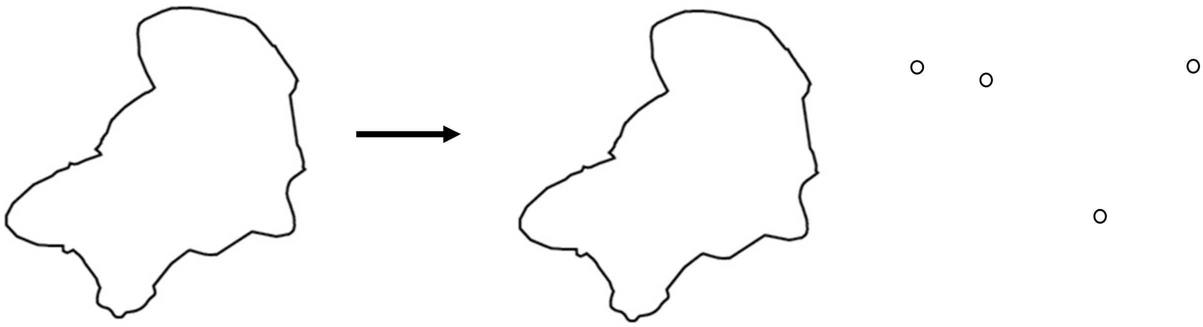
Finally, we can combine the dimensions of fragmentation and shape irregularity into a summary measure of the spatial *distribution* of urban land, which we term the "total interface" indicator. An obvious limitation of the measure of fragmentation – i.e., counting the number of urban plots – is that it does not consider the relative differences in the size of the plots. Suppose that municipality X has a central urban unit of 10 km^2 and nine small plots with around 1 ha each, and that municipality Y has a central urban unit of 1 km^2 and nine other plots also with 1 km^2 each. The number of plots is the same in both cases, but urban land is much more fragmented in case Y. The measure of (area-weighted) mean irregularity, on the other hand, is not influenced by the number of plots, because it is an average indicator. For example, a municipality may have ten urban plots and another municipality only one plot – yet, both municipalities could have very similar *WIRR*s.

We can explore the relationship between total urban perimeter and total urban area in a municipality to produce a measure of the extent to which urban land is scattered across undeveloped land, having in mind that the perimeter of an urban unit constitutes, by definition, its physical line of interface with the surrounding non-urban land. More precisely, we adapt the indicator in Equation (1) and calculate the "total interface" indicator:

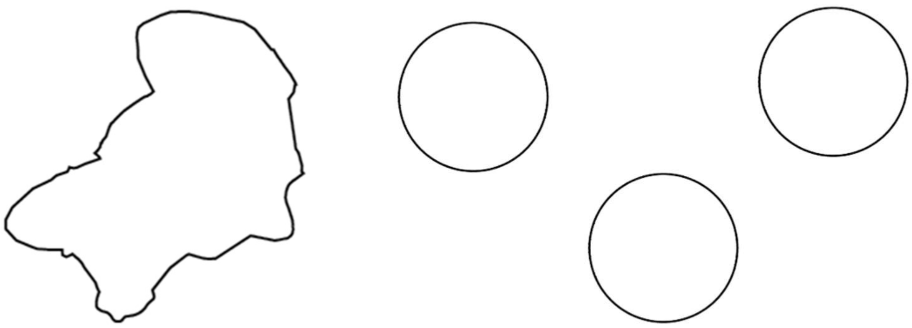
$$TINT_i = \frac{P_i}{2\sqrt{\pi A_i}}, \tag{3}$$

in which P_i is the summation of perimeters of all urban units in municipality i, and A_i is the summation of their respective areas. Suppose that, initially, municipality Z has only one plot of area 1 km^2 and shape *a* in Figure 2 above (i.e., a circle). In the following period, a second plot of the exact same shape and area is built up. While average irregularity is the same in both periods (*WIRR* equals 1), *TINT* increased from 1 to $\sqrt{2} \approx 1.414$. Even if each plot has, individually, a perfectly compact shape, the two plots need, in conjunction, more perimeter to delimit the same area vis-à-vis an alternative situation of a single circle of 2 km^2. The *TINT* indicator is also increasing, of course, with shape irregularity. To continue with the same illustration, if the new plot in municipality Z had shape *c* instead of *a* (and, again, an area of 1 km^2), *TINT* would have increased from 1 to 2.133, i.e., >1.414. Figure 3 provides additional illustrative examples.

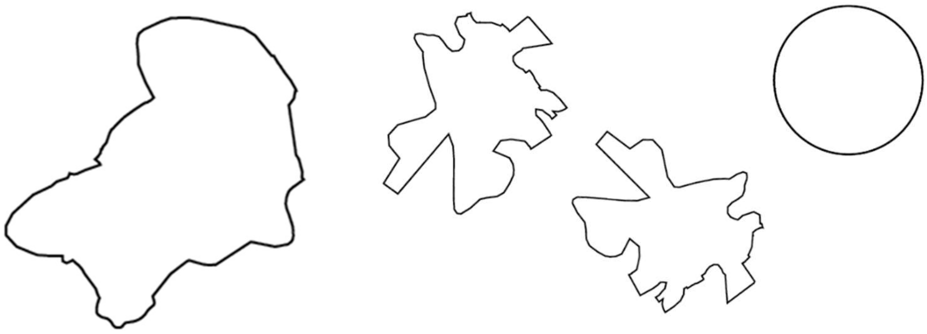
Figure 3. Illustration of scattered urban development



Municipality A: main urban plot (2 km^2) plus four very small and circular urban plots (0.01 km^2 each); *TINT* increases from 1.304 to 1.571.



Municipality B: main urban plot (2 km^2) plus three circular urban plots (1 km^2 each); *TINT* = 2.166.



Municipality C: main urban plot (2 km^2) plus two irregular urban plots and one circular urban plot (all 1 km^2 each); *TINT* = 3.076.

In sum, *TINT* depends on the number of urban plots, their weight in total urban area, and the irregularity of their shapes. The index is, effectively, a measure of the distribution of urban land and, therefore, a useful complement to measures of growth in the size of urban land in a municipality. Table 1 shows that the mean *TINT* increased by 40.9% between 1990 and 2012. Indeed, *TINT* increased in 255 municipalities, and decreased only in 20.

2.2.3 Central vs. non-central urban land

We separate, for each municipality, its "central" urban unit (the urban plot where the Municipal Hall is located) from the rest of its urban land; for the purposes of this article we term this interchangeably as "non-central" or "peripheral" urban land. The current administrative division of mainland Portugal into municipalities has changed little since the second half of the 19th century; in particular, the Municipal Hall is located in the areas that correspond, historically, to the city or the main town in the municipality, as opposed to the many villages in rural areas. The importance of these urban areas is historically persistent, making them reasonable proxies for urban centrality.[7] By making this distinction we can evaluate, for instance, if the growth of urban land occurred mostly through the contiguous expansion of the central unit or, in contrast, the development of non-central urban land. Ultimately, we are interested in using the variables described in this section to find if motorways have different effects on central vs. peripheral urban land.

From Panel A in Table 2 we can highlight that, at the aggregate level, both central and peripheral urban land expanded considerably between 1990 and 2012, but the former increased more rapidly than the latter, i.e., by 79.7% vs. 40%, or by 831 km^2 vs. 622.8 km^2. As a result, the share of central urban land in total urban land increased from 40.1% to 46.2%. The population in central urban land increased by 42.3%, and, in 2012, represented 73.3% of total urban population in mainland Portugal (from 64.9% in 1990). The population in peripheral urban land, on the other hand, decreased by 4.3%, i.e., by around 91.4 thousand residents. The mean shares of central vs. peripheral urban population and area are essentially stable – indeed, part of the growth in the share of central urban population at the aggregate country level can be explained by the forming of large central urban units in a few municipalities, which expanded to absorb peripheral urban plots.[8]

[7] A more complex definition of centrality could involve factors like population density, availability of public services, economic activity, commuting patterns, etc. Yet, the choice and weighting of criteria would be, to some extent, subjective, and for many of them there would be no data. In the absence of a universally accepted "objective" criterion for defining central urban units across municipalities, we believe our approach combines a valid rationale with practical feasibility.

[8] The decrease of 91.4 thousand residents in peripheral urban land is due in part to the fact that, in a number of highly populated municipalities in the Metropolitan Area of Lisbon (e.g., Sintra and Oeiras), the central urban unit expanded to absorb peripheral urban plots.

Table 2. Central vs. non-central urban units

Variable	Aggregate (country)				Municipalities (mean)			
	Central urban unit		Non-central urban units		Central urban unit		Non-central urban units	
	1990	2012	1990	2012	1990	2012	1990	2012
Panel A. Size and population density								
Urban land, km^2	1042.7	1873.7	1556.8	2179.6	3.792	6.813	5.661	7.926
% of urban land	40.11	46.23	59.89	53.77	40.73	40.56	59.27	59.44
Residential land, km^2	949.20	1648.1	1389.1	1841.9	3.452	5.993	5.051	6.698
% of residential land	40.59	47.22	59.41	52.78	41.86	42.35	58.14	57.65
Resident pop. in urban land, 000s	3964.6	5642.2	2148.2	2056.8	14.417	20.517	7.812	7.479
% of resident pop. in urban land	64.86	73.29	35.14	26.71	54.13	53.99	45.87	46.01
Gross pop. density, residents/km^2	3802.2	3011.3	1379.9	943.64	2498.2	2035.7	1554.6 d)	959.00 d)
Net pop. density, residents/km^2	4176.8	3423.4	1542.1	1114.2	2680.0	2263.6	1505.2 e)	1114.3 d)
Panel B. Fragmentation and irregularity								
IRR (single-unit shape irregularity indicator)	4.215 a)	4.811 a)			2.493	3.001		
WIRR (multi-unit shape irregularity indicator)			2.486 b)	2.428 b)			1.810 d)	1.958 d)
TINT (total interface indicator)			95.409 c)	130.77 c)			5.165 d)	7.800 d)

Notes. Variables as defined in the main text. a) is equal to the area-weighted average of the *IRR*s of the 275 central urban units. b) is equal to the area-weighted average of the *IRR*s of the 3983 (= 4258 minus 275) and 10596 (= 10871 minus 275) non-central urban units in 1990 and 2012, respectively; c) is calculated using the sum of the perimeters and the sum of the areas of these units. The number of observations used in the calculation of the means is 275, except for d) (272) and e) (271).

As expected, population density is clearly higher in central than in peripheral urban land. Yet, in both cases the gross (net) density decreased considerably over the period of analysis, by around 20.8% (18%) for central urban land and by 31.6% (27.7%) for peripheral urban land.

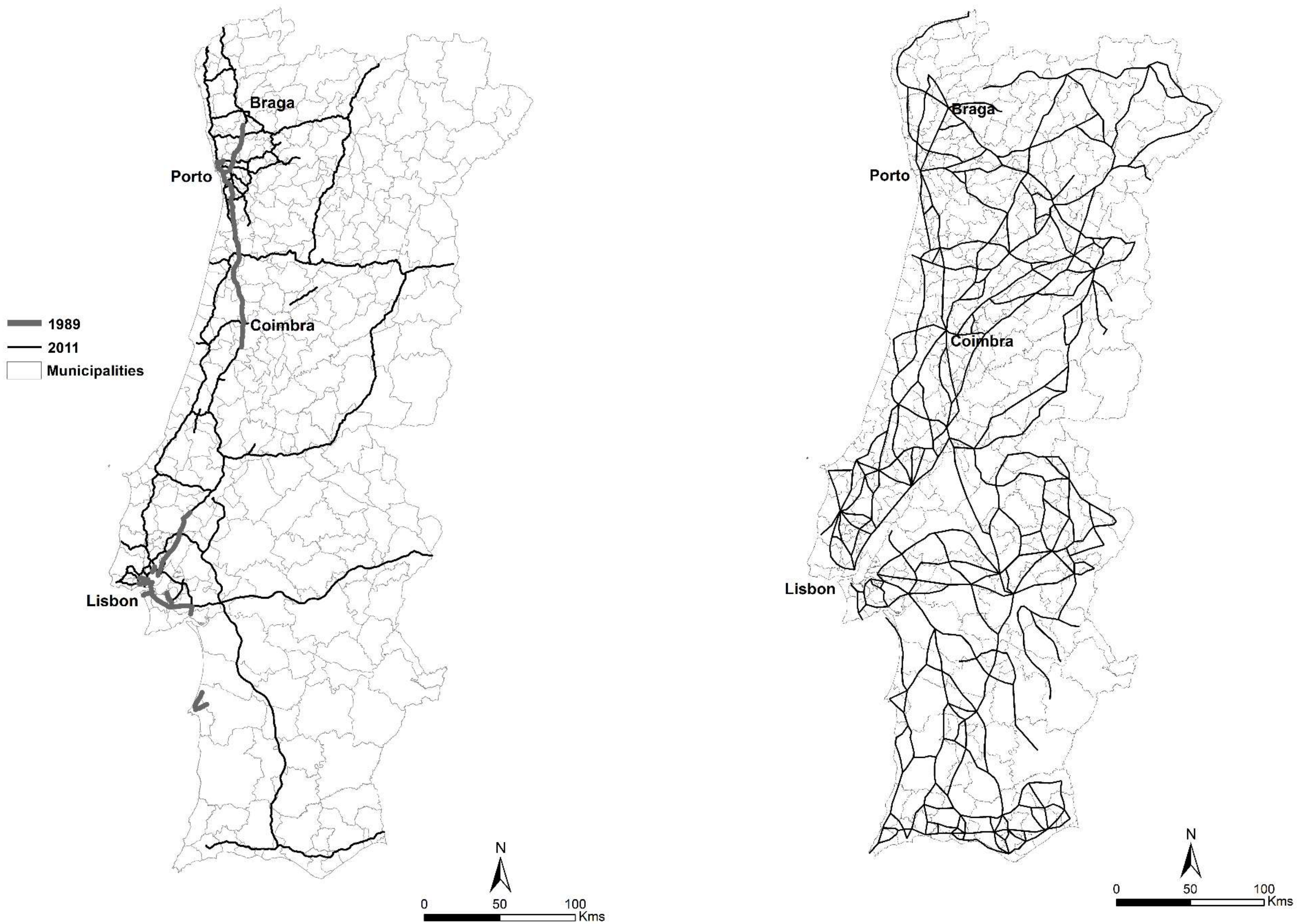
Panel B shows that the mean *IRR* of the central unit increased by 20.4%, from 2.493 to 3.001. The indicator increased in 216 municipalities and decreased in the other 59, that is, about 4/5 of the central urban units became more irregularly shaped. In contrast, the mean *WIRR* for non-central units increased by no more than 8.2% (although this indicator also increased in most municipalities, 205). The modest growth is largely due to the fact that peripheral urban land developed to a significant extent through the building-up of many small urban units, which normally have more compact forms and, therefore, low individual *IRR*s. To this respect, note that the mean *TINT* for non-central units, the interface indicator that is influenced by both shape irregularity and the number of non-central urban units, increased very significantly by 51%; the indicator increased in 251 municipalities. Overall, we interpret Table 2 as depicting a general trend for increasing sprawl, which occurred both through the expansion of the central urban unit, usually into more irregular shapes, and the development of fragmented peripheral urban land.

2.3 The development of the motorway network

Figure 4 shows the Portuguese motorway network in 1989 and 2011; the motorway km built between these years correspond to our explanatory variable of interest and represent around 5/6 of the total length of motorways that exist today. In the early 1980s, the Portuguese road network was largely outdated and unfit for modern automobile traffic, in particular in comparison with other European countries. The country almost did not have motorways, which were basically limited to parts of the country's two metropolitan areas, Lisbon and Porto. In 1981, according to Eurostat data,[9] total motorway length in Portugal and Spain represented respectively no more than 4% and 12% of their current (2022) motorway networks, which stands in contrast with the early development of motorways in Italy (78%), Belgium (75%), Germany (59%), and France (45%), for example. Most notably, the two main Portuguese cities were not connected by motorway, something that would happen only in 1991, when the A1 corridor was concluded.

[9] See https://ec.europa.eu/eurostat/databrowser/view/road_if_motorwa___custom_11520463/.

Figure 4. Road networks: motorways (left) and 18th century road itineraries (right)



Portugal (and Spain) joined the European Community in 1986 and gained access to significant amounts of European funding. Part of the funds were invested in the much-needed modernisation of the country's infrastructure and, more specifically, in building a motorway network. In the following two decades, the network expanded to create connections to Spain (thereby connecting Portugal to the rest of Europe) and serve low-density regions in the interior of the country, connecting them to coastal regions (which concentrate the majority of the population). The latter aligns with the cohesion-oriented objective of leveraging road accessibility to reduce regional asymmetries, as stated in the 1989 *Operational Programme for the Development of Accessibilities* (PRODAC) and other planning/strategy documents (see Pacheco, 2004, Ch. 3). Yet, at the same time, more motorways were built in the metropolitan areas of Lisbon and Porto and in the coastal regions between the Lisbon area and the north, thus augmenting the density of the network in this part of the country.

As a result of all this investment, Portugal built one of the largest motorway networks in Europe. At present (2022), Portugal has approximately 301 motorway km per million inhabitants, the third highest ratio in the EU after Croatia (347 km/million) and Spain (334 km/million). Accessibility improved dramatically. To illustrate, according to the TiTuSS database (Afonso et al., 2024), the time needed to travel by car from the northernmost municipality (Melgaço) to the southernmost one (Faro) decreased from around 10h15m in 1981 to 6h15m in 2011, i.e., a reduction of 39%. The main objective of the present study is to estimate the effects of this profound transformation in the country's transport infrastructure and accessibility on the several dimensions of urban sprawl.[10]

3 Empirical methodology and data

3.1 Estimation framework

We set out to identify the effect of motorways on the growth of a set of urban sprawl measures between 1990 and 2012 at the municipality level. More formally, our main objective is to estimate the following general model for municipality i:

$$100 * \Delta_{12,90} \ln Y_i = \alpha + \boldsymbol{\theta} \ln Y_{90,i} + \beta \Delta_{11,89} H_i + \boldsymbol{X_i'} \boldsymbol{\delta} + \varphi_d + \varepsilon_i, \qquad (4)$$

where Y stands for each one of the urban sprawl indicators that were detailed in Section 2 (e.g., urban area, the number of urban plots, or *TINT*, the total interface indicator), ΔH is the length of motorways that were built between 1989 and 2011, $\boldsymbol{X}$ is a set of control variables (e.g., geographical and historical variables, detailed in

[10] For more information and studies about the development of the Portuguese motorway network, see Pacheco (2004), Pereira and Pereira (2016), and Rocha et al. (2022), among others.

Section 3.3 below), and φ_d represents district-level fixed effects (mainland Portugal has 18 districts). We include data for all 275 municipalities.[11]

We are interested in estimating coefficient β. However, motorways are not allocated across the country in way that should be assumed exogenous to urban sprawl. For instance, the authorities may decide to build motorways in certain areas because of growing sprawl, which would result in reverse causality. Because of this endogeneity problem, Equation (4) should not be estimated by means of OLS. In order for the estimated β to reflect a causal relationship, we need to use a quasi-random source of variation for motorways. The next section describes our instrumentation strategy.

Our model assigns the effect of motorways to the 148 municipalities that received them. However, one could argue that motorways could have an effect, for example, in the 98 "non-treated" municipalities adjacent to the treated ones. In this context, it should be noted that Portuguese municipalities are relatively large. The 275 municipalities have an average area of around 324 km^2, much larger than Spain (62 km^2) or Italy (44 km^2), for instance. The distance by road from the 1981 population-weighted centroid to the nearest motorway entry in 2011 is equal, on average, to 25.1 km for the 98-municipality group, compared with only 5.9 km for the 148 treated municipalities – i.e., the two groups are separated by a factor of 4.2. Hence, we regard the assumption that urban sprawl in bordering municipalities is not, in general, significantly affected by motorways as a plausible one. Nevertheless, in a robustness test in Section 4.3 we model accessibility in a different way, assuming that every municipality in the country could be affected by motorways, with the intensity of the effect being stronger for the municipalities closer to a motorway entry.

3.2 Road itineraries of the 18th century

We follow most of the recent literature in using historical transport networks as instrumental variables for motorways, e.g., Baum-Snow (2007), Duranton and Turner (2012), Percoco (2016), and Garcia-López (2019), among others. Building on previous work on the link between motorways and suburbanisation, employment, and local gross value added (Rocha et al., 2023, 2024), we use a map of road itineraries of the mid-18th century – see Figure 4 – and calculate their length per municipality, which we then use as the instrumental variable for motorways. The map was constructed by Matos (1980) using, principally, a detailed list of itineraries compiled by João Baptista de Castro, a priest and scholar born in 1700. Martins (2014) clarifies that the map is based on the 1767 edition of this list, which, in turn, is very similar to the list first published in 1748.

Our identification strategy is based on the assumption that, conditional on control variables, the instrumental variable is both a good predictor of motorways and uncorrelated with ε, the error term in Equation (4). That is, we consider that 18th

[11] We report descriptive statistics and data sources in Appendix A.

century roads represent persistent corridors of movement that are correlated with the spatial distribution of modern transport infrastructure. Motorways follow, to a significant extent, the trajectories of these historical routes, reflecting both topographical constraints and path-dependent development. Also, we posit that, after the inclusion of controls (e.g., geographical variables and a proxy for local economic development in 1981), the instrument is not correlated with the dependent variable (the evolution of urban sprawl between 1990 and 2012), except through its correlation with the explanatory variable (motorways built between 1989 and 2011).

We regard exogeneity as a plausible assumption. Collated more than 200 years before our period of analysis, these itineraries – mostly dirt roads – developed before over the centuries in a largely unplanned way, in an historical context that was extremely different from modern societies, including with regards to land use patterns and mobility patterns. The economy was essentially rural and the country was sparsely populated: in 1770-1838, in the same area as today, Portugal had less than 1/3 of its current population of 10 million inhabitants and, even as late as 1864, there were only five cities in mainland Portugal with more than 10,000 inhabitants: Lisbon (193,100), Porto (86,800), Braga (16,900), Coimbra (11,500), and Setúbal (10,700) (INE, 2001). In this historical period, roads were used mainly for short distances and were largely subsidiary to rivers and coastal navigation, the most efficient option for the long-distance transport of goods (Pacheco, 2004, Ch. 3). Indeed, transport by water was, according to a contemporaneous source, ten times cheaper than transport by land (de Mordau, 1872). Travelling 50 km on horse by road would normally take more than 12 hours; roads were poor in comparison to other European countries and vulnerable to weather – often they were not in condition to be used during the winter, as mud would make them almost impassable (Matos, 1980; Justino, 1988; Pacheco, 2004, Ch. 3). In general, mobility was very limited: most people would not travel, as this was not only difficult and expensive, but also quite dangerous (Alegria, 1990).

These facts suggest that, within our empirical framework, the historical road itineraries should be exogenous to urban sprawl patterns in our modern era. It can be argued that these itineraries could have had an influence on the historical development of towns and small cities that, later on in our era, experienced urban growth and sprawl. However, we account for this possible channel of influence through controlling for variables referring to before our period of analysis, e.g., population in and electricity consumption per capita in 1981 (as a proxy for initial economic development). On the other hand, the hypothesis that geographical conditions may have influenced both the geographical distribution of road itineraries and the extent of urban sprawl is certainly plausible. For this reason, we have to control for a number of geographical factors, e.g., terrain ruggedness and average altitude.

3.3 Control variables

This section describes the variables in $\boldsymbol{X}$ in Equation (4), which include the following physical/geographical and historical variables: average altitude, a measure of terrain ruggedness based on the standard deviation of altitude, surface area, the log of the straight-line distance from the municipality centroid to the coast (with centroids being identified using 1981 population weights), and the official age of the municipality (79.3% of the municipalities have more than 500 years).

We also include a binary variable that equals one for Lisbon and Porto and zero otherwise, since in 1990 the share of urban land in these two municipalities was already 92.7% and 91.1% respectively, i.e., there was little margin for intra-municipal urban sprawl. In addition, the literature shows that the population of central cities in metropolitan areas tends to *decrease* with motorways due to suburbanisation (e.g., Baum-Snow, 2007; Garcia-López et al., 2015). Conversely, we include a binary variable that equals one if a municipality is a "suburb" of Lisbon or Porto and zero otherwise; a suburb is defined here as a municipality that has a travel time to either Lisbon or Porto using 1981 roads no larger than 60 minutes, with travel times being calculated using 1981 population-weighted centroids. That is, we control for the fact that the spatial proximity to the two historically large cities of the country is expected to be associated, on the one hand, with a greater density of road itineraries in the 18th century and, on the other hand, with extensive urban sprawl in our era. We also include a binary variable that equals one if a municipality is a district capital (with the exception of Lisbon and Porto) and zero otherwise.

As said in the section above, we control for the log of population in 1981 and the log of electricity consumption per capita in 1981; the latter works as a proxy for the initial level of local economic development. In addition, we control for motorway length in 1989, although it should be noted that this variable is equal to zero for 239, or 86.9% of the municipalities. Finally, note again that outside $\boldsymbol{X}$ we control for the initial (1990) log of urban sprawl and for district-level fixed effects.

4 Empirical results

4.1 Total urban land

This section presents the results regarding the effects of motorways on variables related to urban land as a whole within municipalities (in the following section we separate between central and peripheral urban land). The estimated coefficients correspond to semi-elasticities. Although we also report OLS estimates, these are very likely to be biased, and are reported only for comparison – our focus is on the two-stage least squares (TSLS) results. In Table 3, columns 1 and 2 show that motorways have a statistically significant effect on urban land and residential land, respectively. The Kleibergen-Paap F-statistic is large, indicating that the instrument is not weak (we also report the respective first-stage coefficients). According to our estimates, 10 km of motorways lead to an increase of approximately 6.8% in urban land and 4.9% in residential land (10 km corresponds to 0.79 and 1.07 of, respectively, the standard deviation and the mean of the explanatory variable, i.e., motorways opened between 1989 and 2011). The effect on the more restrict category of residential land is somewhat smaller, suggesting that motorways may have a relatively stronger effect on industrial and commercial units than on residential developments.

These results mean that motorways contributed in a significant way to the growth of urban land between 1990 and 2012 in mainland Portugal. A simple calculation can give us an approximate idea about the potential magnitude of the effect. By multiplying the coefficient estimated in column 1 by the value of the explanatory variable and then by urban land in 1990, we obtain a measure of the growth in km^2 of urban land potentially due to motorways for each municipality. We sum this across all municipalities (the value is zero, of course, for the 127 municipalities with no motorways built in the period) and obtain a total of 312.9 km^2, which is about 22.1% of the observed growth of 1453.7 km^2 of urban land in mainland Portugal. The equivalent calculation for residential land results in a total of 211.9 km^2 that can be attributed to motorways, or 18.4% of an observed growth of 1151.8 km^2.

Column 3 shows an effect of the same 10 km of motorways on the population that resides in urban land of 4.5%, larger than the effect on the overall population of the municipality of 3.4% (column 4), which suggests that motorways contribute to the relative concentration of population in urban (residential) land within municipalities. Lastly, columns 5 and 6 show that, on average, motorways have no effects on urban gross and net population density. It should be noted that, while urban sprawl is normally associated with a decrease in urban population density and the spatial redistribution of urban population, the literature typically focus on cities or metropolitan areas, that is, high-density urbanised areas (see, e.g., Garcia-López, 2019). In contrast, our national sample contains a large majority of sparsely populated municipalities, often with very extensive rural and forest areas, with urban land representing a small share of the total area.[12] Interestingly, our results may imply that, at least for the low-density municipalities, the growth of urban land tends to be associated with an important increase in the number of residents in urban land, perhaps in tandem with a decrease in the number of residents in non-urban areas and/or the attraction of residents from other municipalities. Yet, at this point we should not exclude the hypothesis that, for a relatively small group of more urbanised, high-density municipalities, the nexus between motorways and decreasing urban population density may indeed be present in the data – more on this in Section 4.4 below.

[12] For example, in 1991, about 2/3 of the municipalities had a population density smaller than 120 inhabitants/km^2.

Table 3. Effects of motorways on urban land: size and population density

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Population	Gross urban pop. density	Net urban pop. density
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011	1991-2011 a)	1991-2011 a)
Panel A. OLS						
Δ length of motorways 1989-2011	0.252**	0.166*	0.243*	0.165*	-0.0160	0.0647
	(0.123)	(0.100)	(0.131)	(0.0844)	(0.101)	(0.0944)
R^2	0.603	0.636	0.699	0.695	0.452	0.486
Panel B. TSLS						
Δ length of motorways 1989-2011	0.681**	0.491**	0.447*	0.344**	-0.132	0.0345
	(0.285)	(0.251)	(0.266)	(0.172)	(0.290)	(0.275)
Kleibergen-Paap F-statistic	39.01	39.13	43.46	42.12	38.59	38.20
IV (first-stage): length of 18th century itineraries	0.215***	0.215***	0.222***	0.219***	0.217***	0.216***
	(0.0345)	(0.0343)	(0.0337)	(0.0337)	(0.0349)	(0.0349)

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table 4. Effects of motorways on urban land: fragmentation, shape irregularity, and interface

	(1)	(2)	(3)	(4)	(5)
Dependent variable = 100*log-difference of:	Number of urban units	Number of urban units > 0.5 ha	Number of urban units > 1 ha	*WIRR*	*TINT*
Period:	1990-2012	1990-2012	1990-2012	1990-2012	1990-2012
Panel A. OLS					
△ length of motorways 1989-2011	0.355	0.371	0.401*	0.113	0.0574
	(0.251)	(0.238)	(0.229)	(0.0912)	(0.105)
R^2	0.710	0.718	0.683	0.335	0.709
Panel B. TSLS					
△ length of motorways 1989-2011	2.142**	1.958***	1.900***	0.192	0.690**
	(0.848)	(0.733)	(0.673)	(0.176)	(0.316)
Kleibergen-Paap F-statistic	36.34	36.56	36.54	42.06	34.09
IV (first-stage): length of 18th century itineraries	0.211***	0.211***	0.211***	0.219***	0.205***
	(0.0349)	(0.0349)	(0.0350)	(0.0337)	(0.0351)

Notes. Estimates based on Equation (4). *WIRR* is the area-weighted measure of the shape irregularity of the urban units, while *TINT* is a "total interface indicator" based on the relation between the summation of all the perimeters of the urban units in each municipality and the total urban area that is delimited by those perimeters (see Section 2.2.2 in the text). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table 4 reports the effects of motorways on the fragmentation and shape irregularity of urban land. Columns 1 to 3 focus on the number of urban plots. We find in column 1 that 10 km of motorways result in an increase of 21.4% in the number of plots. As with urban area, we calculate an indicative measure of the total number of plots potentially due to motorways, and find that this number – 1521 – represents about 23% of the observed factual increase of 6613 plots in the country. As a sensitivity check, we analyse in the following columns if these results could be driven by the smaller patches, which represent little urban land, and exclude the patches that are smaller than 0.5 ha (1 ha); this results in the subtraction of 1114 (2391) patches from the 6613. The estimated coefficients remain essentially the same.

As seen in column 4, the effect of motorways on the area-weighted average shape irregularity, *WIRR*, is positive but not statistically significant. This indicator is calculated using the shape of the central urban unit and the shapes of the non-central urban units. Yet, the effect of motorways on these two categories of urban land may be substantially different (more on this in the following section), which may be the reason why, in this case, it is not possible to estimate a statistically significant (common) slope. In contrast, as seen in column 5, the average effect on the total interface indicator, *TINT*, is statistically significant: 10 km of motorways lead to an increase of *TINT* of 6.9%. By multiplying the estimated coefficient by the mean number of motorway km in the 148 municipalities where motorways were built (17.3 km), we obtain an indication of the mean growth in *TINT* that potentially can be attributed to motorways, 11.9%, whilst the mean growth in *TINT* for mainland Portugal was 54.2%. That is, the estimates suggest that motorways contributed to a relevant extent to the growth of the total perimeter of urban units vis-à-vis their total area, or, as explained in Section 2.2.2, the general "non-compactness" of urban land.

Finally, we note that, according to OLS results in both Tables 3 and 4, the effect of motorways on the various measures of urban sprawl would be either small or statistically non-significant, which does not seem very plausible. This highlights the importance of using quasi-experimental methods to estimate causal effects, which in turn can be used as a sound input in policymaking decisions.

4.2 Central vs. peripheral urban land

This section presents the results on the separate effects of motorways on the central urban unit and the summation of the non-central urban units, i.e., the peripheral urban land. The estimates in Table 5 reveal a particularly interesting pattern: motorways have no effect on central urban land (column 1), central residential land (column 2), and residents in central urban land (column 3); conversely, the effects on peripheral urban land are substantial.[13,14] To illustrate, 10 km of motorways generate a growth of 12.8% in non-central urban land, 12% in non-central residential land, and 18.9% in the number of residents in non-central urban land. In other words, although in the country central urban land has expanded more than non-central land between 1990 and 2012 (as described in Section 2.2.3), the effect of motorways on the expansion of urban land reported in Table 3 appears to operate *exclusively* through the effect on non-central urban land. Therefore, motorways appear to act as a "dispersive" force, inducing the growth of the part of urban land that is fragmented into numerous plots, instead of the contiguous growth of the central, and typically largest urban unit.

As shown in columns 4 and 5, motorways have no significant impact on the gross and net population density of both central and peripheral urban land, although this happens for different reasons. As mentioned above, in central urban land motorways do not affect either the urban area or the urban population, whereas in non-central land motorways have a positive effect on both urban area and urban population.

In column 6, we examine the effect of motorways on the shape irregularity of urban plots. For the central urban unit, we measure this with *IRR*. It is interesting to observe that motorways appear to play a role in shaping the layout of central urban plots, despite not contributing to their expansion, as seen before. This suggests that, while central urban land may grow for other reasons – recall that central urban land expanded by 79.7% in the country –, the construction of motorways may introduce physical barriers and alter transport flows. The city or town adapts to accommodate the new transport infrastructure, leading to a more irregularly shaped central urban unit. Although the coefficient is estimated without much precision, given that the corresponding p-value is 0.099, the effect of motorways on the central *IRR* is of considerable magnitude. More specifically, the average effect for the municipalities where motorways were built equals 8.6%, which, to give a sense of magnitude, can be compared to 21.6%, the mean growth of central *IRR* in the country.

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[13] From this point onwards, we only report TSLS estimates. The corresponding OLS estimates are available from the authors upon request.

[14] We note that the Municipal Hall of Seixal, a municipality in the Lisbon Metropolitan Area, was relocated from one urban unit to another during the period of analysis (for consistency, we consider the same central unit both in 1990 and in 2012). In addition, the three new municipalities established in 1998 have their own central units, which we do not classify as such, since we use the pre-1998 administrative division. As a sensitivity check, we re-estimated the models in Table 5 excluding Seixal and the five pre-1998 municipalities that lost part of their territory due to the creation of the new municipalities. The results are very similar to those reported in Table 5.

Table 5. Effects of motorways on central vs. peripheral urban land

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Gross urban pop. density	Net urban pop. density	*IRR* (Panel A) / *WIRR* (Panel B)	*TINT*
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011 a)	1991-2011 a)	1990-2012	1990-2012
Panel A. TSLS, central urban land							
△ length of motorways 1989-2011	-0.0993	-0.129	-0.219	-0.0793	-0.0311	0.498*	
	(0.490)	(0.471)	(0.523)	(0.365)	(0.346)	(0.302)	
Kleibergen-Paap F-statistic	43.90	43.70	43.95	41.57	40.94	40.29	
Panel B. TSLS, peripheral urban land							
△ length of motorways 1989-2011	1.280**	1.201**	1.892***	0.155	0.173	0.272*	1.006***
	(0.635)	(0.536)	(0.644)	(0.421)	(0.343)	(0.161)	(0.391)
Kleibergen-Paap F-statistic	38.91	39.22	41.18	40.79	40.92	43.78	35.66

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The instrument for △ length of motorways is the length of 18th century road itineraries. *IRR* is the shape irregularity indicator for the central urban unit (i.e., the urban unit where the Municipal Hall is located); *WIRR* is the area-weighted measure of the shape irregularity of the non-central urban units; *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the non-central urban units in each municipality and the total urban area that is delimited by those perimeters (see Sections 2.2.2 and 2.2.3 in the text). The number of observations is 275 in Panel A and 265 in Panel B. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects. The first-stage coefficients are all very similar, as they range from 0.209 to 0.226 (the robust standard errors range from 0.0320 to 0.0356); to avoid repetition we do not report these 13 coefficients, which are available from the authors upon request.

The same column shows that the effect on the peripheral *WIRR*, i.e., the area-weighted shape irregularity in non-central areas, is also relevant. The average effect in the 148 municipalities with motorways built in the period of analysis is 4.8%, whereas, in comparison, the mean growth of observed non-central *WIRR* is 9.1%. Column 7 shows the coefficient for peripheral *TINT*, which is statistically significant at the 1% level. This is likely due to the fact that this indicator also captures the number of urban plots, and, as seen in the preceding section, the impact of motorways on the fragmentation of urban land is identified with high statistical precision. The average effect on peripheral *TINT* for the group of 148 "treated" municipalities is 17.7%, which we compare to 81.4%, that is, the mean growth of peripheral *TINT* in the country.

Taking stock of the main findings in Sections 4.1 and 4.2, we can conclude that the construction of motorways has a significant impact on various aspects of urban sprawl. The analysis suggests that about 1/5 or urban land built between 1990 and 2012 can be attributed to motorways built between 1989 and 2011. Interestingly, this effect appears to operate only through the expansion of peripheral and fragmented urban land; the only impact on the central urban unit operates through contributing to make it less compact, i.e., more irregularly shaped. Also, motorways contribute to the growth of population in non-central urban land. Yet, we did not find any significant effects of motorways on the population density of (both central and peripheral) urban land.

4.3 Sensitivity tests

Some of the analyses in Sections 4.2 and 4.3 can already be considered as sensitivity tests. These include examining the effects of motorways not only on urban land, but also on the more restrict category of residential land. We also check the robustness of our results on the number of urban plots to the exclusion of a large number of small plots that, in total, represent a minimal portion of urban land. In this section, we submit our estimates to the following additional tests (to save space and avoid repetition, we report these results in Appendix B).

First, we capture the geographical availability of motorways from a different angle. Instead of focusing on the length of motorways that were built in each municipality, we consider the travel time by road from the municipality centroid (calculated using 1981 population weights) to the nearest motorway access ramp. Denoting this by D, we adapt Equation (4) by replacing the explanatory variable of interest with $\Delta_{11,89}\ln D_i = \ln D_{11,i} - \ln D_{89,i}$ for municipality i, similarly to Rocha et al. (2023). A high value for this variable means a small relative reduction between 1989 and 2011 in the travel time to the nearest motorways ramp, that is, we expect the coefficient of this variable to be negative. The relatively low correlation between the new variable and our original measure, -0.37, indicates that the two explanatory variables are significantly different. For example, while the original variable is equal to zero for 127 municipalities, the new variable is different from zero for all but one observation. We re-estimated all the 24 models and report them in Appendix B.

The results in Tables B1 to B3 reveal that the first-stage Kleibergen-Paap F-statistic varies in the range from 19.4 to 24.2, compared to 35.6–43.9 in Tables 3 to 5. This indicates a lower predictive power of the historical instrument for the new explanatory variable compared to the original length-based explanatory variable. Nevertheless, it is reassuring that the estimated patterns are similar in both cases. To summarise, Tables 3–5 and Tables B1–B3 report statistically significant coefficients for 14 and 13 dependent variables, respectively, with a minimal difference in terms of statistical precision for the remaining variable, the shape irregularity of the central urban unit (the corresponding p-value is 0.099 in column 6 of Table 5 and 0.105 in column 6 of Table B3). We highlight that, as with the original explanatory variable, the effect estimated with the new variable is stronger for urban population than for the total population of the municipality, and that no effects are observed on urban population densities, central urban land, and central urban population.

Second, we winsorize all the dependent variables at the 2.5% and 97.5% levels, in order to rule out that our results could be driven by extreme observations. Overall, the estimates reported in Tables B4–B6 are similar to those in Tables 3-5. The more relevant differences are as follows. The coefficient for urban population is around 20% larger and estimated with more precision in Table B4 than in Table 3, i.e., 0.535 (with a p-value of 0.037) vs. 0.447 (0.094). Conversely, the coefficients for non-central urban land, non-central residential land, and non-central urban population are smaller in Table B6 than in Table 5 – by around 15%, 17%, and 12%, respectively (the significance levels are very similar, however). Also, the coefficient for the shape irregularity of the central urban unit becomes statistically insignificant, with a p-value of 0.138.

Third, as in Pratama et al. (2022), we carry out a falsification test to provide confirmation that our causal results are not due to chance. The test is implemented through the random reshuffling across municipalities of the observations of the instrumental variable. If using the false instrument yields statistically significant results, this will suggest that our previous results are influenced by placebo effects. Tables B7–B9 show that all the 24 point estimates obtained with the randomized instrument are clearly statistically insignificant (the smallest p-value is equal to 0.716) and the Kleibergen-Paap F-statistic is always close to zero.

Lastly, we note that it is complicated to find other suitable instrumental variables for motorways. Rocha et al. (2023, 2024) use the main roads of the 1945 National Road Plan as a complementary or secondary instrumental variable in their studies of the effects of motorways on local employment and economic activity. In the context of the present study, however, we are sceptical that this instrument could be deemed valid. While motorways form the central framework of the modern Portuguese road system (with a number of expressways providing complementary connections), the 1945 first-class roads are, today, part of the more capillary components of the road network. Visual evidence shows that many residential and commercial developments were built close to these roads, which suggests that it is likely that they have an effect on urban sprawl that is independent from the effect they can have through motorways, therefore violating the exclusion restriction assumption.

Yet, for completeness we also experimented with this instrumental variable, i.e., the length of first-class 1945 roads. An additional limitation is that this instrument is not as strong as the historical road itineraries, since the Kleibergen-Paap F-statistic is within the range of 21.8–27.4, compared to 35.6–43.9. The estimates, which are reported in Tables B10–B12 in the Appendix, have to be interpreted with caution. Overall, the results are analogous in qualitative terms to those shown in Tables 3–5; for example, we confirmed that motorways appear to have no effects on central urban land or population, in contrast with the strong effects estimated for non-central urban land or population. However, many of the estimated effects are suspiciously high. For instance, the coefficients for urban land (0.948) and urban population (1.083) are, respectively, 39% and 142% higher than our preferred estimates in Table 3. The coefficient for the number of urban plots (3.478) is 62% higher than the corresponding estimate in column 1 of Table 4.

If we combine the two instrumental variables, 18th century road itineraries and 1945 first-class roads in over-identified models, we can apply the Sargan-Hansen test of overidentifying restrictions. Given the considerations above on the (doubtful) validity of the 1945 instrument, this means that we are effectively stacking the odds against the non-rejection of the null hypothesis of the test, according to which the instruments are uncorrelated with the error term. The estimated effects are very similar to but slightly stronger than those in Tables 3-5 (the results are available from the authors upon request). Importantly, the null was rejected only once, with a p-value of 0.07. That is, we failed to reject the null in 23 out of 24 models. We regard this a strong indication that our main instrument is valid and, therefore, that our results can be interpreted as causal estimates.

Finally, we experimented with using roman roads as the instrumental variable, similarly to Percoco (2016) and Garcia-López (2019). The analysis revealed that, in our case, roman roads have absolutely no predictive power for motorways, as indicated by the Kleibergen-Paap F-statistic always below 0.2, i.e., essentially zero.

4.4 Cross-municipal heterogeneity and urban population density

Our results in Table 3 show that, on average, motorways do not lead to a reduction in urban population density in Portuguese mainland municipalities, since motorways appear to have a similar effect on both the growth of urban area and the growth of urban population. As described in Duranton and Puga (2015), normally the literature associates urban sprawl with decreasing population densities, often in the context of the predictions for the demand of residential space of the monocentric city model. Accordingly, Garcia-López (2019) finds evidence that motorways cause a reduction in city residential density in a sample of 579 European Functional Urban Areas.[15] Yet, the focus of the literature is on large and densely urbanised areas. We focus, quite differently, on urban sprawl at the level of the country. As noted earlier, most of the 275 municipalities are low-density areas, with small urban centres, typically a town or a small city. For example, in 1990, residential urban land represented less than 1% (4%) of the total area in 41% (70%) of the municipalities.

Our analysis can be adapted to analyse if there are deviations from the estimated average effects and, in this way, to nest the hypothesis that, in the small group of more urbanised municipalities, motorways cause a reduction in urban population density. This can be done by adapting Equation (4) to include a moderator variable, i.e., a dummy variable that identifies the group of the more urbanised municipalities and that is interacted with the motorways variable. A way of identifying this group of municipalities would be through the share of urban (residential) land in relation to total municipality area, but we only have this variable for 1990. Using this recent information to create the moderator binary variable could induce endogeneity in the interaction term. However, we can use population density in the municipality in 1970 (before the construction of the motorway network started) as a proxy for the share of urban land in 1970. This is based on the fact that the correlation between the log of the share of residential land in 1990 and the log of population density in the municipality in 1991 is equal to 0.924. The relationship is not only well defined but also stable over time, as the correlation between the log of the share of residential land in 2012 and the log of population density in the municipality in 2011 is equal to 0.965.[16]

We create a binary variable that is equal to 1 if a municipality is in the top 33% of the distribution of population density in 1970 and zero otherwise.[17] The average population density in the bottom 67% and in the top 33% is equal to 49.9 and 581.4 inhabitants/km^2, respectively. Extrapolating, these figures correspond to a projected share of residential land of 1.2% and 13.4% in 1970, respectively.[18,19] The moderator

[15] See https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Functional_urban_area for details on the concept of Functional Urban Area.

[16] The correlations between urban land and population density are almost identical. See Appendix C for scatterplots.

[17] We have experimented with other cut-off points, e.g., 40%, 30%, and 25%, and obtained similar empirical results. These results are available upon request.

[18] The extrapolation is done in the following way. First, we regress the log of the share of residential land in 1990 against the log of population density in 1991, and obtain: $\ln\widehat{ShareResidential}_{90,i} = -\underset{(-73.18)}{8.320} + \underset{(\ 39.90)}{0.991} * \ln PopDens_{91,i}$ (t-statistics in brackets), $R^2 =$ 0.854. Second, we plug the aforementioned average population densities into this equation, and retrieve the projected shares of residential land.

[19] For reference, in Garcia-López (2019) residential land represents about 10% of the total land of the Functional Urban Areas.

dummy is denoted by D_{70}. Formally, we are interested in estimating the following nonlinear version of Equation (4):

$$100 * \Delta_{12,90} \ln Y_i = \alpha + \boldsymbol{\theta} \ln Y_{90,i} +$$

$$\beta_H \Delta_{11,89} H_i + \beta_{HD} \Delta_{11,89} H_i * D_{70,i} + \beta_D D_{70,i} + \boldsymbol{X_i'\delta} + \varphi_d + \varepsilon_i. \quad (5)$$

The effect of motorways on the log-difference of Y is given by β_H for the low-density group and by $\beta_H + \beta_{HD}$ for the high-density, more urbanised group. As we have a second endogenous variable (the interaction term), we need a second instrument, which is given by the interaction of the moderator dummy, D_{70}, and the historical instrument, i.e., the length of road itineraries of before 1800.

The results in Table 6 reveal important differences between the two groups. For the larger low-density group (67% of the municipalities), motorways cause increases in both urban land and urban population, with no effects on urban population density. However, for the smaller high-density group, there is a relatively large effect on urban land (about 51% larger than for the low-density group) and residential land (about 73% larger), but no effect on urban population. As a result, the effect on urban population density is negative. To illustrate, 10 km of motorways lead to a 9% decrease in gross population density (column 5) and a 7.9% decrease in net population density (column 6).

In sum, when we focus on the more urbanised municipalities, we are able to reconcile our results with the general understanding in the literature that urban sprawl is usually associated with a decrease in urban population density. In particular, our results suggest that, for the high-density group, motorways generate an expansion of urban land that occurs in tandem with the *redistribution* of population across urban land; conversely, for the low-density group, urban sprawl is associated with an *increase* in population. While examining the reasons for this increase is beyond the scope of this paper, we can speculate: it is possible that motorways contribute to attract inhabitants from municipalities with poorer road accessibilities, due, for instance, to their impact on local or regional economic activity and employment opportunities. As these workers relocate to municipalities that are part of the motorway network, they tend to choose the municipalities that are less densely urbanised, where congestion costs are smaller and housing is cheaper. We intend to investigate these relocation dynamics in future research.

Table 6. Effects of motorways on urban land: low- vs. high-density municipalities

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Population	Gross urban pop. density	Net urban pop. density
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011	1991-2011 a)	1991-2011 a)
TSLS, Δ length of motorways 1989-2011, if:						
$D_{70} = 0$ (low-density)	0.606**	0.459*	0.533*	0.373**	-0.0162	0.122
	(0.303)	(0.267)	(0.291)	(0.188)	(0.311)	(0.291)
$D_{70} = 1$ (high-density)	0.916***	0.794**	-0.100	0.186	-0.901**	-0.793**
	(0.355)	(0.332)	(0.329)	(0.194)	(0.411)	(0.385)
Kleibergen-Paap F-statistic	16.81	17.01	19.41	19.04	17.33	17.44

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (5). Two instrumented variables: Δ length of motorways and its interaction with D_{70}, the dummy variable for the municipalities in the top 33% of population density in 1970 (see Section 4.4 in the text). The instruments are the length of 18th century road itineraries and its interaction with D_{70}. The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, district-level fixed effects, and the D_{70} dummy variable. The 24 first-stage coefficients are reported in Appendix D.

5 Conclusion

The present study documents the evolution of urban sprawl in mainland Portugal between 1990 and 2012 and investigates the effect of the development of the Portuguese motorway network on urban sprawl across mainland municipalities. We account for the endogeneity of motorways using 18th century road itineraries as an instrumental variable. The analysis suggests that motorways caused a relevant increase in both urban land and the number of urban plots, suggesting that motorways contributed to a significant extent to the fragmentation of urban land. Related to this, we find that motorways did *not* contribute to the contiguous growth of the central urban units (towns and cities), only to the expansion of the more fragmented non-central urban area. There is also some evidence that motorways contributed to the irregularity of the shape of urban plots, although the effect is more robust for non-central urban land. Finally, we implement an exploratory cross-municipal heterogeneity analysis, which shows that motorways caused a decrease in urban population density, but only in the relatively small group of the more urbanised municipalities.

Our results have significant policy implications. As outlined in the Introduction, urban sprawl has environmental, economic, and social indirect costs. For example, spreading populations across dispersed areas hampers the efficiency of both public transport and waste collection, as this increases service distances and raises operational costs due to fewer users or pickups per km; less frequent and more circuitous routes make public transport less competitive with private cars. We agree with Pratama et al. (2022) as they argue that the evaluation of motorway projects should incorporate factors of this type in cost-benefit analyses, although, we add, this may be a challenging exercise in some cases. Importantly, policymakers should implement in a timely fashion the necessary measures to moderate or control emerging urban sprawl dynamics induced by motorways. That may require implementing regular monitoring mechanisms to detect early indications of the impacts of motorways, particularly in non-central urban areas, which initially may be relatively overlooked. Indeed, our within-municipality heterogeneity analysis finds that the effects of motorways on the growth of urban land and urban population operates, essentially, through the scattered growth of peripheral urban areas. When necessary, policymakers could consider the implementation of measures that help counterbalance the "dispersive" effect of motorways by encouraging the revitalization and/or the compact development of central urban areas – depending on the specific context, these measures may include improving walkability, cyclability and public transport, as well as changes in land use regulations and housing policies, among others. Finally, our cross-municipality heterogeneity analysis shows significant effects of motorways on urban land growth for both more and less urbanised municipalities, although the effects appear to be somewhat stronger for the former, suggesting that public authorities should pay (even) more attention to those cases. We note that these considerations may be relevant for many emerging and developing economies, which at present are investing in the building of modern road networks and other large-scale transport projects.

The analysis suggests interesting avenues for future research. For instance, as the effect of motorways on urban sprawl is likely to be heterogenous across a number of dimensions, it would be important to understand what are the factors that interact with motorways (or roads in general) to create or amplify urban sprawl dynamics. These factors may include more permissive land use regulations or structural problems in housing markets in central urban areas. Another significant aspect is that relatively little is known about the determinants of urban sprawl in low-density areas (which cover most of the land in most countries), as the usual focus of the literature is on large cities and metropolitan areas. Yet, the fragmented development of urban land is a more general phenomenon, as the maps in our study and other papers and reports show. Our results suggest that the motorway-induced expansion of urban land occurs, for low-density municipalities, in tandem with an increase in population, which means that part of the new urban land is developed, probably, to accommodate incoming residents that originate from other municipalities. More research is needed to identify these spatial reallocation effects. Finally, it would be interesting to understand the impact of motorways on other land use classes, i.e., agricultural and forest land, and how this is related to the expansion of urban land. We expect to explore these ideas in our future research program, although the data requirements to explore some of them may be particularly demanding.

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Appendix A. Descriptive statistics and data sources

	Variable	Unit	Type	Mean	St.dev.	Min.	Max.	Notes
1.	(log urban area 2012 - log urban area 1990)*100	km^2	D	54.44	31.70	2.98	240.32	
2.	(log residential area 2012 - log residential area 1990)*100	km^2	D	47.86	30.77	2.98	235.40	
3.	(log urban population 2011 - log urban population 1991)*100	#	D	35.54	37.04	-31.01	186.23	
4.	(log population 2011 - log population 1991)*100	#	D	-3.19	20.04	-44.92	66.73	
5.	(log gross population density 2011 - log gross population density 1991)*100	#/km^2	D	-18.90	25.23	-118.03	88.23	
6.	(log net population density 2011 - log net population density 1991)*100	#/km^2	D	-12.37	23.88	-69.55	119.01	
7.	(log urban units 2012 - log urban units 1990)*100	#	D	103.28	86.16	-179.18	345.00	
8.	(log urban units >0.5 ha 2012 - log urban units >0.5 ha 1990)*100	#	D	94.34	79.79	-109.86	340.12	
9.	(log urban units >1 ha 2012 - log urban units >1 ha 1990)*100	#	D	82.14	72.68	-77.32	319.87	
10.	(log *WIRR* 2012 - log *WIRR* 1990)*100		D	11.72	16.81	-47.86	73.79	
11.	(log *TINT* 2012 - log *TINT* 1990)*100		D	37.21	33.57	-50.39	149.49	
12.	(log central urban area 2012 - log central urban area 1990)*100	km^2	D	57.36	49.31	0.23	417.85	
13.	(log peripheral urban area 2012 - log peripheral urban area 1990)*100	km^2	D	55.36	68.88	-249.97	397.97	a)
14.	(log central residential area 2012 - log central residential area 1990)*100	km^2	D	53.63	49.74	0.23	473.98	
15.	(log peripheral residential area 2012 - log peripheral residential area 1990)*100	km^2	D	48.11	66.87	-249.03	397.97	a)
16.	(log central urban population 2011 - log central urban population 1991)*100	#	D	39.30	53.67	-42.41	405.66	
17.	(log peripheral urban pop. 2011 - log peripheral urban pop. 1991)*100	#	D	35.77	80.19	-354.34	431.30	a)
18.	(log central gross pop. density 2011 - log central gross pop. density 1991)*100	#/km^2	D	-18.07	30.02	-111.07	113.06	
19.	(log peripheral gross pop. dens. 2011 - log peripheral gross pop. dens. 1991)*100	#/km^2	D	-19.59	43.56	-164.48	189.27	a)
10.	(log central net pop. density 2011 - log central net pop. density 1991)*100	#/km^2	D	-14.34	28.96	-114.72	113.06	
21.	(log peripheral net pop. density 2011 - log peripheral net pop. density 1991)*100	#/km^2	D	-12.42	40.85	-168.32	179.74	a)
22.	(log central *IRR* 2012 - log central *IRR* 1990)*100		D	16.56	23.72	-47.89	107.67	
23.	(log peripheral *WIRR* 2012 - log peripheral *WIRR* 1990)*100		D	7.20	15.14	-56.10	69.91	a)
24.	(log peripheral *TINT* 2012 - log peripheral *TINT* 1990)*100		D	46.12	45.83	-68.73	193.42	a)

Appendix A. Descriptive statistics and data sources (continuation)

	Variable	Unit	Type	Mean	St.dev.	Min.	Max.	Notes
25.	log urban area 1990	km^2	C	1.544	1.191	-1.406	4.398	
26.	log residential area 1990	km^2	C	1.467	1.155	-1.406	4.372	
27.	log urban population 1991	#	C	8.880	1.391	5.425	13.401	
28.	log population 1991	#	C	9.824	1.008	7.627	13.405	
29.	log gross population density 1991	$\#/km^2$	C	7.336	0.544	5.641	9.429	
30.	log net population density 1991	$\#/km^2$	C	7.412	0.558	5.641	9.506	
31.	log urban units 1990	#	C	2.287	0.948	0	4.828	
32.	log urban units $>$0.5 ha 1990	#	C	2.255	0.956	0	4.796	
33.	log urban units $>$1 ha 1990	#	C	2.227	0.958	0	4.787	
34.	log *WIRR* 1990		C	0.728	0.289	0.268	2.131	
35.	log *TINT* 1990		C	1.610	0.485	0.587	2.845	
36.	log central urban area 1990	km^2	C	0.457	1.163	-2.996	4.362	
37.	log peripheral urban area 1990	km^2	C	0.955	1.421	-5.116	4.216	a)
38.	log central residential area 1990	km^2	C	0.414	1.127	-2.996	4.208	
39.	log peripheral residential area 1990	km^2	C	0.853	1.397	-5.116	4.085	a)
40.	log central urban population 1991	#	C	8.132	1.454	4.205	13.401	
41.	log peripheral urban population 1991	#	C	7.924	1.519	1.099	12.375	a)
42.	log central gross population density 1991	$\#/km^2$	C	7.675	0.541	6.029	9.432	
43.	log peripheral gross population density 1991	$\#/km^2$	C	6.969	0.606	4.222	8.865	a)
44.	log central net population density 1991	$\#/km^2$	C	7.718	0.575	6.029	9.560	
45.	log peripheral net population density 1991	$\#/km^2$	C	7.061	0.574	4.317	8.944	a)
46.	log central *IRR* 1990		C	0.842	0.356	0.171	2.251	
47.	log peripheral *WIRR* 1990		C	0.571	0.214	0.162	1.722	a)
48.	log peripheral *TINT* 1990		C	1.506	0.556	0.162	2.806	a)

Appendix A. Descriptive statistics and data sources (continuation)

	Variable	Unit	Type	Mean	St.dev.	Min.	Max.	Notes
49.	Length of motorways 2011 - length of motorways 1989	km	E	9.301	12.727	0	72.806	
50.	(log travel time by road to the nearest motorway access ramp in 2011 - log travel time by road to the nearest motorway access ramp in 1989)*100	min	E	-146.62	98.37	-520.51	4.48	b)
51.	Length of 18th century road itineraries	km	I	27.861	27.030	0	150.99	
52.	Length of 1945 National Road Plan 1st class roads	km	I	18.703	19.236	0	102.63	
53.	log length of motorways 1989	km	C	1.160	3.551	0	20.532	
54.	log travel time by road to the nearest motorway access ramp in 1989	min	C	3.929	1.040	0.488	5.509	b)
55.	Average altitude	m	C	363.23	241.52	19.830	1272.6	
56.	Standard deviation of altitude	m	C	65.980	49.744	2.656	254.76	
57.	Surface area	km^2	C	323.79	284.20	8.000	1721.5	
58.	log straight-line distance to the coast	km	C	3.598	1.212	-0.607	5.322	b)
59.	Age: 2023 - year of the official creation of the municipality	years	C	616.68	240.38	44	968	
60.	log population 1981	#	C	9.864	0.956	7.676	13.602	
61.	log (electricity consumption / population) 1981	kWh/#	C	6.518	0.926	4.724	10.051	
62.	Binary variable for Lisbon and Porto		C	0.007		0	1	
63.	Binary variable for the other 16 district capitals		C	0.058		0	1	
64.	Binary variable for the 49 municipalities within a travel time by road to either Lisbon or Porto no larger than 60 minutes in 1981		C	0.178		0	1	b)

Notes. Type: D = dependent variable; C = control variable; E = explanatory variable; I = instrumental variable. The number of observations is equal to 275, except for a) (265). The travel times and distances in b) are calculated from population-weighted municipality centroids; the population weights were obtained using 1981 census data from INE (Statistics Portugal).

Sources. Variables 1-3, 5-27, 29-48. Authors' GIS calculations; urban and residential land were defined using the CORINE land cover database for 1990 and 2012, complemented with census spatial data at the statistical subsection level for 1991 and 2011 (see Section 2.1 in the text). **Variables 3, 5-6, 16-21, 27, 29-30, 40-45.** Population data sourced from the 1991 and 2011 censuses. **Variables 4, 28, 60-61.** Authors' calculations using Statistics Portugal data. **Variables 49-50, 53-54.** Authors' GIS calculations: length-based motorway variables based on maps from Portugal Infrastructures (IP);

travel times calculated using road networks based mainly on TomTom/TeleAtlas maps (the 1989 network was constructed through applying downgrading operations to the 1991 network). **Variables 51-52.** Authors' GIS calculations; the map of the 18th century road itineraries is from Matos (1980). **Variables 55-56.** Authors' GIS calculations using altimetric information obtained from a Digital Elevation Model available from ESRI. The model uses a grid of squares with a spatial resolution of 30m, where each square corresponds to an altimetric value; variables 55 and 56 are respectively the average and the standard deviation of these altimetric values. **Variables 57-58.** Authors' GIS calculations. **Variable 59.** Various sources. **Variable 64.** Authors' GIS calculations; road network for 1981 based on maps from the Army Geospatial Information Centre (CIGeoE) and the Portuguese Automobile Club (ACP).

Appendix B. Supplementary results

Table B1. Effects of motorways (distance to access ramp) on urban land: size and population density

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable = log-difference of:	Urban land	Residential land	Urban population	Population	Gross urban pop. density	Net urban pop. density
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011	1991-2011 a)	1991-2011 a)
TSLS, log-difference of travel time by road to the nearest motorway access ramp 1989-2011	-0.114**	-0.0877**	-0.0833*	-0.0643**	0.0152	-0.00650
	(0.0483)	(0.0408)	(0.0445)	(0.0291)	(0.0455)	(0.0429)
Kleibergen-Paap F-statistic	21.64	21.53	24.21	21.81	23.63	23.78
IV (first-stage): length of 18th century itineraries	-0.0136***	-0.0136***	-0.0139***	-0.0134***	-0.0142***	-0.0142***
	(0.00292)	(0.00293)	(0.00283)	(0.00289)	(0.00292)	(0.00292)

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on the adaptation of Equation (4) as described in Section 4.3 (the dependent variable is not multiplied by 100). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), log of travel time by road to the nearest motorway access ramp in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B2. Effects of motorways (distance to access ramp) on urban land: fragmentation, shape irregularity, and interface

	(1)	(2)	(3)	(4)	(5)
Dependent variable = log-difference of:	Number of urban units	Number of urban units > 0.5 ha	Number of urban units > 1 ha	*WIRR*	*TINT*
Period:	1990-2012	1990-2012	1990-2012	1990-2012	1990-2012
TSLS, log-difference of travel time by road to the nearest motorway access ramp 1989-2011	-0.353**	-0.330***	-0.333***	-0.0369	-0.121**
	(0.140)	(0.121)	(0.115)	(0.0298)	(0.0538)
Kleibergen-Paap F-statistic	19.96	20.05	20.08	22.82	20.38
IV (first-stage): length of 18th century itineraries	-0.0134***	-0.0134***	-0.0134***	-0.0138***	-0.0134***
	(0.00301)	(0.00300)	(0.00299)	(0.00290)	(0.00296)

Notes. Estimates based on the adaptation of Equation (4) as described in Section 4.3 (the dependent variable is not multiplied by 100). *WIRR* is the area-weighted measure of the shape irregularity of the urban units, while *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the urban units in each municipality and the total urban area that is delimited by those perimeters (see Section 2.2.2 in the text). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), log of travel time by road to the nearest motorway access ramp in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B3. Effects of motorways (distance to access ramp) on central vs. peripheral urban land

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable = log-difference of:	Urban land	Residential land	Urban population	Gross urban pop. density	Net urban pop. density	*IRR* (Panel A) / *WIRR* (Panel B)	*TINT*
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011 a)	1991-2011 a)	1990-2012	1990-2012
Panel A. TSLS, central urban land							
log-difference of travel time by road to the nearest motorway access ramp 1989-2011	0.0148 (0.0795)	0.0241 (0.0768)	0.0277 (0.0830)	0.00709 (0.0583)	-0.00522 (0.0544)	-0.0823 (0.0508)	
Kleibergen-Paap F-statistic	23.46	23.33	24.18	23.53	23.41	23.26	
Panel B. TSLS, peripheral urban land							
log-difference of travel time by road to the nearest motorway access ramp 1989-2011	-0.233** (0.110)	-0.233** (0.0929)	-0.347*** (0.117)	-0.0352 (0.0685)	-0.0330 (0.0551)	-0.0545* (0.0288)	-0.189*** (0.0700)
Kleibergen-Paap F-statistic	21.51	21.65	22.60	22.31	22.48	23.31	19.39

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on the adaptation of Equation (4) as described in Section 4.3 (the dependent variable is not multiplied by 100). The instrument for log-difference of travel time by road to the nearest motorway access ramp is the length of 18th century road itineraries. *IRR* is the shape irregularity indicator for the central urban unit (i.e., the urban unit where the Municipal Hall is located); *WIRR* is the area-weighted measure of the shape irregularity of the non-central urban units; *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the non-central urban units in each municipality and the total urban area that is delimited by those perimeters (see Sections 2.2.2 and 2.2.3 in the text). The number of observations is 275 in Panel A and 265 in Panel B. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B4. Effects of motorways on urban land: size and population density (winsorized dependent variables)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Population	Gross urban pop. density	Net urban pop. density
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011	1991-2011 a)	1991-2011 a)
TSLS, △ length of motorways 1989-2011	0.644**	0.445*	0.535**	0.338**	-0.135	0.0719
	(0.276)	(0.244)	(0.257)	(0.163)	(0.270)	(0.261)
Kleibergen-Paap F-statistic	39.01	39.13	43.46	42.12	38.59	38.20
IV (first-stage): length of 18th century itineraries	0.215***	0.215***	0.222***	0.219***	0.217***	0.216***
	(0.0345)	(0.0343)	(0.0337)	(0.0337)	(0.0349)	(0.0349)

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The number of observations is 275. Dependent variables winsorized at 2.5% and 97.5%. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B5. Effects of motorways on urban land: fragmentation, shape irregularity, and interface

(winsorized dependent variables)

	(1)	(2)	(3)	(4)	(5)
Dependent variable = 100*log-difference of:	Number of urban units	Number of urban units > 0.5 ha	Number of urban units > 1 ha	*WIRR*	*TINT*
Period:	1990-2012	1990-2012	1990-2012	1990-2012	1990-2012
TSLS, Δ length of motorways 1989-2011	2.108**	1.803**	1.782***	0.195	0.640**
	(0.832)	(0.702)	(0.642)	(0.167)	(0.302)
Kleibergen-Paap F-statistic	36.34	36.56	36.54	42.06	34.09
IV (first-stage): length of 18th century itineraries	0.211***	0.211***	0.211***	0.219***	0.205***
	(0.0349)	(0.0349)	(0.0350)	(0.0337)	(0.0351)

Notes. Estimates based on Equation (4). *WIRR* is the area-weighted measure of the shape irregularity of the urban units, while *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the urban units in each municipality and the total urban area that is delimited by those perimeters (see Section 2.2.2 in the text). The number of observations is 275. Dependent variables winsorized at 2.5% and 97.5%. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B6. Effects of motorways on central vs. peripheral urban land (winsorized dependent variables)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Gross urban pop. density	Net urban pop. density	*IRR* (Panel A) / *WIRR* (Panel B)	*TINT*
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011 a)	1991-2011 a)	1990-2012	1990-2012
Panel A. TSLS, central urban land							
△ length of motorways 1989-2011	0.117	0.0185	0.241	-0.131	-0.0957	0.429	
	(0.420)	(0.408)	(0.358)	(0.332)	(0.313)	(0.289)	
Kleibergen-Paap F-statistic	43.90	43.70	43.95	41.57	40.94	40.29	
Panel B. TSLS, peripheral urban land							
△ length of motorways 1989-2011	1.088**	1.002**	1.662***	0.175	0.142	0.251*	0.957**
	(0.522)	(0.410)	(0.562)	(0.397)	(0.309)	(0.146)	(0.379)
Kleibergen-Paap F-statistic	38.91	39.22	41.18	40.79	40.92	43.78	35.66

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The instrument for △ length of motorways is the length of 18th century road itineraries. *IRR* is the shape irregularity indicator for the central urban unit (i.e., the urban unit where the Municipal Hall is located); *WIRR* is the area-weighted measure of the shape irregularity of the non-central urban units; *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the non-central urban units in each municipality and the total urban area that is delimited by those perimeters (see Sections 2.2.2 and 2.2.3 in the text). The number of observations is 275 in Panel A and 265 in Panel B. Dependent variables winsorized at 2.5% and 97.5%. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B7. Effects of motorways on urban land: size and population density (falsification test)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Population	Gross urban pop. density	Net urban pop. density
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011	1991-2011 a)	1991-2011 a)
TSLS, Δ length of motorways 1989-2011	-2.069	-6.639	-0.328	1.142	2.701	8.270
	(8.060)	(20.52)	(12.37)	(5.251)	(11.01)	(29.30)
Kleibergen-Paap F-statistic	0.108	0.104	0.0244	0.0595	0.0710	0.0715
"False" IV (first-stage): randomly-reshuffled	-0.00796	-0.00778	-0.00379	-0.00588	-0.00650	-0.00649
length of 18^{th} century itineraries	(0.0242)	(0.0241)	(0.0242)	(0.0241)	(0.0244)	(0.0243)

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B8. Effects of motorways on urban land: fragmentation, shape irregularity, and interface (falsification test)

	(1)	(2)	(3)	(4)	(5)
Dependent variable = 100*log-difference of:	Number of urban units	Number of urban units > 0.5 ha	Number of urban units > 1 ha	*WIRR*	*TINT*
Period:	1990-2012	1990-2012	1990-2012	1990-2012	1990-2012
TSLS, $\triangle$ length of motorways 1989-2011	-0.332	-2.974	-6.188	-35.78	-1.836
	(12.56)	(14.87)	(21.45)	(618.4)	(7.791)
Kleibergen-Paap F-statistic	0.0974	0.101	0.104	0.00304	0.0866
"False" IV (first-stage): randomly-reshuffled length of 18th century itineraries	-0.00747	-0.00758	-0.00772	-0.00131	-0.00688
	(0.0239)	(0.0239)	(0.0239)	(0.0237)	(0.0234)

Notes. Estimates based on Equation (4). *WIRR* is the area-weighted measure of the shape irregularity of the urban units, while *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the urban units in each municipality and the total urban area that is delimited by those perimeters (see Section 2.2.2 in the text). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B9. Effects of motorways on central vs. peripheral urban land (falsification test)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Gross urban pop. density	Net urban pop. density	*IRR* (Panel A) / *WIRR* (Panel B)	*TINT*
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011 a)	1991-2011 a)	1990-2012	1990-2012
Panel A. TSLS, central urban land							
Δ length of motorways 1989-2011	-11.06	-11.28	-1.856	10.26	9.730	41.01	
	(49.98)	(50.77)	(25.71)	(49.41)	(44.05)	(352.2)	
Kleibergen-Paap F-statistic	0.0537	0.0532	0.0213	0.0406	0.0454	0.0118	
Panel B. TSLS, peripheral urban land							
Δ length of motorways 1989-2011	-3.636	-9.303	-9.446	-1.704	4.369	-0.262	-0.909
	(12.74)	(25.60)	(29.95)	(7.802)	(14.91)	(4.475)	(6.093)
Kleibergen-Paap F-statistic	0.149	0.139	0.111	0.110	0.104	0.111	0.128

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The "false" instrument for Δ length of motorways is the randomly-reshuffled length of 18th century road itineraries. *IRR* is the shape irregularity indicator for the central urban unit (i.e., the urban unit where the Municipal Hall is located); *WIRR* is the area-weighted measure of the shape irregularity of the non-central urban units; *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the non-central urban units in each municipality and the total urban area that is delimited by those perimeters (see Sections 2.2.2 and 2.2.3 in the text). The number of observations is 275 in Panel A and 265 in Panel B. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B10. Effects of motorways on urban land: size and population density (alternative instrument)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Population	Gross urban pop. density	Net urban pop. density
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011	1991-2011 a)	1991-2011 a)
TSLS, Δ length of motorways 1989-2011	0.948**	0.580	1.083**	0.615**	0.298	0.615*
	(0.477)	(0.381)	(0.435)	(0.244)	(0.364)	(0.343)
Kleibergen-Paap F-statistic	24.91	24.66	26.72	26.44	24.03	23.59
IV (first-stage): length of first-class roads	0.223***	0.223***	0.233***	0.229***	0.225***	0.223***
of the 1945 National Road Plan	(0.0448)	(0.0450)	(0.0451)	(0.0445)	(0.0458)	(0.0460)

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B11. Effects of motorways on urban land: fragmentation, shape irregularity, and interface

(alternative instrument)

	(1)	(2)	(3)	(4)	(5)
Dependent variable = 100*log-difference of:	Number of urban units	Number of urban units $>$ 0.5 ha	Number of urban units $>$ 1 ha	*WIRR*	*TINT*
Period:	1990-2012	1990-2012	1990-2012	1990-2012	1990-2012
TSLS, $\triangle$ length of motorways 1989-2011	3.478***	3.045***	2.906***	0.0270	0.891**
	(1.132)	(0.985)	(0.910)	(0.242)	(0.380)
Kleibergen-Paap F-statistic	23.27	23.51	23.60	27.41	21.83
IV (first-stage): length of first-class roads of the 1945 National Road Plan	0.217***	0.218***	0.218***	0.231***	0.212***
	(0.0450)	(0.0449)	(0.0448)	(0.0441)	(0.0453)

Notes. Estimates based on Equation (4). *WIRR* is the area-weighted measure of the shape irregularity of the urban units, while *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the urban units in each municipality and the total urban area that is delimited by those perimeters (see Section 2.2.2 in the text). The number of observations is 275. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Table B12. Effects of motorways on central vs. peripheral urban land (alternative instrument)

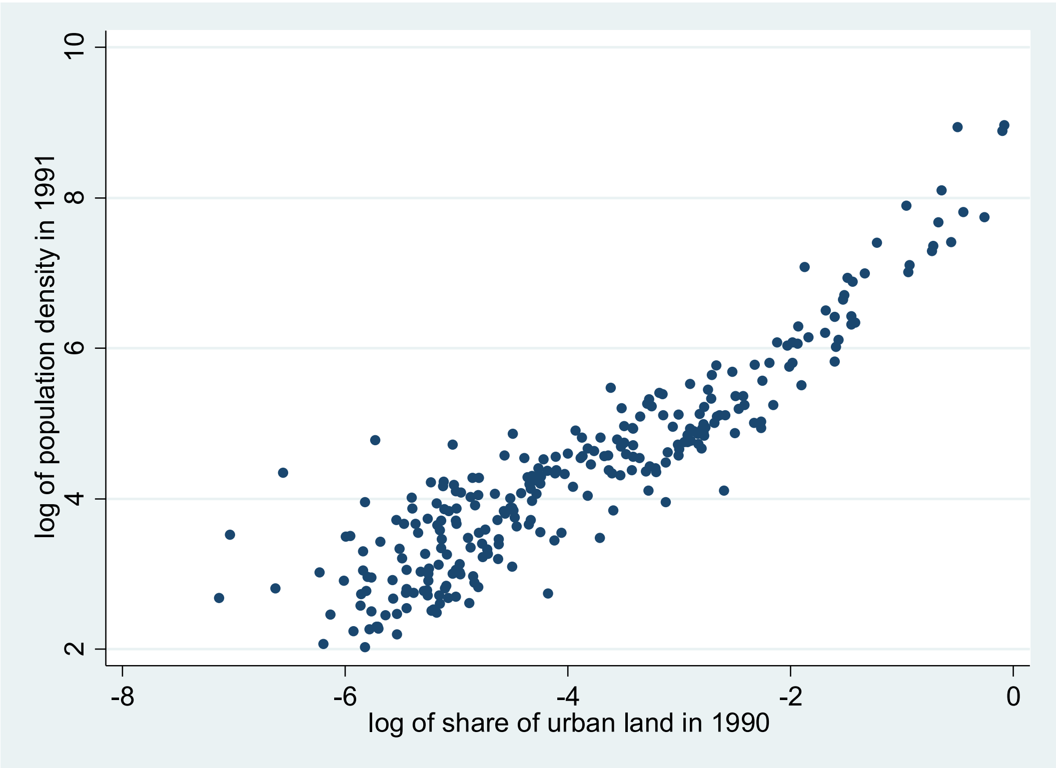
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable = 100*log-difference of:	Urban land	Residential land	Urban population	Gross urban pop. density	Net urban pop. density	*IRR* (Panel A) / *WIRR* (Panel B)	*TINT*
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011 a)	1991-2011 a)	1990-2012	1990-2012
Panel A. TSLS, central urban land							
△ length of motorways 1989-2011	0.322	0.511	0.517	0.275	0.163	-0.00683	
	(0.674)	(0.684)	(0.599)	(0.442)	(0.441)	(0.440)	
Kleibergen-Paap F-statistic	26.27	25.48	26.95	26.17	24.95	25.13	
Panel B. TSLS, peripheral urban land							
△ length of motorways 1989-2011	2.072**	1.555**	2.744***	0.248	0.623	0.264	1.524***
	(0.812)	(0.719)	(0.975)	(0.527)	(0.481)	(0.188)	(0.519)
Kleibergen-Paap F-statistic	24.96	25.09	25.66	25.17	25.29	26.18	22.86

Notes. a) The CORINE Land Cover data used to compute this variable is from 1990 and 2012, while the census population data is from 1991 and 2011. Estimates based on Equation (4). The instrument for △ length of motorways is the length of first-class roads in the 1945 National Road Plan. *IRR* is the shape irregularity indicator for the central urban unit (i.e., the urban unit where the Municipal Hall is located); *WIRR* is the area-weighted measure of the shape irregularity of the non-central urban units; *TINT* is the "total interface indicator" based on the relation between the summation of all the perimeters of the non-central urban units in each municipality and the total urban area that is delimited by those perimeters (see Sections 2.2.2 and 2.2.3 in the text). The number of observations is 275 in Panel A and 265 in Panel B. Robust standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for the log of the initial value of the corresponding sprawl variable, municipality surface area, average altitude, terrain ruggedness, log of the distance to the coast, municipality age, a dummy variable for Lisbon and Porto, a dummy variable for "suburban" municipalities, a dummy variable for district capitals (except Lisbon and Porto), length of motorways in 1989, log of population in 1981, log of electricity consumption per capita in 1981, and district-level fixed effects.

Appendix C. Population density in the municipality as a proxy for the share of urban/residential land

Figure C1. In 1990

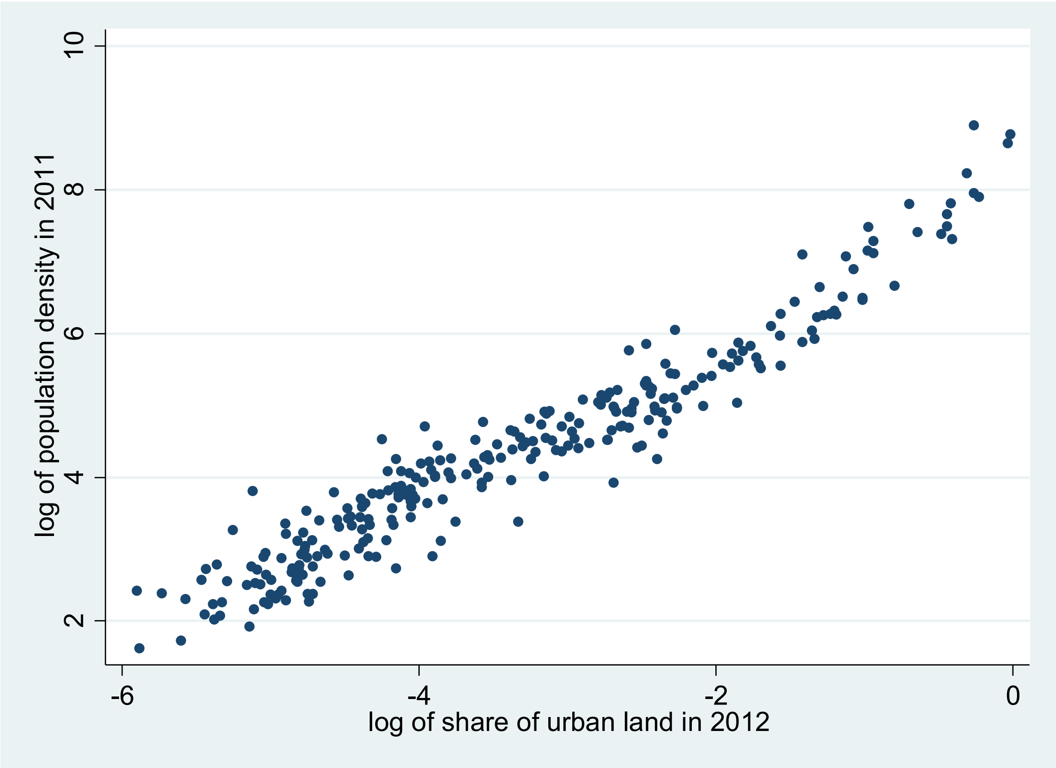
Panel A. Urban land (correlation = 0.916)



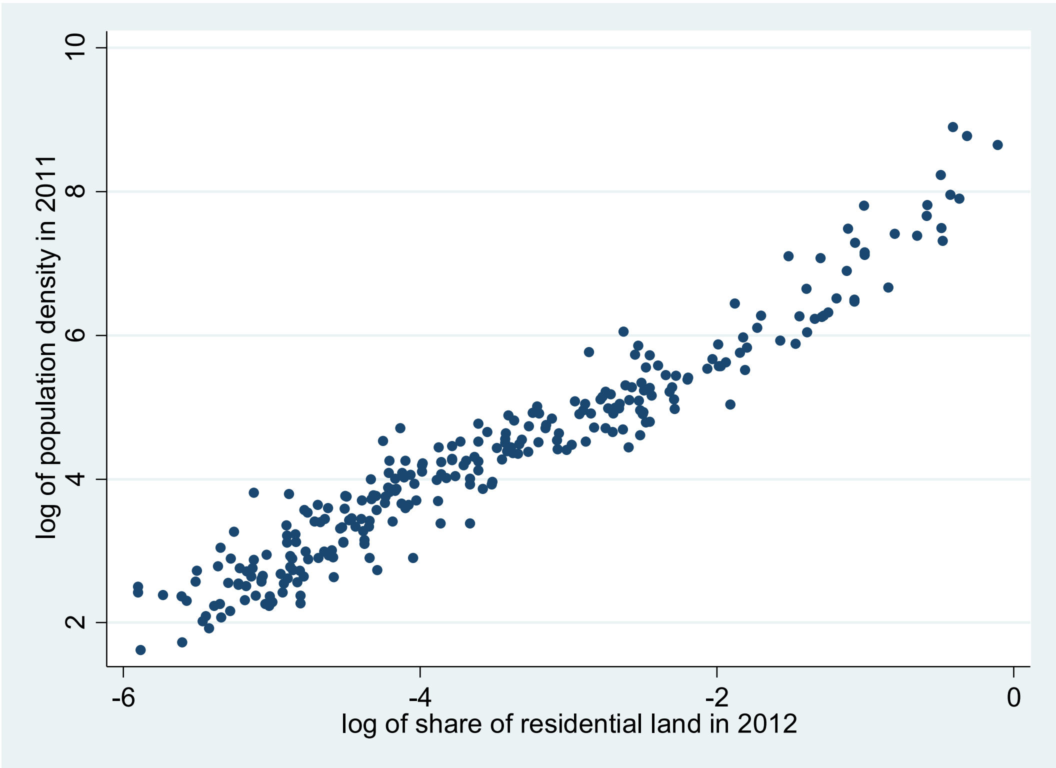
Panel B. Residential land (correlation = 0.924)

Figure C2. In 2012

Panel A. Urban land (correlation = 0.963)



Panel B. Residential land (correlation = 0.965)



Appendix D. Effects of motorways on urban land: low- vs. high-density municipalities (first-stage coefficients)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable in Table 6 = 100*log-difference of:	Urban land	Residential land	Urban population	Population	Gross urban pop. density	Net urban pop. density
Period:	1990-2012	1990-2012	1991-2011 a)	1991-2011	1991-2011 a)	1991-2011 a)
Endogenous variable: Δ length of motorways 1989-2011						
IV: length of 18th century itineraries	0.188***	0.187***	0.191***	0.188***	0.190***	0.189***
	(0.0381)	(0.0380)	(0.0375)	(0.0377)	(0.0380)	(0.0380)
IV: D_{70}*length of 18th century itineraries	0.199*	0.198*	0.209**	0.210**	0.205**	0.203*
	(0.102)	(0.102)	(0.102)	(0.102)	(0.104)	(0.103)
Endogenous variable: D_{70}*Δ length of motorways 1989-2011						
IV: length of 18th century itineraries	-0.0370**	-0.0366**	-0.0363**	-0.0376**	-0.0347*	-0.0338*
	(0.0174)	(0.0174)	(0.0172)	(0.0173)	(0.0178)	(0.0180)
IV: D_{70}*length of 18th century itineraries	0.431***	0.433***	0.434***	0.434***	0.439***	0.441***
	(0.100)	(0.100)	(0.0995)	(0.0996)	(0.101)	(0.101)

Notes. See Table 6 in the main text.