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Motorways, urban growth, and suburbanisation: evidence from three decades of motorway construction in Portugal

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Abstract

Portugal moved from having less than 200 km of motorways before joining the European Union in 1986 to having the fifth highest motorway density relative to population in the Union in 2017. This paper studies the relationship between the expansion of the Portuguese motorway network between 1981 and 2011 and the growth of population and employment in the 275 mainland municipalities of the country. We address the endogeneity of the geography of motorways using instrumental variables based on historical transport networks from 1800 and 1945. Our findings suggest that, on average, new motorways caused large increases in both population and employment. In line with existing evidence for other countries, we also find that motorways contributed to suburbanisation, as the impact of motorways on population growth (but not on employment growth) is particularly strong in suburban municipalities. In addition, motorways also appear to have influenced urban agglomeration dynamics, as their effect on population growth depends positively on the municipality's population size in 1970.

Keywords: transport infrastructure, motorways, population redistribution, employment, suburbanisation, instrumental variables.

JEL codes: O18, R11, R49, R58.

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1. Introduction

Investment in transport infrastructure networks and the resulting reduction in transport costs is often seen as a way to boost economic growth and regional development, in particular in lagging regions, which are expected to benefit from being connected to larger markets. The European Union, for example, has provided massive funding support for the development of transport infrastructures – namely motorways – in many of its member states, with the objective of promoting economic growth, economic integration, and regional cohesion within the Union. A crucial issue is, of course, that the development of large-scale transport networks is likely to induce significant changes in the spatial distribution of population and employment within a given country or region. The effect of the expansion of transport networks on urban growth has indeed been studied for a number of countries e.g., the US, Germany, Spain, and Italy. We contribute to this growing literature by focusing on the expansion of the Portuguese motorway network. While in the early 1980s Portugal had less than 200 km of motorways, the network increased to around 1500 km in 2000 and to more than 3000 km in 2013 (ceasing to expand thereafter). According to Eurostat data, in 2017 Portugal had the third highest endowment of motorways relative to GDP in the European Union, and the fifth relative to population. In other words, the country moved from having an evident lack of motorways to, quite possibly, a state of over-investment in this type of infrastructure.

The main findings of the empirical literature are that motorways contribute, on the one hand, to the growth of population and/or employment across metropolitan regions or municipalities, and, on the other hand, to suburbanisation (i.e. the shift of population from central cities to their suburbs). Duranton and Turner (2012) estimate strong effects of interstate highways in US metropolitan areas both on employment and on population; Möller and Zierer (2018) implement a similar analysis and focus on the effect of the expansion of the German autobahn network on employment in West German regions, finding that this is highly significant. Garcia-López et al. (2015) provide evidence for the 851 metropolitan municipalities in Spain (i.e. central cities plus suburbs) and show that, after controlling for distance to the CBD (a proxy for suburbanisation dynamics), population growth is higher the closer a municipality is to a highway ramp. Percoco

(2016) considers all 7,480 Italian municipalities and finds that access to a highway increases employment and the number of plants; there are some hints of a positive effect on population as well, but in most cases this is not significant in statistical terms. The evidence on the link between motorways and suburbanisation appears to be equally clear. The Baum-Snow's (2007) analysis for the US indicates that one new highway passing through a central city reduced its population by about 18 percent between 1950 and 1990, while Baum-Snow et al. (2017) present qualitatively similar conclusions for Chinese prefectures. Garcia-López (2012) and Garcia-López et al. (2015) focus respectively on the Barcelona metropolitan region and in mainland Spain and find that highways have a negative impact on the population of central cities and, conversely, a positive impact on population growth in suburban areas. More recently, Levkovich et al. (2020) show that in the Netherlands highway expansions caused a leapfrog sprawl pattern in which suburban growth skipped development-restricted areas and expanded into farther located peripheral areas.

A key methodological issue in this literature is that the spatial placement of transport networks is not random. As emphasised inter alia by Garcia-López et al. (2015), planners typically want to serve areas with expected high population growth or, alternatively, areas with poor growth prospects (as a way to foster their development). Reverse causation would be a problem in both cases. There could be also omitted variables that affect both the growth of population (or employment) and the expansion of the motorway network. The pivotal study of Baum-Snow (2007) addresses this issue by instrumenting the total number of highways built between 1950 and 1990 with the number of highways in a 1947 national interstate highway plan. All the other aforementioned studies follow this approach, i.e. they employ historical transport networks as sources of exogenous variation in order to identify the causal effect of motorways on population or employment growth.[1] To be more precise, these instrumental variables were sourced from: maps of the early 1528-1850 explorations, a 1898 map of railroads, and the aforementioned 1947 highway plan (for the US; Baum-

[1] Redding and Turner (2015) provide a detailed survey of the literature on the effects of transport infrastructure on the location of population and economic activities, including some studies that employ the "inconsequential units" approach proposed by Chandra and Thompson (2000). This method relies on choosing a sample based on the idea that the unobserved characteristics of the areas between large cities connected by a given transport project are inconsequential to the choice of route; Chandra and Thompson (2000), for example, restrict attention to rural US counties that received interstate highways "accidentally" i.e. by virtue of lying between larger cities.

Snow, 2007, Duranton and Turner, 2012); roman roads and 1760 Bourbon roads (Spain; Garcia-López et al., 2015); roman roads (Italy; Percoco, 2016); roads and railways in 1962 (China; Baum-Snow et al., 2017); a 1890 plan for the railroad network and a 1937 plan for the autobahn and major roads network (Germany; Möller and Zierer, 2018); and, finally, roads in 1821 (for the Netherlands; Levkovich et al., 2020).

We follow the same approach for the case of Portugal and construct a set of instrumental variables for the expansion of the motorway network using the maps of roads in 1800 and 1st-class roads as defined in the 1945 National Road Plan. In line with previous research, our findings suggest that motorways have a significant effect on the growth of both population and employment in Portugal's mainland municipalities. To illustrate, we find that an increase of one standard deviation (13.2 km) in motorways between 1981 and 2011 leads, on average, to an additional population growth of about 10.2% over the same period. The effect, however, is clearly larger in suburban municipalities (around 17-20%), which is an indication that motorways have contributed to suburbanisation in Portugal. The fact that the effect of motorways on employment in these municipalities is much smaller is an additional sign of suburbanisation. We also find that, in addition to suburbanisation, motorways appear to have reinforced urban agglomeration dynamics, in the sense that the magnitude of the effect of motorways on population growth depends positively on the initial population size of municipalities.

The rest of the paper is organised as follows. The next section describes the data and explains the more relevant aspects of our research context, while Section 3 describes our empirical strategy. Section 4 reports and discusses the results, including a series of sensitivity analyses. Section 5 concludes.

2. Data and background

2.1. The Portuguese motorway network

The development of the Portuguese motorway network occurred relatively late for European standards. Figure 1 shows that, as of 1991, existing motorways served essentially to connect Lisbon and Porto to each other and to their suburban areas. Yet, in the following two decades the network expanded at a fast pace to other regions, creating

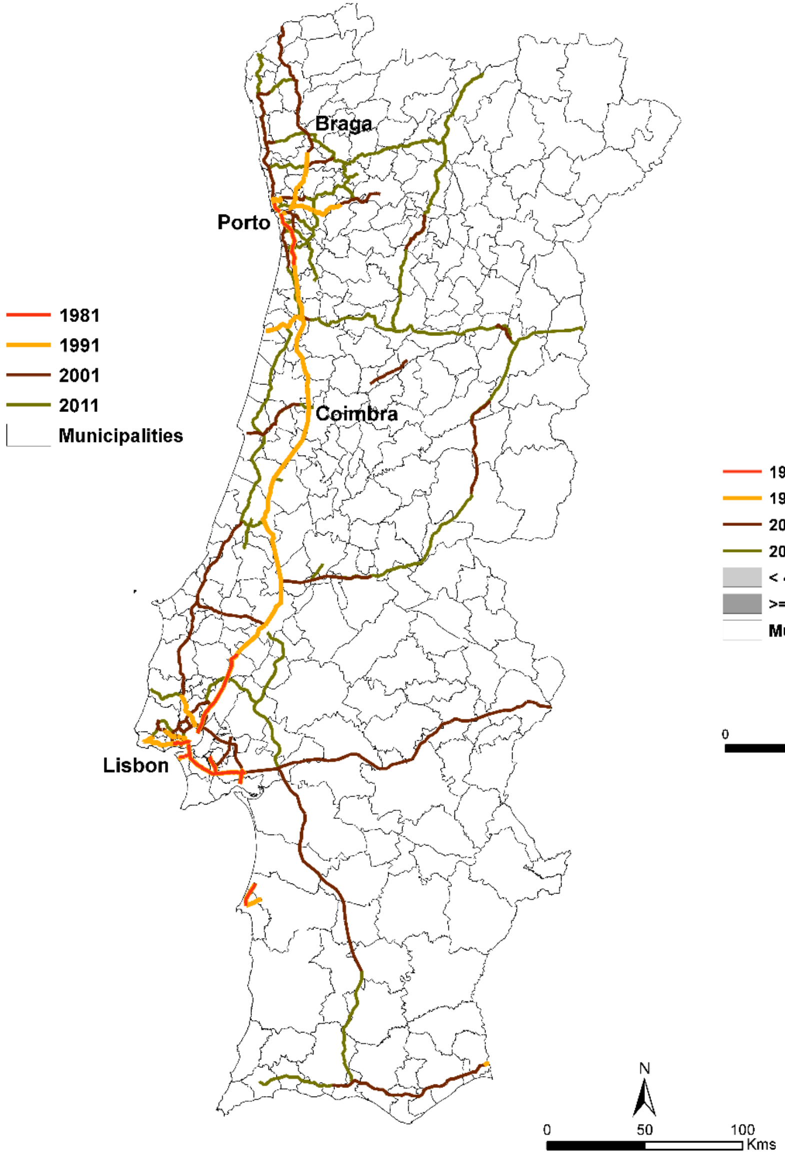
connections to Spain and serving low-density regions in the interior of the country, in accordance with cohesion-oriented objectives of promoting a regionally balanced development of the Portuguese territory (PRODAC, 1989; Pacheco, 2004). At the same time, more motorways were built in the metropolitan areas of Lisbon and Porto and in the coastal strip between the Lisbon area and the north, increasing the network density in this part of the country. For example, since 2009 it is possible to travel by motorway between Lisbon and Porto without using the original A1 corridor (concluded in 1991), as the two cities are connected by a "parallel motorway" located between the A1 and the coast formed by the A8, A17, A25 (a small section), and A29.

The main explanatory variable in our study is a direct measure of the expansion of the motorway network – the increase in the length of motorways between 1981 and 2011 in the 275 municipalities of mainland Portugal (see Table A1 in the Appendix for descriptive statistics for all the variables used in this study).[2] Note that this variable corresponds largely to the stock of motorways that existed in 2011, since in 1981 only 19 municipalities had motorways within their boundaries. In 1991 that number was already 52, increasing rapidly to 116 in 2001 and to 156 in 2011. In a complementary analysis we use the variation in a measure of access to the motorway network as the explanatory variable of interest, i.e., the decrease in the distance from the centroid of each municipality to the nearest motorway access node (the population-weighted centroids were calculated using the 1981 spatial distribution of the population). In 1981, the average distance to the nearest access node was around 98 km; as the network expanded, this reduced by almost a factor of five to about 20 km in 2011.

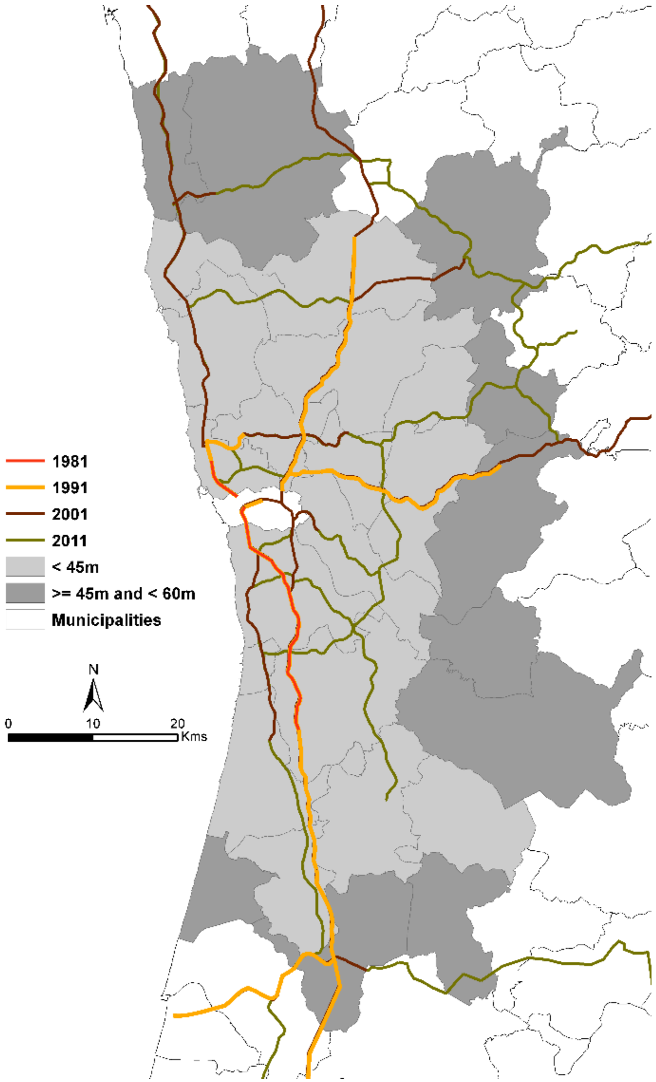
[2] We have geo-referenced the evolution of the motorway network for Census years. Mainland Portugal has 278 municipalities since 1998; five municipalities lost part of their territory to form the three new municipalities that were created in 1998. To ensure data consistency we use the pre-1998 administrative division consisting of 275 municipalities.

Figure 1. Evolution of the motorway network in Portugal

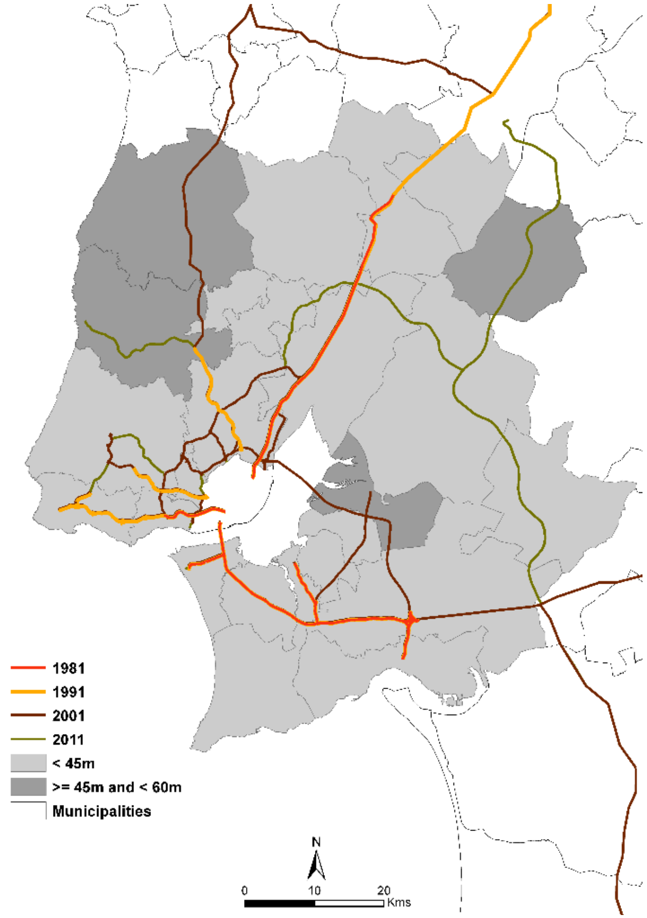
Panel A. Country (mainland)



Panel B. Porto metropolitan area



Panel C. Lisbon metropolitan area

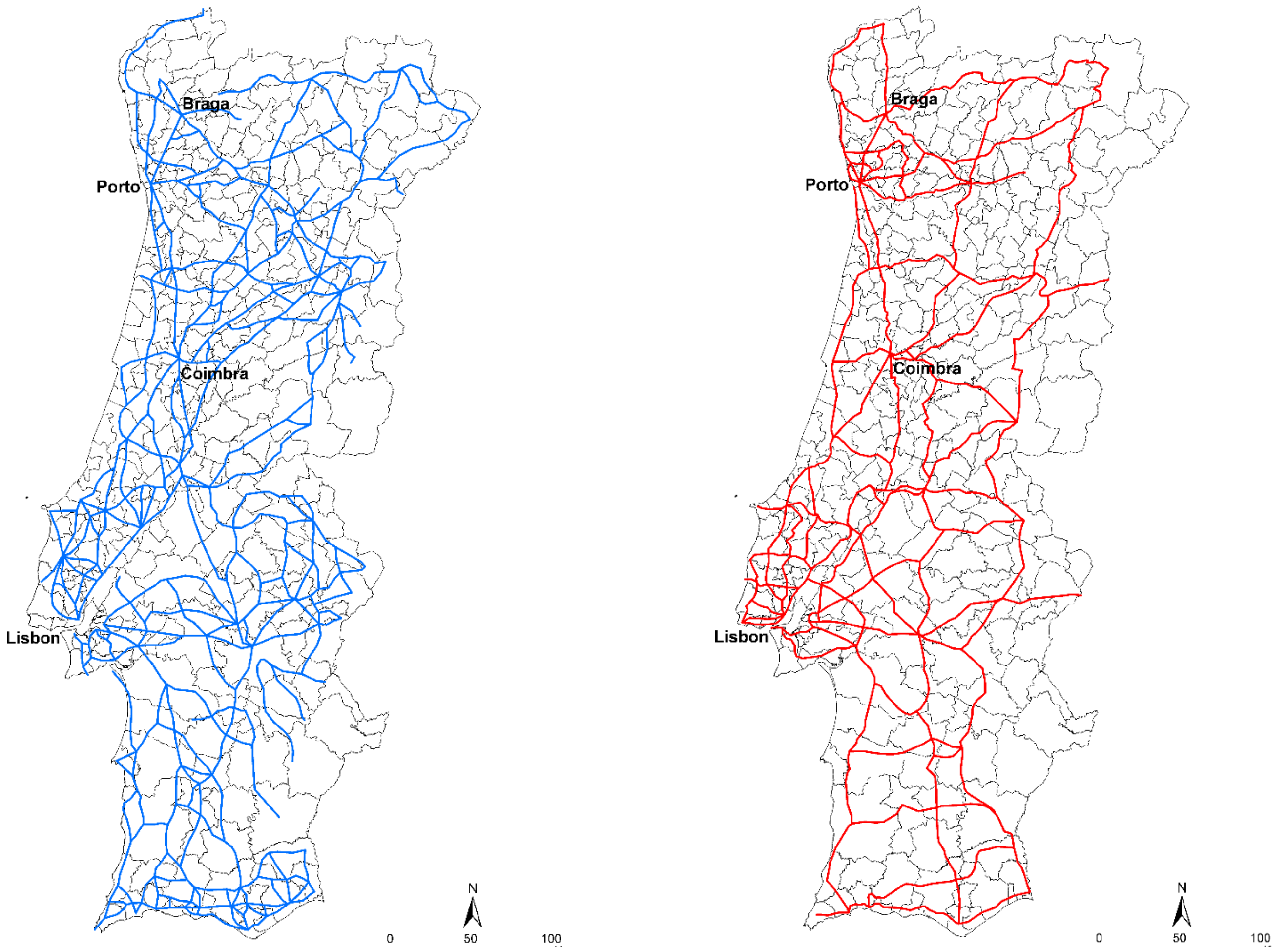


Notes. <45m stands for travel times to either Porto or Lisbon smaller than 45 minutes in 1981; travel times between population-weighted centroids (calculated with 1981 population weights).

Figure 2. Instrumental variables

Panel A. 1800 itineraries

Panel B. 1945 NRP 1st class roads



2.2. Instrumental variables

As the allocation of motorways across the country's territory is potentially endogenous to the growth of population, we constructed a set of candidate instrumental variables using maps of historical transport networks. The first two variables are based on the mainly unpaved, dirt "itineraries" of the year 1800 – we consider both their *length* and the straight-line *distance* of the municipality centroid to the nearest itinerary. In historical terms, these roads preceded by around half a century the period in which roads began to be built in Portugal in a regular and systematic way.[3] Although roads at the end of 18th century were generally in bad condition (Matos, 1980; Pacheco, 2004), Figure 2 shows a dense network: out of the 275 municipalities, 243 have 1800's itineraries in their territory.[4]

The other two candidate instruments were constructed from the first National Road Plan (NRP) approved in 1945 by the Estado Novo autocratic regime (1933-1974) and consist of the length of 1st class roads in each municipality and the straight-line distance from each municipality centroid to the nearest 1st class road.[5] The context of this period was one of rising relevance of road passenger and freight transport in comparison with rail transport, which had been of central importance before, namely during the second half of the 19th century. According to the official NRP text, 1st class roads formed the main network of the country, establishing "easy and fast connections" between the most important centres, between these and the ports or the border with Spain, and, in addition, between district capitals; this was the first time that the importance of easy and fast connections was explicitly mentioned in an official classification of roads, as noted by Sousa (2013). The maximum speed limit in 1st class roads was of 100 or 80 km per

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[3] The concept of a national road network with different road categories was already present in official documents from 1835 and 1843 and was the central object of decrees-law in 1850 and 1862 (the latter established a classification with three categories: 1st-class royal roads, 2nd class district roads, and municipal roads). However, traditional inland waterways, coastal navigation, and the then novel railways – the first rail line opened in 1856 – were generally seen as better options for long-distance transport (Justino, 1988-89; Alegria, 1990).

[4] In 1800, the administrative division of the country was very different from the current one, as there were more than 800 municipalities in mainland Portugal. These were reduced to 351 with the administrative reform of 1836 and to 260 by 1855.

[5] Decree-law 34593 of 1945. The second and third Plans were approved in 1985 and 2000.

hour (the maximum speed limit in current motorways is of 120 km per hour). Our geo-referencing of the 1945 NRP shows that 211 municipalities had 1st class roads.[6]

2.3. Population, employment, and suburbanisation

Our main dependent variable is municipal population growth between the Census years of 1981 and 2011; because there is no Census data for employment in 1981, in supplementary analyses we consider instead employment growth between 1991 and 2011. The average population growth between 1981 and 2011 per municipality is negative, i.e. -3.1%, although total population in mainland Portugal grew by 7.6% over the same 30-year period. This was, in effect, a period of concentration of population in a smaller group of larger municipalities (with the exception of Lisbon and Porto; more on this below). For example, the 52 municipalities with a population growth larger than 20% had, on average, a population of 60,509 inhabitants in 1981, whereas the 98 municipalities (96 excluding Lisbon and Porto) that experienced a loss of population larger than 20% had, on average, a population of only 23,147 (11,803) inhabitants in the same year. Figure 3 shows that population growth is clearly more concentrated in coastal areas, in particular in the metropolitan areas of Lisbon and Porto; conversely, most of the municipalities with negative growth are located in interior regions.

Indeed, a very salient feature of the population dynamics of this period is the huge growth of the suburban municipalities around the central cities of Lisbon and Porto. If we define suburban municipalities as those whose population-weighted centroids were in 1981 at a commutable travel time by road of less than 45 (60) minutes to either Lisbon or Porto, we obtain a group of 38 (52) municipalities (see Figure 3). The average population growth per municipality between 1981 and 2011 was of approximately 31.9% (28.8%), which in absolute terms corresponds to an increase of around 0.98 (1.11) million inhabitants. To emphasise the massive scale of this suburban growth, note that it represents around one tenth of the total population of mainland Portugal in 2011 (i.e. 10.05 million inhabitants). In that year, these 38 (52) municipalities corresponded to 40.7% (48.1%) of the total population in mainland Portugal; their share in total jobs was, as expected, somewhat lower: 34.2% (41.3%). If we add the central cities of Lisbon and Porto to their suburban municipalities, the extended group of 40 (54)

[6] We also constructed analogous length- and distance-based candidate instruments using the Portuguese roman road network. This exercise was unfruitful as these variables have no predictive power for our endogenous regressor.

municipalities represented as much as 48.6% (55.9%) of the total population and 51.7% (58.6%) of total jobs in mainland Portugal.[7]

At the same time, the resident population of Lisbon and Porto decreased by 32.2% and 27.4% respectively, which amounts to a combined loss in absolute terms of around 0.35 million inhabitants from 1981 to 2011 (between 1991 and 2011 the number of jobs decreased by 4.7% in Lisbon and by 17.9% in Porto). The juxtaposition of this large-scale suburbanisation dynamics and the polarisation of the Portuguese urban system around two conurbations that concentrate about half of the population and jobs of the country is, not surprisingly, a dominant topic in the Portuguese literature in the fields of human geography and urban studies. Gaspar and Jensen-Butler (1992), for example, emphasise that urban growth processes in these two metropolitan areas are markedly different from those in the rest of the country, while Abrantes et al. (2019) note that they have spilled beyond administrative boundaries, forming important functional regions. These are the only areas for which Alves et al. (2016) identify instances of city shrinkage associated with urban sprawl dynamics; related to this, Ferrão (2003) uses the expression “urban craters” to characterise the loss of population in Lisbon and Porto. For these reasons, we focus our econometric analysis of (cross-municipality) suburbanisation dynamics in section 4.3 below on the two Portuguese metropolitan areas.

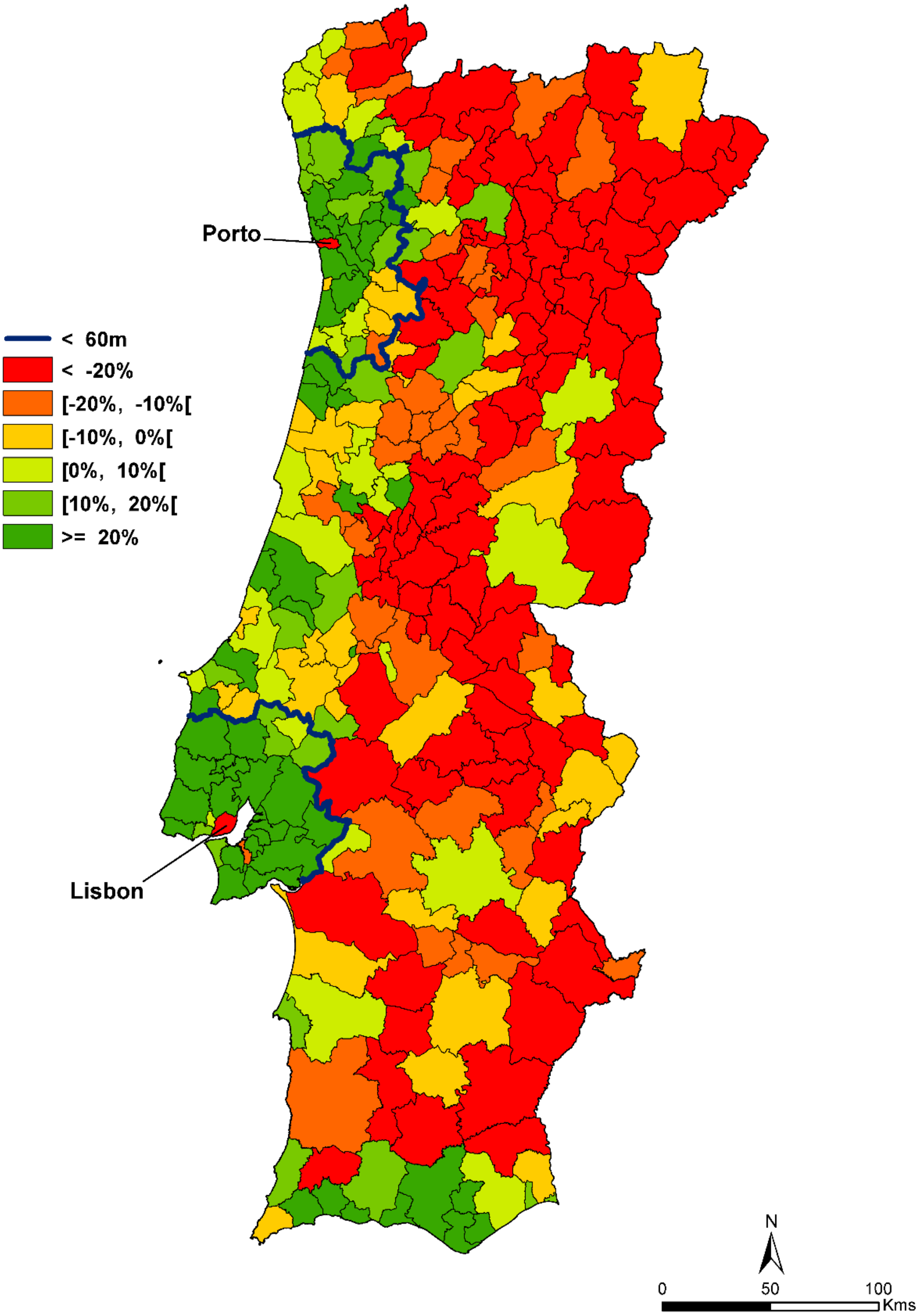
2.4. Control variables

As said above, the main aim of this study is to estimate the effect of motorway expansion on population growth; as motorway expansion is likely endogenous, we use two-stage instrumental variables methods. However, this may not be sufficient to ensure that the error term in the second-stage equation is not correlated with the instrumented variable, given that some variables can influence both the instruments and the dependent variable (more on this below). We thus include the following geography- and history-related control variables (see definition details in Table A1): average altitude, a measure of terrain ruggedness, the straight-line distances from each municipality centroid to both the coast and the border with Spain, and the age of the municipality since its official establishment (it should be noted that 238 municipalities were

[7] If we consider instead the *official* membership of the two Metropolitan Areas (MAs), we have 33 municipalities that in 2011 concentrated 45.6% of mainland population and 48.6% of mainland jobs. The MAs are administrative entities that were created in 1991. No other MAs were created in the country since then.

established before 1800, the reference year of our oldest instrument). We also control for district-level heterogeneity (the country has 18 districts; this upper-level administrative division was created in 1835). In most of our model specifications we control for the length of motorways in 1981, which equals zero for 256 municipalities, Census population in 1970, and electricity consumption per capita in 1970 as a proxy for local economic development. All specifications hold surface area fixed.

Figure 3. Population growth, 2011-1981



Notes. <60m stands for travel times to either Porto or Lisbon smaller than 60 minutes in 1981; travel times between population-weighted centroids (calculated with 1981 population weights). See Figure A1 in the Appendix for more detailed maps.

3. Empirical methodology

3.1. Basic estimation framework

Our first objective is to estimate the effect of the expansion of the motorway network on the growth of population between 1981 and 2011 for mainland Portugal's 275 municipalities. In formal terms, we want to estimate the following model for municipality i:

$$\Delta \ln Y_i = \alpha + \beta \Delta H_i + \gamma A_i + \boldsymbol{X_i'\delta} + \varphi_d + \varepsilon_i, \tag{1}$$

where the dependent variable is the log-difference of population between 2011 and 1981 and ΔH is the increase in motorway kilometres over the same period. That is, β is our coefficient of interest, which is always estimated holding surface area, A, fixed. Vector $\boldsymbol{X}$ contains the control variables described in the previous section: average altitude, terrain ruggedness, the logs of distances to the coast and the border with Spain, official municipality age, the length of motorways in 1981, and the logs of population and electricity consumption per capita in 1970. We include 1970 instead of 1981 because population and electricity consumption in 1981 may already be influenced, to some extent, by existing public plans or expectations regarding the construction of specific future highways, e.g. the A1 corridor connecting Lisbon to Porto. In 1970 Portugal was still ruled by a dictatorship, which would invalidate any prospects of membership in the European Community, a major funder of infrastructure projects in the Cohesion countries (Portugal submitted its membership application in 1977 and joined the Community in 1986). Lastly, φ_d denotes district-level fixed effects and ε represents the error term.

A well-known problem is that the placement of motorways is likely to be endogenous with respect to the actual or expected growth of population (due to reverse causality and/or omitted variables), which means that estimating Equation (1) by OLS may lead to a biased estimate of β, our parameter of interest. We address this issue by using an instrumental variables approach to identify this parameter. In other words, we estimate an empirical model composed of two equations, Equation (1) above, i.e. the second-stage equation, and the following first-stage equation, where $\boldsymbol{Z}$ stands for the excluded instruments that we employ:

$$\Delta H_i = \vartheta + \boldsymbol{Z_i'\omega} + \sigma A_i + \boldsymbol{X_i'\pi} + \tau_d + \mu_i. \tag{2}$$

As discussed earlier in the paper, the literature has advocated for the use of historical transport networks as a source of exogenous variation. Baum-Snow (2007), for instance, instruments highways built in the US between 1950 and 1990 with a 1947 national interstate highway plan, while Garcia-López et al. (2015) use roman roads and 1760 Bourbon roads as instrumental variables for highways in Spain and Levkovich et al. (2020) employ 1821 roads for the case of the Netherlands. We also follow this approach and use the maps of the 1800 itineraries and the 1st-class roads in the 1945 National Road Plan to construct instrumental variables based on both the length of these historical networks and the distance of municipalities' centroids to them, as detailed in the previous section. These are instruments which have rather distinct underlying logics. The "itineraries" of the year 1800 formed a dense web of relatively precarious (predominantly dirt) roads that developed over the centuries without the centralised planning of a transport network, in an era when roads were an inferior option for long-distance transport compared to waterways or coastal navigation. Conversely, the main roads of the 1945 Plan represented the backbone of a true (planned) road *network*, in a context in which road transport was seen by the Estado Novo regime as a major element in the country's development strategy.

The validity of these instruments depends on two conditions. First, the relevance condition, i.e. instrumental variables have to be a good predictor of the endogenous regressor of interest. If instruments are weakly correlated with endogenous regressors, IV estimators may be severely biased. Second, instruments cannot be correlated with the error term in the second-stage equation; that is, instruments cannot affect the dependent variable through channels other than through the instrumented variable. To this respect, note that, as emphasised by Duranton and Turner (2012), the exogeneity of excluded instruments hinges on including an appropriate set of controls in the model: what is required is the orthogonality of the dependent variable and the instruments conditional on control variables, not unconditional orthogonality. It is indeed plausible that the control variables we include in Equation (1) may either have an effect on both the instruments and the dependent variable (e.g., geographical variables as terrain ruggedness) or represent channels via which the excluded instruments affect the dependent variable (e.g., historical roads may influence population growth between 1981 and 2011 through population size and the level of economic development in 1970). The inclusion of a comprehensive set of control variables in our empirical model makes the assumption of exogeneity, and therefore the identification of a causal effect,

more credible. In addition, as we have more instruments than endogenous regressors, we can apply Hansen (1982) tests of overidentifying restrictions (more on this below).

We consider a number of adaptations to the estimation framework we have just outlined. The more relevant ones are as follows. First, in some regressions the endogenous variable of interest measures the reduction in the distance from the municipality centroid to the nearest motorway access node between 1981 and 2011. To be more precise, in this case we have $\Delta H_i = \ln Dist_{i,1981} - \ln Dist_{i,2011}$ (with $Dist_{i,year} > 0$, $\forall_{i,year}$). This distance is arguably a finer measure of *access* to the network, given that it allows us to discriminate among municipalities that have no motorways within their boundaries or that are crossed by motorways but do not have access nodes. Second, in additional analyses our dependent variable is the log-difference of employment between 2011 and 1991; this is further complemented by regressions in which the dependent variable is the difference in the employment to population ratio over the same period.[8]

3.2. Heterogeneity analysis: suburbanisation and urban agglomeration

Some studies focus on the link between motorways and suburbanisation, understood as the shift of population from central cities to the suburbs, in the United States (Baum-Snow, 2007), Spain (Garcia-López et al., 2015), China (Baum-Snow et al., 2017), and the Netherlands (Levkovich et al., 2020). We also address this issue in our analysis, although our empirical setting has some specificities vis-à-vis these studies that should be pointed out. An obvious aspect is that almost all of abovementioned countries are much larger in terms of population than Portugal, which means that they have a number of central cities that is sufficiently large to be amenable to standard econometric analysis. In the case of the Netherlands, a relatively small country, Levkovich et al. (2020) identify 20 central cities (municipalities) with at least 50,000 inhabitants (in 1930); however, it should be noted that, as highlighted by Mata and Pereira (1996), historically the Netherlands is perhaps the most urbanised country in Europe, contrarily to Portugal. These authors emphasise the link between the lack of medium-sized urban

[8] This ratio can be seen as a rough measure of the business attraction power or "centrality" of a given municipality in a region. In our dataset the three municipalities with the highest ratio in 2011 are Lisbon, Sines, and Porto, with respectively 0.97, 087, and 0.77 (the ratio for mainland Portugal being 0.41). Sines is a small municipality (14,238 inhabitants in 2011) with a large cargo port and a large oil refinery.

centres and the low rate of urbanisation in Portugal in the second half of the 20th century.[9]

In fact, according to the estimates in INE (2001), in 1981, the initial year of our period of analysis, Portugal had only two cities outside the two metropolitan areas of Lisbon and Porto with a population larger than 50,000, Coimbra (c. 74,600) and Braga (c. 63,000).[10] Note, moreover, that in almost all cases the boundaries of Portuguese cities do not coincide with the boundaries of their corresponding municipalities (Lisbon and Porto are two exceptions where city and municipality borders coincide). An important specificity in this context is the relatively large area of Portuguese municipalities – in 1981, mainland Portugal had 275 municipalities with an average area of around 324 km^2. For comparison, Levkovich et al. (2020) consider 811 municipalities in the Netherlands, with an average area per municipality of 42 km^2 approximately. Municipalities in Spain are also much smaller than in Portugal – mainland Spain has 7974 municipalities, with an average area of around 63 km^2.

The municipalities of Coimbra and Braga had in 1981 a population of respectively 138,930 (for an area of 319.4 km^2) and 125,472 (183.2 km^2), implying that around half of the population of these municipalities lived in areas that were suburban (broadly defined) or largely rural. Hence, while we cannot exclude that suburbanisation dynamics may have taken place in these cities between 1981 and 2011, the municipality-level structure of our dataset is not appropriate to identify them, as it is likely that a substantial part, if not the bulk of this smaller-range urban sprawl occurred within municipal boundaries.

Our analysis of the link between motorways and suburbanisation focuses, therefore, on the municipalities around the central cities of Lisbon and Porto, which form the mass of (cross-municipal) suburbanisation dynamics that occurred in Portugal in the period of analysis. As seen in the previous section, these two metropolitan areas represent roughly half of the population and jobs of the country. We consider the municipalities whose population-weighted centroids were in 1981 at a travel time of less than 45 or 60

[9] Their data on the geographical intensity of the urbanisation phenomenon in European countries is revealing in this regard. In 1992 (1950), the ratio of the country's area to the number of towns of more than 100,000 inhabitants was of 31 (46) thousand km^2 per city for Portugal and only 2 (4) for the Netherlands. This is, of course, also related to the fact that population density in the Netherlands is much higher than in Portugal (440.5 and 108.3 inhabitants per km^2 in 1990).

[10] This is also the reference threshold level considered in Baum-Snow (2007), Garcia-López et al. (2015), and Levkovich et al. (2020).

minutes to their central city (travel times were calculated assuming no traffic congestion). These criteria identify 38 and 52 suburban municipalities, respectively. That is, we identify a minimum and a maximum of 13.8% and 18.9% of suburban municipalities in mainland Portugal, a proportion broadly in line with the 9.7% reported for Spain (Garcia-López et al., 2015) and the 16.4% reported for the Netherlands (Levkovich et al., 2020). We consider the following nonlinear version of equation (1):

$$\Delta \ln Y_i = \alpha + \beta \Delta H_i + \beta_S \Delta H_i S_i + \beta_P \Delta H_i \ln Pop70_i + \gamma A_i + \boldsymbol{X}_i' \boldsymbol{\delta}$$
$$+ \theta_S S_i + \theta_C C_i + \varphi_d + \varepsilon_i, \qquad (3)$$

in which S is a dummy variable that equals one if a given municipality is suburban, as defined above, and zero otherwise (C is an additional control variable, a dummy variable that equals one for Lisbon and Porto and zero otherwise).

First, we assume that $\beta_P = 0$. The specific effect of motorways on population growth in suburban municipalities is thus given by $\beta + \beta_S$. In addition to motorway expansion, ΔH, the interaction term $\Delta H \times S$ is also instrumented due to its likely endogeneity – we consider as additional excluded instruments multiplicative terms of the type $Z \times S$. In our empirical implementation we will select the most relevant Z instrument as a way to avoid weak instrument bias.

Second, we consider the more general model and estimate parameter β_P as well. The inclusion of a second interaction term, that of motorway expansion with the logarithm of the 1970 population ($\Delta H \times \ln Pop70$), allows us to provide more detailed evidence on the heterogenous effects of motorway expansion on population growth. If this effect depends positively on the size of the initial population, this will suggest that motorways contribute to population concentration or agglomeration dynamics. Estimating Equation (3) also serves to rule out that the specific effect associated to suburban municipalities is not, in reality, a mere reflection of the fact that suburban municipalities are relatively large in the Portuguese context. In sum, the nonconstant marginal effect that we want to estimate is given by $\beta + \beta_S S + \beta_P \ln Pop70$. We have now three endogenous variables, as the second interaction term also has to be instrumented. The additional excluded instruments are terms of the type $Z \times S$ and $Z \times \ln Pop70$.

4. Results and discussion

4.1. Baseline results

The first two columns in Table 1 report OLS estimates of Equation (1). The difference between the two is that in column 1 we impose $\boldsymbol{\delta} = 0$ and $\varphi_d = 0$, i.e. we do not consider any control variables except for holding municipality area fixed. While in both cases there is a positive, statistically significant association between motorways and population growth, the inclusion of control variables in column 2 leads to a sizeable reduction of around 60% in the size of the estimated coefficient. This is a clear, if unsurprising, indication that omitted variable bias is of an important magnitude in this context. However, as discussed above, OLS estimates may still be significantly biased due to reverse causality and/or unobserved variables that remain uncontrolled for. Hence, in columns 3 to 6 we instrument motorways (individually) with the four instrumental variables described in Section 2.2, respectively: length of 1800 itineraries, distance to the nearest 1800 itinerary, length of 1st class roads in the 1945 NRP, and distance to the nearest 1st class road in the 1945 NRP. The latter instrumental variable is weak, as the first-stage Kleibergen-Paap (2006) rk Wald F statistic is low, i.e. below the usual threshold of 10. This explains why the coefficient of interest is estimated in an imprecise way in the second-stage regression reported in column 6.

The point estimates of the coefficient of interest are very similar across these four second-stage regressions, ranging from 0.00665 to 0.00787. This is interesting, as the pairwise correlations between the instruments used in columns 3 to 6 are in most cases low – indeed, the average (minimum) absolute correlation coefficient is 0.366 (0.176).[11] That is, we use different sources of plausible exogenous variation of motorway extent and obtain similar results, which gives us additional confidence that the estimated associations reflect, in reality, a causal effect of motorways on population growth. In column 7 we collapse the length of 1800 itineraries and the length of 1st class 1945 NRP roads (the two instruments with the highest pairwise correlation, 0.67) into a single instrument, the average length of the two historical road networks. This "composite" instrument is the "strongest" one, in the sense that it displays the highest first-stage F-statistic, leading to the most precise estimate of the coefficient of interest with a t-statistic of 3.14.

[11] See pairwise correlations in Table 2 or in the correlation matrix in the Appendix.

Table 1. Expansion of the motorway network and population growth

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A							
Δ Motorways 2011-1981	0.00973***	0.00407***	0.00735***	0.00670**	0.00787**	0.00665	0.00753***
	(7.81)	(2.86)	(3.00)	(2.33)	(2.00)	(1.17)	(3.14)
Estimation method:	OLS	OLS	TSLS	TSLS	TSLS	TSLS	TSLS
Control variables:	N	Y	Y	Y	Y	Y	Y
R^2	0.275	0.636	0.622	0.627	0.617	0.627	0.620
Kleibergen-Paap F-statistic			50.47	21.58	20.25	7.955	53.12
Panel B							
IV1: length of 1800 itineraries			0.233***				
			(7.10)				
IV2: log of dist. to 1800 itinerary				-2.546***			
				(-4.65)			
IV3: length of 1945 NRP 1st-class roads					0.253***		
					(4.50)		
IV4: log of dist. to 1945 NRP 1st-class road						-1.311***	
						(-2.85)	
Composite IV = (IV1+IV3)/2							0.338***
							(7.29)

Notes. The dependent variable is the log-difference of population between 2011 and 1981; estimates based on Equation (1). The number of observations is 275. In parentheses: *t*-statistics based on robust standard errors; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and hold surface area fixed; models (2) to (7) also control for average altitude, terrain ruggedness, the logs of distances to the coast and to the border, official municipality age, length of motorways in 1981, the logs of population and electricity consumption per capita in 1970, and district-level fixed effects (not reported to save space). Panel B reports first-stage coefficients of the instrumental variables.

Table 2. Expansion of the motorway network and population growth

	(1)	(2)	(3)	(4)	(5)
Panel A					
Δ Motorways 2011-1981	0.00720***	0.00748***	0.00729***	0.00733***	0.00734***
	(3.25)	(3.20)	(2.83)	(3.43)	(3.42)
R^2	0.623	0.621	0.623	0.622	0.622
Kleibergen-Paap F-statistic	27.65	27.39	18.78	19.49	28.93
Effective F-statistic	25.90	24.01	19.98	17.71	30.02
Hansen J-statistic	0.0472	0.0170	0.0654	0.0743	0.0707
Hansen J-statistic p-value	0.828	0.896	0.798	0.964	0.790
Correlation between used IVs	-0.375	0.667	-0.176		-0.324
Panel B					
IV1: length of 1800 itineraries	0.196***	0.194***		0.152***	
	(5.17)	(4.97)		(3.32)	
IV2: log of dist. to 1800 itinerary	-1.170**		-2.182***	-1.254**	-1.288**
	(-1.99)		(-4.20)	(-2.14)	(-2.40)
IV3: length of 1945 NRP 1st-class roads		0.127**	0.218***	0.134**	
		(2.07)	(4.03)	(2.17)	
Composite IV = (IV1+IV3)/2					0.289***
					(5.89)

Notes. The dependent variable is the log-difference of population between 2011 and 1981; TSLS estimates based on Equation (1). The number of observations is 275. In parentheses: *t*-statistics based on robust standard errors; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for surface area, average altitude, terrain ruggedness, the logs of distances to the coast and to the border, official municipality age, length of motorways in 1981, the logs of population and electricity consumption per capita in 1970, and district-level fixed effects (not reported to save space). Panel B reports first-stage coefficients of the instrumental variables.

That the effect estimated by TSLS is larger than the comparable effect estimated by OLS is, possibly, a sign of reverse causality. This difference is also evident in Duranton and Turner (2012), who argue that some motorways could have been allocated to cities that have experienced negative growth shocks. While this seems plausible for the Portuguese case, probably in the context of policies that aimed at promoting regional equity or as the result of political economy interactions between the national and the local levels of government, testing this hypothesis is nonetheless beyond the scope of the present study. The causal effect that we identify is not only statistically significant but also important in magnitude. Considering, for example, the point estimate of 0.00735 in column 3, we find that an increase of one standard deviation in motorways between 1981 and 2011 (approximately 13.2 km) leads population to increase by about 10.2% over the same period, all else equal. The effect is substantial, as the observed average population growth between 1981 and 2011 per municipality is actually negative (around minus 3.1%), and total population in mainland Portugal grew by no more than 7.6% in the same period.[12]

In the remainder of our analysis, we do not use the weaker instrument of the model reported in column 6 of Table 1, i.e. the distance to the nearest 1st class road of the 1945 road plan. Panel A of Table 2 shows second-stage estimates of the coefficient of interest obtained with all the combinations of the instruments that we retain (the composite instrument is used in the last column). The estimates are all very similar, ranging narrowly from 0.00720 to 0.00748, and all of them are statistically significant at the 1% level. That is, the use of combinations of instruments results in a sensible gain in precision vis-à-vis the estimates presented in Table 1. The first-stage F-statistics are high,[13] in particular when the composite instrument is used. The fact that we have one endogenous variable and more than one excluded instrument allows us to implement over-identification tests – importantly, we are never close to reject the null hypothesis that the over-identifying restrictions are valid, since the Hansen's J-stat is close to zero in all cases. At this point it should be noted that, as recalled by Duranton and Turner

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[12] As noted in Section 2.3, this was a period of population concentration, i.e. on average population grew more in municipalities that were already larger in 1981 (with the outliers of Lisbon and Porto, which, as also seen above, experienced massive population losses).

[13] Andrews et al. (2019) the effective F-stat of Montiel Olea and Pueger (2013) as the preferred statistic for detecting weak instruments in over-identified, non-homoscedastic settings with one endogenous variable; the statistic can be compared to the critical values in Montiel Olea and Pueger (2013) or to the rule-of-thumb value of 10. In the just-identified case this effective F-stat coincides with the Kleibergen-Paap Wald statistic.

(2012), instruments can pass the Hansen test and be all endogenous if the bias induced by this endogeneity is of similar sign and magnitude. In this regard, Parente and Santos Silva (2012) advise against the use of instruments that are similar, i.e. that have essentially the same underlying motivation (for example, using mother's and father's schooling as instruments for schooling in a wage equation). However, it seems implausible that this kind of "coincident" or "parallel" endogeneity might be at work in our case. The correlation between the different instruments is almost always low (see Table 2), and, moreover, all the different combinations of instruments point in the same direction.

4.2. Robustness and extensions

Changes to the treatment variable: network accessibility and recent motorways

Our results above suggest that motorway expansion has a causal effect on population growth. In this section we test the sensitivity of our TSLS estimates to a number of changes in model specification. First, we note that, while our main explanatory variable based on motorway length is positive for 153 municipalities, in 23 of these municipalities there were no motorway access nodes (ramps). In principle, the effect that we have estimated above may be different if we take this information on motorway accessibility into account. We modify the explanatory variable by setting these 23 observations to zero and hence consider as the treatment the allocation of motorways between 1981 and 2011 with at least one access node. We instrumented this adjusted variable with the five combinations of instruments used in Table 2 but, to avoid repetition, in Table 3 we report only the lowest and the highest estimates of coefficient β. These estimates are, as we can see in columns 1 and 2, very close to our previous baseline results, although the estimated range of variation is slightly wider.

Table 3. Expansion of the motorway network and population growth: different endogenous variables

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A						
Δ length of motorways 2011-1981, with access node	0.00719***	0.00798***				
	(2.81)	(3.19)				
Δ- log of distance to access node 2011-1981			0.0970***	0.106***		
			(3.17)	(3.17)		
Δ length of motorways 2001-1981					0.0102***	0.0114***
					(2.77)	(2.81)
R^2	0.619	0.611	0.615	0.603	0.564	0.547
Kleibergen-Paap F-statistic	18.58	21.25	15.10	14.62	18.28	16.52
Effective F-statistic	19.40	16.53	13.87	13.82	20.36	19.91
Hansen J-statistic	0.0488	0.0143	0.0182	0.156	0.156	0.0221
Hansen J-statistic p-value	0.825	0.905	0.893	0.693	0.693	0.882
Panel B						
IV1: length of 1800 itineraries		0.163***	.0145***		0.162***	
		(3.54)	(3.61)		(5.14)	
IV2: log of dist. to 1800 itinerary	-2.178***		-0.0812	-0.103*	-0.264	-0.504
	(-4.11)		(-1.43)	(-1.95)	(-0.62)	(-1.30)
IV3: length of 1945 NRP 1st-class roads	0.225***	0.154**				
	(3.99)	(2.21)				
Composite IV = (IV1+IV3)/2				.0185***		0.207***
				(3.56)		(5.09)

Notes. The dependent variable is the log-difference of population between 2011 and 1981; TSLS estimates based on Equation (1). The number of observations is 275. In parentheses: *t*-statistics based on robust standard errors; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for surface area, average altitude, terrain ruggedness, the logs of distances to the coast and to the border, official municipality age, length of motorways in 1981, the logs of population and electricity consumption per capita in 1970, and district-level fixed effects (not reported to save space). Panel A reports for each endogenous variable the minimum and the maximum estimates of their respective coefficient (provided the instrumentation is not "weak"; see footnotes 14-15). Panel B reports first-stage coefficients of the instrumental variables.

Table 4. Expansion of the motorway network and employment growth

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	Employment growth (log-difference), 2011-1991		Population growth (log-difference), 2011-1991		Difference in employment/population ratio, 2011-1991	
Panel A						
Δ length of motorways 2011-1981	0.00998***	0.0110***	0.00517***	0.00559***	0.00142*	0.00183***
	(3.42)	(4.19)	(2.75)	(3.08)	(1.80)	(2.75)
R^2	0.392	0.368	0.577	0.572	0.175	0.146
Kleibergen-Paap F-statistic	18.78	27.39	+	++	+	++
Effective F-statistic	19.98	24.01	+	++	+	++
Hansen J-statistic	0.865	0.124	0.446	0.117	0.0958	0.0942
Hansen J-statistic p-value	0.352	0.724	0.504	0.732	0.757	0.759
Panel B						
IV1: length of 1800 itineraries		0.194***	+	++	+	++
		(4.97)				
IV2: log of dist. to 1800 itinerary	-2.182***		+		+	
	(-4.20)					
IV3: length of 1945 NRP 1st-class roads	0.218***	0.127**		++		++
	(4.03)	(2.07)				
Composite IV = (IV1+IV3)/2						

Notes. TSLS estimates based on Equation (1). The number of observations is 275. In parentheses: *t*-statistics based on robust standard errors; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for surface area, average altitude, terrain ruggedness, the logs of distances to the coast and to the border, official municipality age, length of motorways in 1981, the logs of population and electricity consumption per capita in 1970, and district-level fixed effects (not reported to save space). Columns 1 and 2 of Panel A report the minimum and the maximum estimates of the coefficient of the endogenous variable. Panel B reports first-stage coefficients of the instrumental variables; + and ++ stand respectively for “equal to column 1” and “equal to column 2”.

Second, we consider as the endogenous explanatory variable a measure of accessibility gains, i.e. the reduction in the distance from each municipality centroid to the nearest motorway access node (as described in Section 3). Again, to avoid repetition, in columns 3 and 4 of Table 3 we report only the minimum and the maximum estimated β.[14] Our results suggest that improved proximity to a motorway access node has a causal effect on population growth. An increase of one standard deviation in our accessibility measure (about 1.28 log points) leads to a population growth of 13.2% between 1981 and 2011. That these estimates convey the same message as the estimates in the previous section is reassuring, as the two endogenous variables are rather distinct – in fact, the correlation between them is of only 0.43. Regardless of how we measure the presence of motorways across the territory, they appear to have an important impact on population growth at the local level.

Third, as described above, Portugal's motorway network is currently one of the densest in the European Union. It is possible that the construction of the more recent corridors was, to some extent, redundant and resulted in a situation of over-investment in this type of infrastructure. According to Pereira and Pereira (2015, 2017), the marginal product of the investment in motorways on output decreased enormously between 1979-1988 and 2002-2011. If this is the case, our estimates in the previous section may be under-estimating the effect of motorways on population growth. In order to examine this issue, we modify our explanatory variable to include the expansion of the motorway network only between 1981 and 2001. The results in columns 5 and 6 seem to confirm our intuition, as the estimated β coefficient ranges between 0.0102 and 0.0114,[15] higher than the maximum of 0.00787 obtained before. We interpret these results as an indication that our baseline estimates should be regarded as a lower bound of the causal effect that motorways could have on population growth.

Motorways and employment growth

In Table 4 we look at the effect of motorways on employment growth. Unfortunately, there is no Census data for jobs at the local level in 1981, so our dependent variable is now the difference in the log of employment between 2011 and 1991. Columns 1 and 2

[14] We do not report a higher estimate of 0.111 (with a t-stat of 2.76), i.e. slightly higher than the reported maximum of 0.106 (3.17), as the first-stage instrumentation is weaker. The Kleibergen-Paap F-statistic is equal to 9.45.

[15] Again, we do not report a higher estimate, as the respective Kleibergen-Paap F-statistic is 8.60. This estimate of 0.0133 is more imprecise (t-stat of 2.28) and may be biased upwards.

show that motorways have an important effect on employment growth. In order to carry out a direct comparison, we also estimate the effect of motorways on population growth for the same period using the same combinations of instrumental variables – see columns 3 and 4, which show that the estimated β for population is actually smaller than that for employment. To further detail the comparison, in the two last columns the dependent variable is the difference in the ratio of employment to population over this 20-year period. According to the coefficient estimated in column 6 – the one obtained with the strongest first-stage instrumentation –, an increase of one standard deviation in motorways between 1981 and 2011 (approximately 13.2 km) leads to an increase in the jobs to population ratio of around 0.024 between 1991 and 2011. Such an effect is of a substantial magnitude, as in mainland Portugal this ratio decreased slightly by -0.003 in the same period. This is to say that the extent to which a municipality's employment market grew relative to the size of own resident population was influenced by the expansion of the motorway network. Since motorways facilitate daily commutes, it is certainly plausible to assume that an important part of this effect occurred via the employment of non-resident workers.

4.3. Heterogenous effects: suburbanisation and population agglomeration

All the results above were obtained from linear specifications, i.e. so far we have presented a set of estimates for constant marginal effects of motorways on the growth of population and employment. In this part of our analysis, we implement nonlinear specifications to explore whether there could be deviations from estimated average effects that could help explain observed trends that have marked, if not largely defined, the main population dynamics in mainland Portugal over the past 30-40 years. More specifically, the main additional hypothesis that we want to test is whether motorways have contributed to suburbanisation, as discussed in Section 2.3 above.

Table 5 contains our TSLS estimates based on Equation (3) for the case in which β_P is assumed to be zero, i.e. the effect of motorways on the outcome of interest is modelled as depending on whether municipalities are suburban or not. There are now two endogenous variables: increase in motorways and its interaction with the suburban dummy variable. Section 3 above describes the instrumentation strategy implemented in this case, which is based on employing the instruments used above and their interactions with the suburban dummy. As this results in a maximum of six instruments, we implement the just-identified case with the strongest instruments to avoid weak IV

bias.[16] More specifically, making use of the composite instrument allows us to construct a compact set of instruments and hence use available information in a more efficient way, in the sense of obtaining an overall stronger first-stage. Columns 1 and 2 focus on our main dependent variable, population growth from 1981 to 2011. Recall that our definition of "suburban" comprises the municipalities that are located within a travel time to their central city (Lisbon or Porto) of less than 45 or 60 minutes – with these rules we identify 38 and 52 suburban municipalities respectively. To guard against possible endogeneity, travel times were calculated using the 1981 road network (the travel times in 2011 are lower and influenced by the motorways that were built after 1981). Our estimates for the two cases are similar and, whilst confirming that there is a general positive effect of motorways on population growth, show as well that this effect is clearly larger for the group of suburban municipalities.[17] Using the point estimates reported in column 1, which were obtained with the 45-minute threshold, we find that an increase of 13.2 km (i.e. one standard deviation) in motorways leads ceteris paribus to a population growth of 7.9% and 20.5% in non-suburban and suburban municipalities respectively. With the 60-minute threshold (column 2), the effect in non-suburban and suburban municipalities is respectively of 7.8% and 17.0%.

[16] This is recommended by Angrist and Pischke (2009) and Pischke (2018). The authors emphasise that adding weak instruments leads to bias, in particular when there are many instruments compared to endogenous regressors. We estimated an over-identified version of Table 5 with *three* excluded instruments (length of 1800 itineraries, length of 1st class 1945 roads, and the interaction of the composite instrument with the suburban dummy) in order to be able to apply Hansen tests. The estimated effects are quantitively almost identical and the Hansen J-stat is always close to zero. These results are available upon request.

[17] An alternative could be to use the official membership of the two Metropolitan Areas i.e. 31 suburban municipalities. Results are very similar to those in Table 5, but we prefer to report them in the Appendix (see Table A4), as these administrative entities were created in 1991, i.e., after the beginning of our period of analysis and thus their membership may be, to some extent, endogenous to the expansion of the motorway network.

Table 5. Expansion of the motorway network and suburbanisation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable:	Population growth (log-difference), 2011-1981		Employment growth (log-difference), 2011-1991		Population growth (log-difference), 2011-1991		Difference in employment/population ratio, 2011-1991	
Δ length of motorways 2011-1981								
if non-suburban	0.00577**	0.00568**	0.0110***	0.0117***	0.00432**	0.00429**	0.00222***	0.00254***
	(2.27)	(2.21)	(3.69)	(3.85)	(2.14)	(2.11)	(2.90)	(3.33)
if suburban	0.0141**	0.0119**	0.00863*	0.00664*	0.0120**	0.0101***	-0.000956	-0.00116
	(2.26)	(2.54)	(1.91)	(1.76)	(2.34)	(2.63)	(-0.89)	(-1.10)
Suburban definition:	< 45m	< 60m	< 45m	< 60m	< 45m	< 60m	< 45m	< 60m
R^2	0.606	0.627	0.391	0.397	0.520	0.551	0.174	0.170
Conditional F-statistics for:								
Δ length of motorways 2011-1981	56.65	55.63	+	++	+	++	+	++
interaction with suburban dummy	55.82	58.28	+	++	+	++	+	++

Notes. TSLS estimates based on Equation (3) (two endogenous variables and two instruments; see main text). The number of observations is 275. In odd (even) columns, the suburban dummy variable is equal to one for 38 (52) municipalities and zero otherwise. In parentheses: *t*-statistics based on robust standard errors; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for surface area, average altitude, terrain ruggedness, the logs of distances to the coast and to the border, official municipality age, length of motorways in 1981, the logs of population and electricity consumption per capita in 1970, district-level fixed effects, and a dummy variable for Lisbon and Porto (not reported to save space). As we have two endogenous variables, we report Sanderson-Windmeijer (2006) conditional first-stage F-statistics; + and ++ stand respectively for “equal to column 1” and “equal to column 2. The first-stage coefficients of the instrumental variables are reported in Table A3 in the Appendix.

These results suggest that motorways have contributed to suburbanisation in Portugal.[18] We seek additional indications of this by analysing if employment and resident population respond in different ways to the expansion of the motorway network in suburban municipalities vis-à-vis the rest of the sample. As seen in Table 4 above, in the general sample the effect of motorways on employment appears to be particularly strong (larger than the effect on population) – we expect this pattern to be different for suburban municipalities, as many residents in suburban areas work in the central cities. In columns 3 and 4 the dependent variable is the difference in the log of employment between 2011 and 1991; we use, again, our two classifications of "suburban municipalities". For comparison, in columns 5 and 6 the dependent variable is the difference in the log of population over the same period (recall that we have no jobs data for 1981). The results confirm our intuition: while in non-suburban municipalities the effect of motorways on jobs is, as for the general sample, larger than that on population, in suburban municipalities the opposite is true. For completeness, in columns 7 and 8 we report regressions in which the dependent variable is the difference between 2011 and 1991 in the ratio of jobs to population. Motorways appear to have contributed to the increase of this ratio in non-suburban municipalities, but clearly not in the suburban ones. In this case there is even evidence of a negative effect, although the coefficients are not statistically significant.

In sum, results in Table 5 provide evidence on the link between motorways and suburbanisation, as the expansion of motorways led to an above-average growth in resident population in suburban municipalities and this effect was not accompanied by an effect on the growth in jobs of the same magnitude. Yet, as many of the largest municipalities in Portugal are located in these suburban areas, the possibility remains that this result could reflect, at least in part, the possible effect that motorways could have on more general population agglomeration dynamics (i.e., larger municipalities absorbing more population and thus growing relatively faster). In order to test this hypothesis, we enrich our analysis with an additional interaction term of motorway

[18] While we cannot use econometric techniques to analyse the relationship between motorways and the loss of population in Lisbon and Porto, the juxtaposition of these results on suburban municipalities with Figure A2 in the Appendix suggests that the increase in the number of motorway rays emanating from the two central cities played an important role in the large reduction in population size that these two cities experienced between 1981 and 2011.

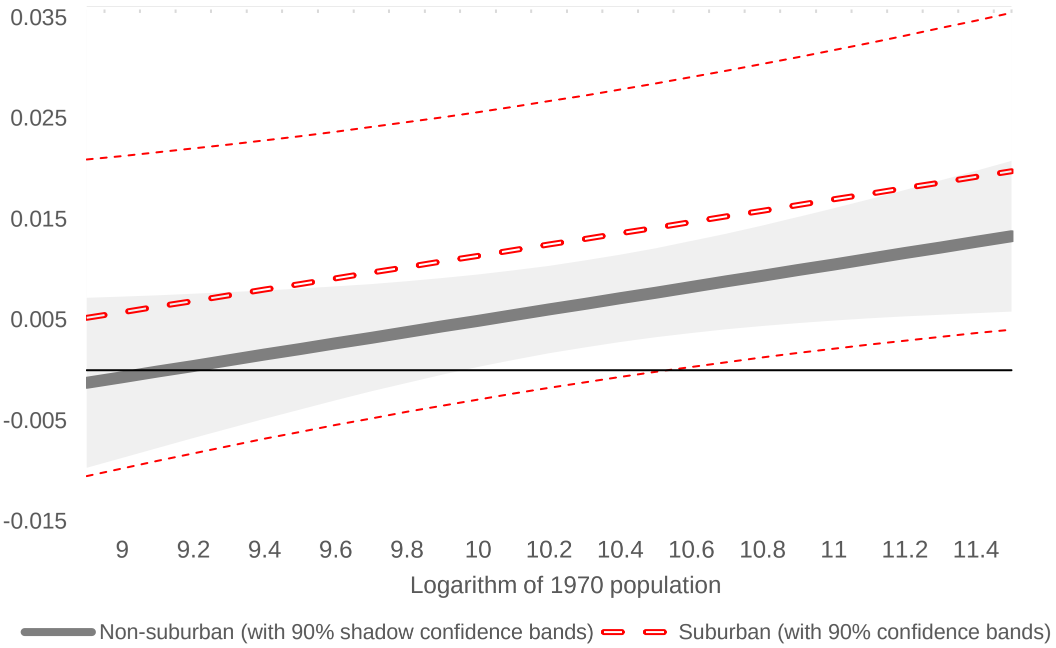
expansion and the logarithm of the population in 1970. This is to say that we now estimate the more general version of Equation (3), in which coefficient β_P is allowed to be different from zero. This additional interaction term is also treated as being endogenous and, as before, we implement the just-identified case with the strongest first-stage. The three instruments – out of a possible maximum of nine – are the composite instrument and its interactions with the suburban dummy variable and the logarithm of 1970 population.

By estimating the marginal effect of population growth with respect to the increase in motorway kms we can examine if this is (*i*) indeed larger in suburban municipalities and/or (*ii*) in municipalities that had more population in 1970. Figure 4 summarises our results considering both groups of 38 and 52 suburban municipalities (the estimates in Panel A are less precise for suburban municipalities due probably to the smaller number of municipalities).[19] It is clear that hypothesis (*i*) remains valid. For example, if in Panel B we evaluate the marginal effect for an initial population of 30,000 inhabitants for the cases of suburban and non-suburban municipalities, we obtain point estimates of 0.0119 (with a p-value of 0.054) and 0.0065 (p-value of 0.013) respectively. Yet, it is interesting to note that hypothesis (*ii*) is also supported by the data, as the estimated marginal effect is a positive function of the initial population size. For a suburban municipality of, say, 50,000 inhabitants in 1970, the estimated marginal effect is of 0.0148 (p-value of 0.019).

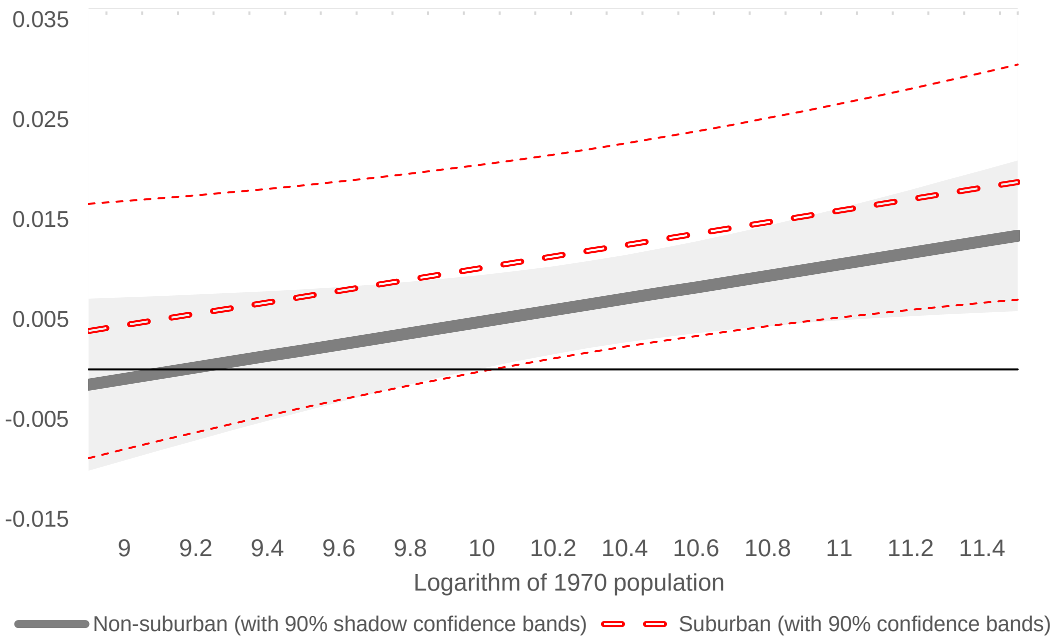
[19] As with Table 5, we estimated an over-identified version of Figure 4 – in this case, with *four* excluded instruments (length of 1800 itineraries, length of 1st class 1945 roads, and the interactions of the composite instrument with the suburban dummy and the log of population in 1970). Again, the estimated effects are quantitively almost identical and the Hansen J-stat is close to zero in both cases A and B. These results are available upon request.

Figure 4. Marginal effect of motorway expansion on population growth as a function of initial population

Panel A. with 38 suburban municipalities (less than 45m to central city)



Panel B. with 52 suburban municipalities (less than 60m to central city)



Notes. TSLS estimates based on Equation (3) (three endogenous variables and three instruments; see main text). The number of observations is 275. All estimations included a constant and control for surface area, average altitude, terrain ruggedness, the logs of distances to the coast and to the border, official municipality age, length of motorways in 1981, the logs of population and electricity consumption per capita in 1970, district-level fixed effects, and a dummy variable for Lisbon and Porto. The first-stage coefficients of the instrumental variables are reported in Table A5 in the Appendix.

5. Conclusion

There is now a sizeable literature that focuses on estimating the causal effect of transport networks on population growth. We analyse this issue in the context of the construction of the Portuguese motorway network in the period between 1981 and 2011. As motorways are potentially endogenous, we implement two-stage least squares methods, using as instruments variables constructed from 1800's itineraries and the 1945 National Road Plan. We find that motorways have a substantial effect on the growth of population in mainland municipalities: an increase of 13.2 km (i.e. one standard deviation) in motorways between 1981 and 2011 leads, on average, to an additional population growth of about 10.2% over the same period. Our findings are robust to several changes in model specification, including, for instance, the use of an alternative explanatory variable based on the distance from each municipality's centroid to the nearest motorway access node. We find, in addition, that motorways have a strong impact on employment growth.

While average effects are estimated with considerable precision, with point estimates being located within relatively tight ranges, we provide complementary evidence that motorways have effects of different magnitudes in suburban municipalities vis-à-vis the rest of the country. They are positive and substantial in both cases, but the effect is considerably larger for suburban municipalities. This suggests that in Portugal motorways have contributed to suburbanisation, something that is in line with findings for other countries. Finally, we show that the effect of motorways on population growth depends positively on the initial municipality's population size, which is an indication that this type of transport infrastructure can influence the onset of population agglomeration dynamics.

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Appendix

Table A1. Variable definitions, descriptive statistics, and data sources

Panel A. Dependent variables

Variable	Definition	Mean (s.d.)	Min. - Max.	Source
Population growth, 2011-1981	Log of population in 2011 - log of population in 1981	-0.0724 (0.280)	-0.611 - 0.863	Authors' calculations using INE (Statistics Portugal) data.
Population growth, 2011-1991	Log of population in 2011 - log of population in 1991	-0.0319 (0.200)	-0.449 - 0.667	
Employment growth, 2011-1991	Log of employment in 2011 - log of employment in 1991	-0.0219 (0.231)	-0.590 - 0.740	
Difference in the employment/population ratio, 2011-1991	Employment/population in 2011 - employment/population in 1991	0.00267 (0.0570)	-0.248 - 0.264	

Panel B. Endogenous variables

Variable	Definition	Mean (s.d.)	Min. - Max.	Source
Expansion of motorways, 2011-1981	Length of motorways in 2011 - length of motorways in 1981 (km)	9.935 (13.207)	0 - 83.74	Authors' GIS calculations.
Expansion of motorways, 2011-1981, with access node	Length of motorways in 2011 - length of motorways in 1981 (km) if there is at least one motorway access node in 2011 (zero otherwise)	9.383 (13.348)	0 - 83.74	
Reduction in the log of distance to access node, 2011-1981	- (Log of network distance to nearest access node in 2011 - log of network distance to nearest access node in 1981) (*)	1.950 (1.279)	-0.756 - 9.449	
Expansion of motorways, 2001-1981	Length of motorways in 2001 - length of motorways in 1981 (km)	5.592 (9.671)	0 - 82.16	

(*) Distances from the population-weighted municipality centroid; population weights were calculated using population data from 1981.

Table A1. Variable definitions, descriptive statistics, and data sources (*continuation*)

Panel C. Instrumental variables

Variable	Definition	Mean (s.d.)	Min. - Max.	Source
Length of 1800 itineraries	Length of 1800 itineraries (km)	27.86 (27.03)	0 - 150.99	Authors' GIS calculations; 1800's itineraries from Matos (1980).
Log of distance to 1800 itinerary	Log of straight-line distance to the nearest 1800 itinerary (*)	0.431 (1.255)	-4.582 - 3.826	
Length of 1945 NRP 1st-class roads	Length of 1st-class roads in the 1945 National Road Plan (km)	15.65 (17.20)	0 - 86.02	
Log of distance to 1945 NRP 1st-class road	Log of straight-line distance to the nearest 1st-class road of the 1945 National Road Plan (*)	0.892 (1.509)	-4.377 - 4.231	
Composite IV	0.5*(Length of 1800 itineraries) + 0.5*(Length of 1st-class roads in the 1945 National Road Plan)	21.75 (20.27)	0 - 114.08	

(*) Distances from the population-weighted municipality centroid; population weights were calculated using population data from 1981

Table A1. Variable definitions, descriptive statistics, and data sources (*continuation*)

Panel D. Control variables

Variable	Definition	Mean (s.d.)	Min. - Max.	Source
Area	Surface area (km^2)	323.8 (284.2)	8 - 1721.5	Authors' GIS calculations.
Altitude	Average altitude, calculated at a 30-meter spatial resolution (meters)	363.2 (241.5)	19.83 - 1272.6	
Terrain ruggedness	Standard deviation of altitude, calculated at a 30-meter spatial resolution (meters)	65.98 (49.74)	2.656 - 254.8	
Log of distance to coast	Log of straight-line distance to the coast (*)	3.598 (1.212)	-0.607 - 5.322	
Log of distance to border	Log of straight-line distance to the border (*)	3.901 (1.128)	-1.262 - 5.199	
Age	2021 - year of official foundation	614.7 (240.4)	42 - 966	Several sources.
Log of population, 1970	Log of resident population in 1970	9.817 (0.863)	7.899 - 13.55	Authors' calculations using INE (Statistics Portugal) data.
Log of electricity consumption per capita, 1970	Log of (electricity consumption / resident population) in 1970	5.271 (1.306)	1.539 - 9.346	
Length of motorways, 1981	Length of motorways in 1981 (km)	0.627 (2.929)	0 - 28.92	Authors' GIS calculations.
Log of distance to access node, 1981	Log of network distance to nearest access node in 1981	4.233 (1.095)	-0.294 - 5.632	

(*) Distances from the population-weighted municipality centroid; population weights were calculated using population data from 1981.

Table A2. Correlation matrix

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) Population growth, 2011-1981													
(2) Population growth, 2011-1991	0.97												
(3) Employment growth, 2011-1991	0.73	0.77											
(4) Difference in the employment/population ratio, 2011-1991	-0.16	-0.14	0.50										
(5) Expansion of motorways, 2011-1981	0.42	0.40	0.34	0.00									
(6) Expansion of motorways, 2011-1981, with access node	0.41	0.39	0.33	-0.01	0.98								
(7) Reduction in the log of distance to access node, 2011-1981	0.14	0.12	0.04	-0.10	0.43	0.42							
(8) Expansion of motorways, 2001-1981	0.34	0.31	0.32	0.08	0.78	0.75	0.32						
(9) Length of 1800 itineraries	0.07	0.09	0.17	0.15	0.37	0.33	0.15	0.38					
(10) Log of distance to 1800 itinerary	-0.23	-0.19	-0.16	0.01	-0.35	-0.34	-0.18	-0.27	-0.37				
(11) Length of 1945 NRP 1st-class roads	0.20	0.22	0.27	0.12	0.45	0.43	0.12	0.39	0.67	-0.18			
(12) Log of distance to 1945 NRP 1st-class road	-0.39	-0.39	-0.32	0.04	-0.36	-0.35	-0.17	-0.27	-0.23	0.23	-0.51		
(13) Composite IV	0.13	0.15	0.23	0.15	0.44	0.40	0.15	0.42	0.95	-0.32	0.87	-0.37	
(14) Area	-0.26	-0.22	-0.09	0.15	0.12	0.09	-0.03	0.13	0.66	0.01	0.52	0.05	0.66
(15) Altitude	-0.51	-0.49	-0.45	-0.03	-0.24	-0.22	0.10	-0.29	-0.07	0.10	-0.21	0.34	-0.14
(16) Terrain ruggedness	-0.36	-0.35	-0.31	-0.01	-0.21	-0.19	0.06	-0.21	-0.18	0.15	-0.19	0.22	-0.20
(17) Log of distance to coast	-0.64	-0.62	-0.45	0.10	-0.30	-0.30	-0.04	-0.30	0.05	0.06	-0.10	0.34	-0.01
(18) Log of distance to border	0.41	0.39	0.31	-0.03	0.21	0.20	-0.01	0.20	0.04	-0.20	0.16	-0.38	0.09
(19) Age	-0.22	-0.19	-0.10	0.13	0.02	0.03	-0.06	-0.05	0.26	0.04	0.17	0.13	0.25
(20) Log of population, 1970	0.42	0.38	0.24	-0.10	0.55	0.55	0.10	0.46	0.18	-0.20	0.36	-0.32	0.27
(21) Log of electricity consumption per capita, 1970	0.50	0.44	0.32	-0.06	0.34	0.33	0.01	0.31	0.01	-0.23	0.15	-0.35	0.07
(22) Length of motorways, 1981	0.25	0.22	0.25	0.14	0.18	0.18	-0.28	0.18	0.03	-0.14	0.03	-0.06	0.04
(23) Log of distance to access node, 1981	-0.53	-0.48	-0.40	0.00	-0.27	-0.27	0.32	-0.26	0.10	0.16	-0.09	0.32	0.03

Table A2. Correlation matrix (*continuation*)

	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
(15) Altitude	0.11								
(16) Terrain ruggedness	-0.08	0.81							
(17) Log of distance to coast	0.31	0.56	0.31						
(18) Log of distance to border	-0.18	-0.32	-0.23	-0.34					
(19) Age	0.30	0.21	0.09	0.22	-0.24				
(20) Log of population, 1970	0.09	-0.15	-0.03	-0.40	0.28	0.00			
(21) Log of electricity consumption per capita, 1970	-0.18	-0.37	-0.29	-0.34	0.33	-0.13	0.41		
(22) Length of motorways, 1981	-0.05	-0.20	-0.16	-0.22	0.19	0.04	0.29	0.27	
(23) Log of distance to access node, 1981	0.27	0.48	0.31	0.54	-0.50	0.21	-0.52	-0.50	-0.65

Table A3. Expansion of the motorway network and suburbanisation: first-stage estimates

	(1)	(2)
Suburban definition:	< 45m	< 60m
Δ length of motorways 2011-1981		
Composite IV	0.287***	0.294***
	(6.50)	(6.38)
Composite IV x suburban dummy	0.385**	0.201
	(2.15)	(1.58)
Conditional F-statistics	56.65	55.63
Δ length of motorways 2011-1981 x suburban dummy		
Composite IV	-0.0196	-0.0224
	(-1.49)	(-1.50)
Composite IV x suburban dummy	0.582***	0. 456***
	(3.05)	(3.79)
Conditional F-statistics	55.82	58.28

Note. See Table 5 in the main text.

Table A4. Expansion of the motorway network and suburbanisation: official MA membership

	(1)	(2)	(3)	(4)
Dependent variable	Population growth (log-difference), 2011-1981	Employment growth (log-difference), 2011-1991	Population growth (log-difference), 2011-1991	Difference in employment/population ratio, 2011-1991
Δ length of motorways 2011-1981				
if non-suburban	0.00580**	0.00112***	0.00417**	0.00229***
	(2.18)	(3.66)	(1.98)	(2.82)
if suburban	0.0108**	0.00527	0.0105**	-0.00173
	(2.30)	(1.60)	(2.42)	(-1.46)
R^2	0.643	0.401	0.564	0.158
Conditional F-statistics for:				
Δ length of motorways 2011-1981	51.06	+	+	+
interaction with suburban dummy	65.08	+	+	+

Notes. TSLS estimates based on Equation (3) (two endogenous variables and two instruments; see main text). The number of observations is 275. The suburban dummy variable is equal to one for 31 municipalities and zero otherwise. In parentheses: *t*-statistics based on robust standard errors; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. All estimations include a constant and control for surface area, average altitude, terrain ruggedness, the logs of distances to the coast and to the border, official municipality age, length of motorways in 1981, the logs of population and electricity consumption per capita in 1970, district-level fixed effects, and a dummy variable for Lisbon and Porto (not reported to save space). As we have two endogenous variables, we report Sanderson-Windmeijer (2006) conditional first-stage F-statistics; + stands for "equal to column 1".

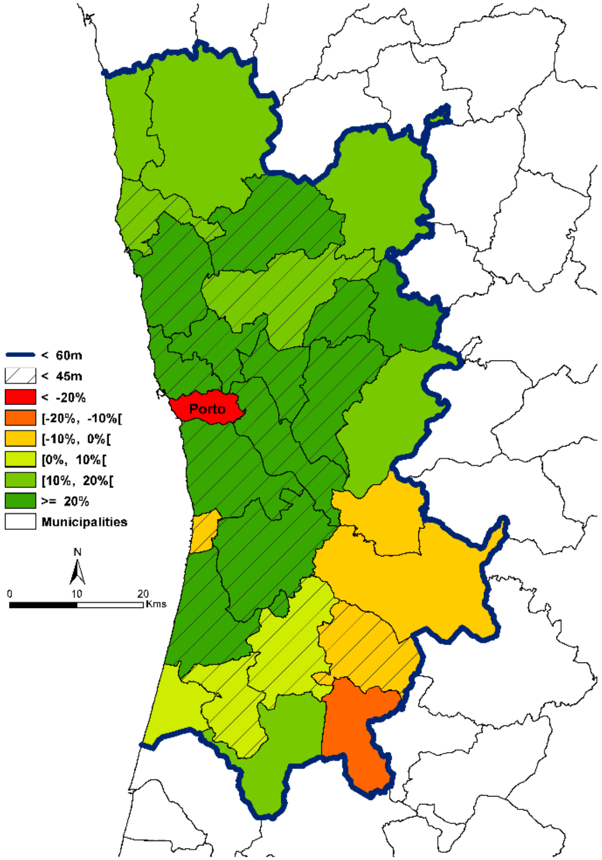
Table A5. Expansion of the motorway network, suburbanisation, and initial population: first-stage estimates

	(1)	(2)
Suburban definition:	< 45m	< 60m
∆ length of motorways 2011-1981		
Composite IV	-0.660	-0.649
	(-1.09)	(-1.05)
Composite IV x suburban dummy	0.371**	0.174
	(2.11)	(1.27)
Composite IV x log of population in 1970	0.0938	0.0936
	(1.52)	(1.47)
Conditional F-statistics	31.57	28.90
∆ length of motorways 2011-1981 x suburban dummy		
Composite IV	-0.0526	0.107
	(-0.19)	(0.37)
Composite IV x suburban dummy	0.581***	0.460***
	(3.08)	(3.99)
Composite IV x log of population in 1970	0.00327	-0.0128
	(0.12)	(-0.44)
Conditional F-statistics	54.78	54.10
∆ length of motorways 2011-1981 x log of population in 1970		
Composite IV	-10.40	-10.19
	(-1.55)	(-1.49)
Composite IV x suburban dummy	3.908*	1.735
	(1.95)	(1.16)
Composite IV x log of population in 1970	1.318*	1.307*
	(1.92)	(1.86)
Conditional F-statistics	30.79	27.99

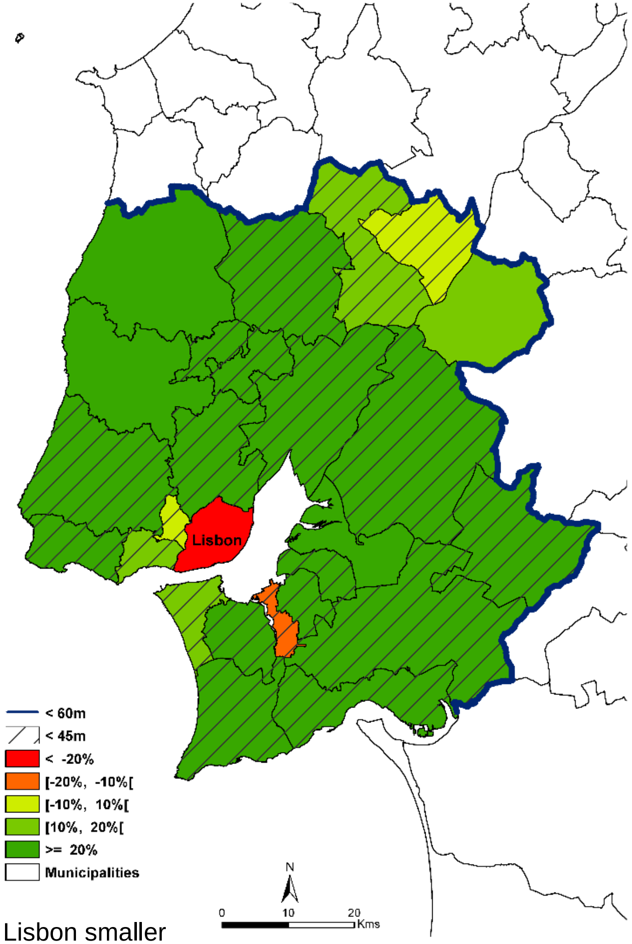
Note. See Figure 4 in the main text.

Figure A1. Population growth, 2011-1981

Panel A. Porto metropolitan area



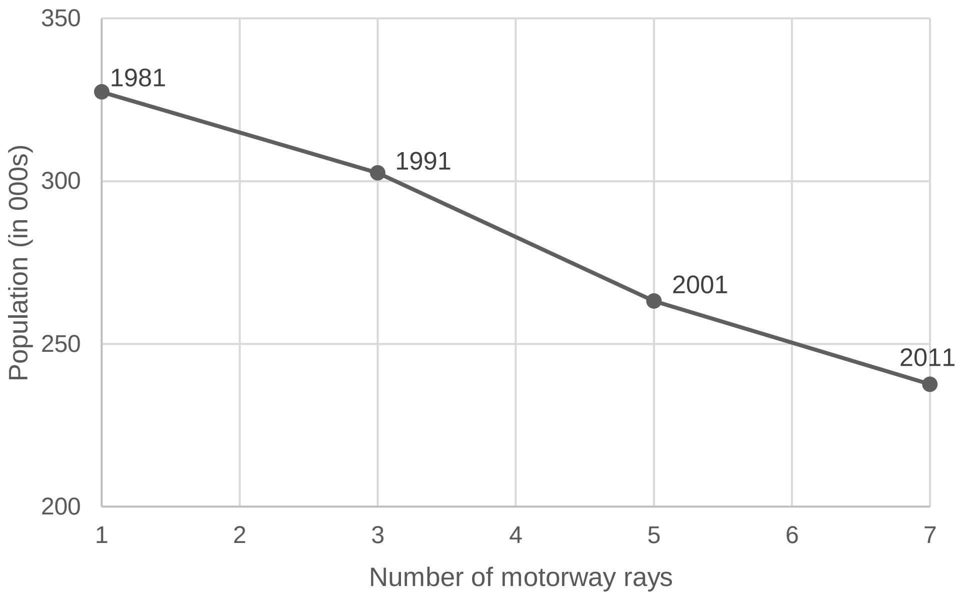
Panel B. Lisbon metropolitan area



Notes. <60m (45m) stands for travel times to either Porto or Lisbon smaller than 60 (45) minutes in 1981; travel times between population-weighted centroids (calculated with 1981 population weights).

Figure A2. Population loss in central cities

Panel A. Porto



Panel B. Lisbon