The local impacts of building a large motorway network: Urban growth, suburbanisation, and agglomeration

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ABSTRACT

Portugal moved from having less than 200 km of motorways in the early 1980s to having the fourth highest motorway density relative to population in the European Union in 2019. This paper studies the relationship between the development of the Portuguese motorway network between 1981 and 2011 and the growth of population and employment at the local level. We address the endogeneity of the geography of motorways using instrumental variables based on a map of dirt roads from the late 18th century and the main roads of a 1945 road plan. Our findings suggest that, on average, motorways caused large increases in population – and even larger increases in employment – in the municipalities that received them. We also find that motorways contributed to suburbanisation, as the impact of motorways on population growth (but not on employment growth) is stronger in suburban municipalities. Another important nonlinearity is that motorways appear to have influenced urban agglomeration dynamics, as their effect on the growth of the local population between 1981 and 2011 depends on the size of the local population in 1970.

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 extensive funding support for the development of transport infrastructures, namely motorways, in many of its member states, with the objective of promoting economic growth and economic integration within the Union. An important 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. Indeed, these effects have been investigated for a number of countries, e.g., the US, Spain, and Italy. Our study contributes to this growing literature by focusing on the case of the Portuguese motorway network, which developed from less than 200 km in the early 1980s to more than 3,000 km in 2014 (when it stopped expanding).

As the geographical allocation of motorways is, in principle, not exogenous to the growth patterns of local population or employment, we follow Baum-Snow (2007), Duranton and Turner (2012), and others in using instrumental variables methods to identify the causal effects of motorways. More specifically, we construct a set of length- and distance-based instruments using a map of dirt roads in the late 18th century and the 1st class roads as defined in the 1945 National Road Plan. Our findings suggest that motorways had a significant effect on the growth of both population and employment in the municipalities that received them. To illustrate, we find that an increase of one standard deviation (13.03 km) in motorways between 1981 and 2011 led, on average, to a population growth of about 9.5% over the same period. The effect, however, is much larger in suburban municipalities (around 16–19%), which is an indication that motorways have contributed to suburbanisation dynamics. We show, in addition, that the effect of motorways on employment is not particularly strong in suburban municipalities, in contrast with the other municipalities, for which the effect on employment is clearly larger than the effect on population. These are relevant differences that have not been identified before in the literature. We also find that motorways appear to have contributed to 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. This is, to the best of our knowledge, the first time that this connection has been documented.

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Overall, our research suggests that motorways have been a relevant contributing factor in the spatial population dynamics observed in mainland Portugal over the past 30–40 years, since they appear to have contributed to the concentration of population in the municipalities traversed by them, in particular in the suburban municipalities of the metropolitan areas of Lisbon and Porto and, across the country, in those municipalities that were already relatively large before the construction of the motorway network. In this way, our findings can be seen as an attempt to bring together two complementary angles in the literature – the one that focuses on the relationship between motorways and the growth of population or employment at subnational levels, as in Duranton and Turner (2012), and the other which analyses the link between motorways and suburbanisation, as in the seminal work of Baum-Snow (2007) on population decline in central cities in the US (we focus, conversely, on the growth of suburban municipalities).

The rest of the paper is organised as follows. The next section is a brief review of the most relevant literature. Section 3 describes the data and explains the more significant aspects of our research context. Section 4 focuses on estimating the average effects of motorways on population growth at the municipality level, while section 5 extends our empirical framework through using nonlinear specifications to study the relation between motorways and suburbanisation and population agglomeration dynamics. Section 6 concludes and discusses policy implications.

2. Related literature

Our study can be seen as pertaining to two closely related strands of the empirical literature. While one tends to conclude that (*i*) motorways contribute to the growth of population and/or employment across metropolitan regions or municipalities, the other finds that (*ii*) motorways contribute to suburbanisation, i.e., the shift of population from central cities to their suburbs. Regarding (*i*), Duranton and Turner (2012) estimate positive effects of interstate highways in US metropolitan areas on employment (and population), which, according to the authors, are quantitatively large vis-à-vis other drivers of urban growth in the US, e.g., good weather and human capital. Möller and Zierer (2018) implement a similar analysis for West German regions and find that the effect of the expansion of the autobahn network on employment is highly significant. Garcia-López et al. (2015) focus on 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 (*ii*), the link between motorways and suburbanisation, appears to be equally clear. Baum-Snow (2007) shows that one new highway passing through a central city in the US reduced its population by about 18% between 1950 and 1990, while Baum-Snow et al. (2017) present 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 exogenous. As emphasised 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. 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-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).

Whilst our discussion has focused so far on studies that use historical networks as instrumental variables, the identification strategy used in this paper, it should be noted that other studies have followed different approaches.[1] Most notably, Chandra and Thompson (2000) established the "inconsequential units" approach, which relies on selecting 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. The authors restrict attention to rural US counties that received interstate highways "accidently", i.e., because they are located between larger cities, and find that highways raise the level of economic activity in the counties that they pass directly through, but draw activity away from adjacent counties.

Although Redding and Turner (2015) note that the validity of this strategy is difficult to evaluate, it is undeniable that its logic has influenced other scholars. Banerjee et al. (2020), for instance, draw a hypothetical straight-line network connecting historical Chinese Treaty Ports to major interior trading centres, assuming that counties are located near this network in an "accidental", exogenous way. Also for China, Faber (2014) constructs a cost-minimizing network connecting major cities, with the identifying assumption being that the distance of peripheral counties to this hypothetical network is a valid instrument for highway connections. More recently, Ciani et al. (2022) study the impact of a freeway in the Italian region of Calabria through exploiting the fact that the final route was chosen due to the influence of two powerful politicians – among three possible alternatives, these politicians lobbied for the route crossing Cosenza, their constituency. The authors compare the growth of "inconsequentially" treated municipalities, traversed only because they were in the route crossing Cosenza, with the growth of a control group formed by the municipalities in the two discarded routes; the results suggest that the freeway caused a reorganisation of both economic activity and population from untreated to treated locations. This research represents an interesting variation of the inconsequential units approach, yet it exploits a rather specific historical context, i.e., in methodological terms it does not appear to be easily transposable to the analysis of the effects of large-scale networks, often made of dozens of motorways.

3. Data and background

3.1. The Portuguese motorway network

The development of the Portuguese motorway network, which occurred relatively late for European standards, can be regarded as a

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[1] See Redding and Turner (2015) for a detailed survey of the literature on the effects of transport infrastructure on the location of population and economic activities.

national-scale "policy experiment". While in the early 1980s Portugal had less than 200 km of motorways, the network increased to around 1,500 km in 2000 and to more than 3,000 km in 2014, ceasing to expand thereafter. According to Eurostat data, in 2019 Portugal had the second highest endowment of motorways relative to GDP in the European Union, and the fourth relative to population. In other words, the country moved in only three decades from having almost no motorways to, quite possibly, an over-investment in this type of infrastructure. This dramatic variation represents an interesting opportunity to evaluate the effects of the construction of a whole motorway network on the growth of population and employment at the local level.

Fig. 1 shows that, as of 1991, existing motorways served essentially to connect Lisbon and Porto to each other and to their suburban areas. 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. This corresponds to around 86% of the length of the current motorway network. In 1981, only 19 municipalities had motorways within their boundaries; in 1991 that number was already 51, increasing rapidly to 115 in 2001 and to 157 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 travel time by road from the centroid of each municipality to the nearest motorway access node (travel times were calculated assuming no traffic congestion and population-weighted centroids were calculated using the 1981 spatial distribution of the population). In 1981, the average time-distance to the nearest access node was around 97 minutes; as the network expanded, this reduced by more than a factor of five to about 17 minutes in 2011.[2]

3.2. 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 circa 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. Fig. 2 shows a dense network: out of the 275 municipalities, 243 have 1800's itineraries in their territory.[3]

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. 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[4]; as noted in Sousa (2013), this was the first time that the importance of fast connections was explicitly mentioned in an official classification of roads. The maximum speed limit in 1st class roads was of 100 or 80 km per hour (the maximum speed limit in current motorways is 120 km per hour). Our geo-referencing of the 1945 NRP shows that 211 municipalities had 1st class roads.[5]

3.3. Population, employment, and suburbanisation

Our main dependent variable is the 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 was negative (-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 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 in the same year of only 23,147 (11,803) inhabitants. Fig. 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.

A very salient feature of the population dynamics of this period is, indeed, 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 travel time by road of no more than 60 minutes to either Lisbon or Porto, we obtain a group of 50 municipalities (see Fig. 3). The average population growth per suburban municipality between 1981 and 2011 was approximately 29.9%, which in absolute terms corresponds to an increase of around 1.09 million inhabitants. To emphasise the scale of this growth, note that it represents around one tenth of the total population of mainland Portugal in 2011 (10.05 million inhabitants). In that year, these 50 suburban municipalities corresponded to 46.2% of the total population in mainland Portugal; their share in total jobs was, as expected, somewhat lower: 39.2%. If we add the central cities of Lisbon and Porto to their suburban municipalities, this extended group of 52 municipalities represented 54.0% of the total population and 56.7% of total jobs in mainland Portugal.[6]

At the same time, the population of Lisbon and Porto decreased by

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[2] See Table A1 in the Appendix for descriptive statistics for all the variables used in this study. Note that 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.

[3] 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.

[4] Decree-Law 34:593 (1945). The second and third Plans were approved in 1985 and 1998.

[5] We discuss the validity of our instrumental variables in section 4.2. We also constructed analogous length- and distance-based candidate instruments using the roman road network. This exercise was unfruitful as these variables have no predictive power for our endogenous regressor.

[6] In our empirical application we also define suburban municipalities based on a 1981 travel time by road of 45 min. This rule identifies 38 municipalities. Together with Lisbon and Porto, they represented 48.6% of the population and 51.7% of jobs in mainland Portugal in 2011. If we consider instead the *official* membership of the two Metropolitan Areas (MAs), we have 33 municipalities that concentrated 45.6% of the population and 48.6% of jobs. The MAs are administrative entities that were created in 1991. No other MAs were created since then.

Panel A. Country (mainland)   **Panel B.** Porto metropolitan area   **Panel C.** Lisbon metropolitan area
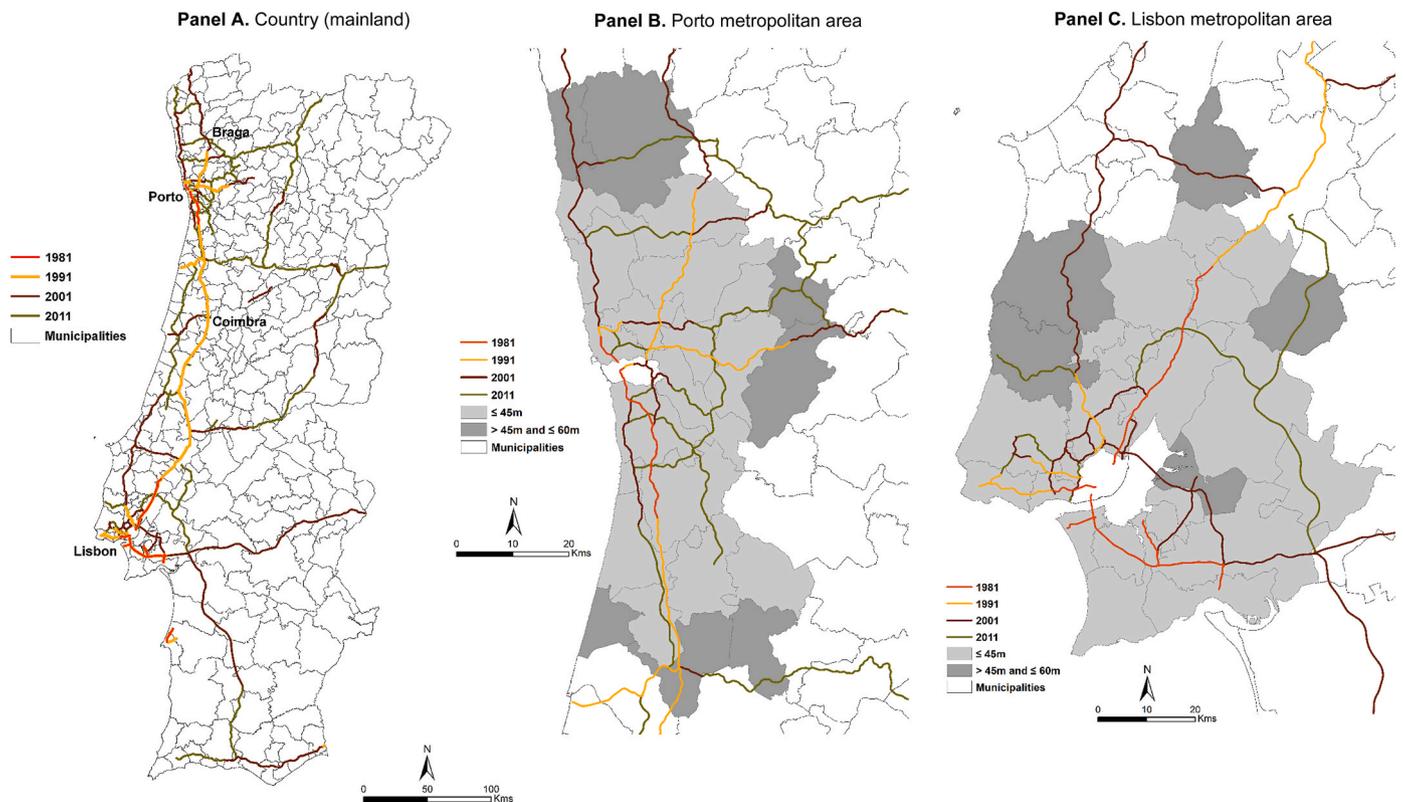
Fig. 1. Evolution of the motorway network in Portugal

Notes. ≤ 45m stands for travel times to either Porto or Lisbon no larger than 45 minutes in 1981; travel times between population-weighted centroids (calculated with 1981 population weights).

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. 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 analysis of (cross-municipality) suburbanisation dynamics in section 5 on the two Portuguese metropolitan areas.

3.4. Control variables

As said above, the main aim of this study is to estimate the effect of motorways on population growth; as motorways are likely endogenous, we use 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, for example, that some variables can influence both the instruments and the dependent variable. 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 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.

4. Motorways and local population growth

4.1. 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:

$$100 * \Delta_{11,81} \ln Y_i = \alpha + \beta \Delta_{11,81} H_i + \gamma A_i + X_i' \delta + \varphi_d + \varepsilon_i, \tag{1}$$

where the dependent variable is the log-difference of population between 2011 and 1981 and ΔH represents the length of the motorways that were built over the same period (this is equal to zero for 122 municipalities, i.e., 44.3% of the observations). Hence, our coefficient of interest is β, which is always estimated holding surface area, A, fixed. Vector 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

Panel A. 1800 itineraries
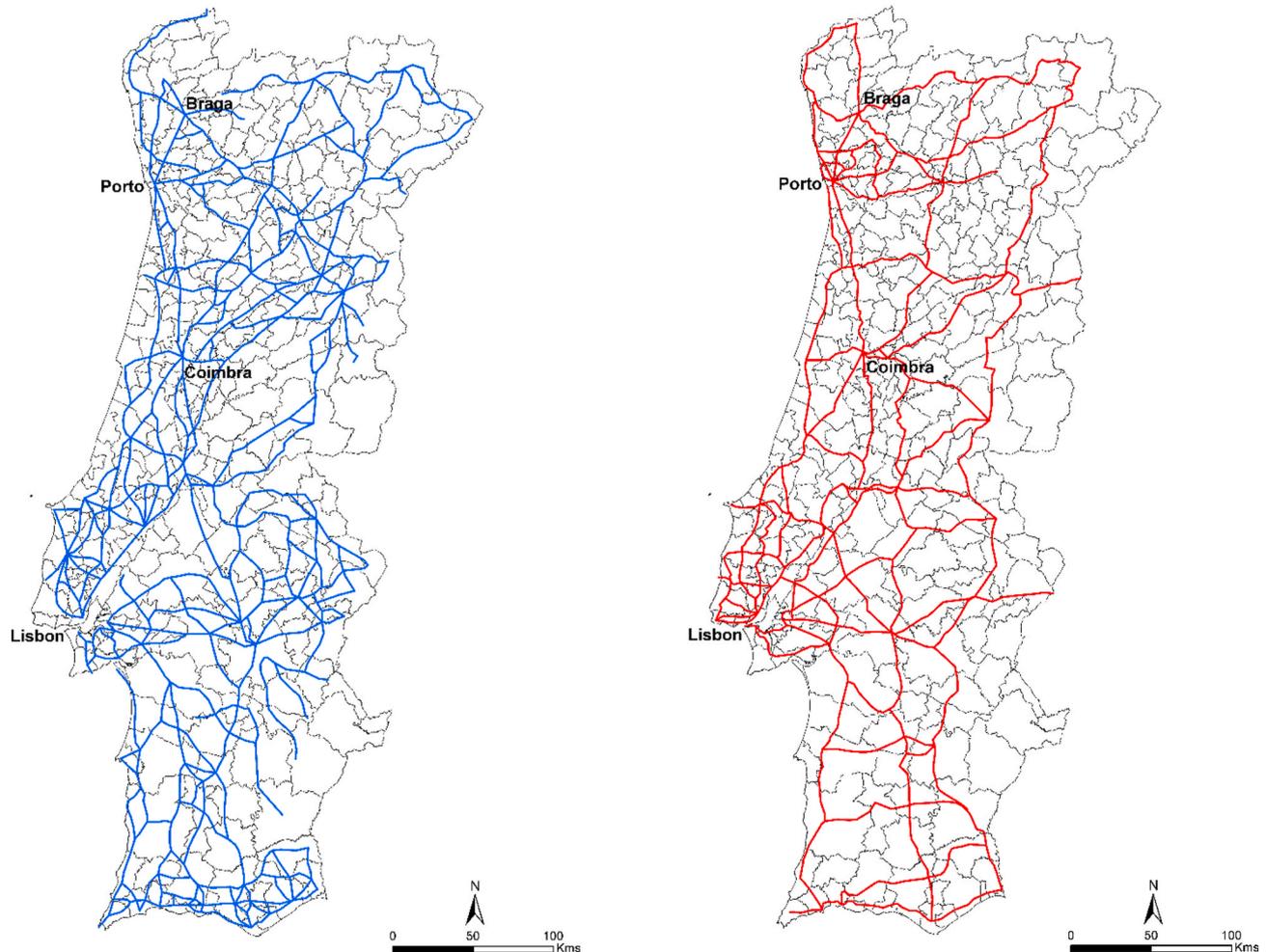
Panel B. 1945 NRP 1st class roads

Fig. 2. Instrumental variables

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.

As the placement of motorways is likely to be endogenous with respect to the growth of population (due to reverse causality or omitted variables), 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 Z stands for the excluded instruments that we employ:

$$\Delta_{11,81}H_i = \vartheta + Z_i'\omega + \sigma A_i + X_i'\pi + \psi_d + \mu_i. \quad (2)$$

As discussed earlier in the paper, the literature has advocated 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. García-López et al. (2015) use both roman roads and 1760 Bourbon roads as instrumental variables for highways in 2006 in Spain, while Levkovich et al. (2020) employ 1821 roads as instruments for motorways in 1970 in the Netherlands. We use a map of the itineraries of circa 1800 and the 1st class roads in the 1945 National Road Plan to construct candidate instrumental variables based on both the length of these historical networks and the distance of municipalities' centroids to

them, as described in section 3.2.[7]

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 travel time by road from the municipality centroid to the nearest motorway access node between 1981 and 2011. To be more precise, in this case we have $\Delta H_i = \ln TimeDist_{i,1981} - \ln TimeDist_{i,2011}$. This time-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. 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]

[7] For essentially the same reasons as in section 4.2 below, we also consider these as valid instruments in a more recent work on the effect of motorways on the local business turnover, local Gross Value Added, and the commuting patterns of workers between 1991 and 2011 (Rocha et al., 2023).

[8] This ratio can be seen as a rough measure of the business attraction power or "centrality" of a given municipality in a region. The three municipalities with the highest ratio in 2011 are Lisbon, Sines, and Porto, with respectively 0.97, 0.87, 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.
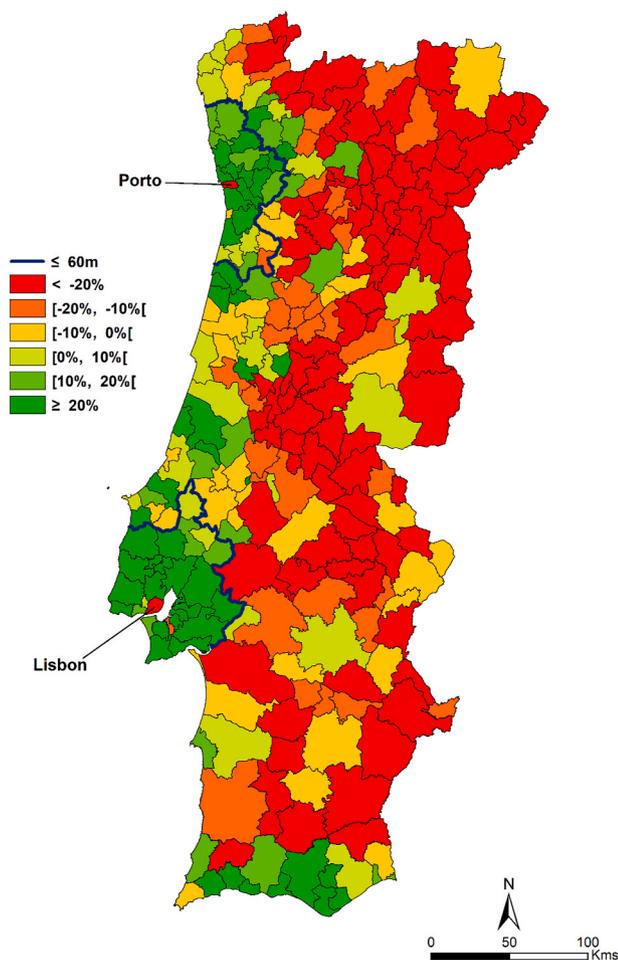
Fig. 3. Population growth, 2011-1981
Notes. ≤ 60m stands for travel times to either Porto or Lisbon no larger than 60 minutes in 1981; travel times between population-weighted centroids (calculated with 1981 population weights). See Figure A1 in the Appendix for more detailed maps.

4.2. Historical networks as valid instruments

The validity of instrumental variables (IV) depends on two conditions. First, 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 biased. Our empirical application below shows that all but one of the candidate variables – the distance to a 1st class 1945 road – are "strong" instruments. Second, instruments cannot be correlated with the error term in the second-stage equation. To this respect, note that 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. Indeed, it is plausible that the geographical and historical control variables included in Equation (1) may have influenced *both* historical networks and the dependent variable – terrain ruggedness is perhaps the most evident example. The rationale for the inclusion of population size and the level of economic development in 1970 is different. While these variables may also have influenced population growth between 1981 and 2011, they represent channels through which the excluded instruments may have influenced the dependent variable and, consequently, should also be controlled for. We argue here that, conditional on controls, our instruments should not affect the dependent variable through channels other than through the instrumented variable. In other words, the instruments can be regarded as exogenous and,

therefore, as identifying a causal effect. In addition, as we have more instruments than endogenous regressors, we can apply Hansen (1982) tests of overidentifying restrictions.

Roads around 1800 were often in very bad condition, in particular due to rain during winter. Many times they simply could not be used (Matos, 1980; Justino, 1988; Alegria, 1990; Pacheco, 2004). These roads were mostly used to travel by foot or by horse or donkey. An express courier travelling from Lisbon to Porto – a road distance of around 313 km today – would take about three days in 1810 (Matos, 1980), which means that the transportation of goods would take much longer. That is, roads were used essentially for short distances; inland waterways or coastal navigation were the country's primary transport network and the best option for long-distance transportation of goods. In general, few people would travel, as travelling was unpractical, dangerous, and too expensive (Alegria, 1990). It does not seem likely that, after controlling for historical and geographical factors, the precarious dirt roads from the late 18th century could be systematically correlated with the growth of population between 1981 and 2011 – apart from the fact that they contain information about "natural" routes between nearby points in space and should display, because of this, a correlation with the shape of transport networks in our era.

The 1945 road plan involved essentially a major reclassification and the modernisation of pre-existing roads; some new connections were also planned. Many important works were carried out in the 1950s, in particular on the main roads (Pacheco, 2004, Chapter 3), but, in general, the plan was executed at a relatively slow pace in the 20–25 years following its approval (Sousa, 2013). The plan was developed by the autocratic Estado Novo regime, in a context where motorisation rates were very low when compared with more developed countries. In 1960 there were only 21.9 cars per 1,000 inhabitants (INE, 2001).[9] That is, nothing suggests that the design of the 1945 plan could have anticipated the massive motorisation era that corresponds to the period of analysis in our paper. On the contrary, by the mid-70s the road network was already considered to be obsolete, with roads that were too narrow and sinuous (Pacheco, 2004, Chapter 3).

The country was poor and largely rural – in 1960, 42.2% of the active population worked in the agricultural sector (INE, 2001). This rurality was a central element of the conservative ideological identity of the Estado Novo and permeates the strategic motivations at the basis of the 1945 road plan. According to the original Decree-Law, it was necessary to improve road accessibility in regions with "fertile soils" which could have a "higher population density", combined with measures like, for example, the "arborisation of their mountains", the use of non-cultivated land, and the construction of water dams to support hydro-agricultural developments (Decree-Law 34:593, 1945, p. 373). This suggests that a main objective of the plan was the promote a type of economic development largely based on the agricultural sector, a strategy that has little to do with the impact that transport can have on the growth drivers of an open and modern economy, for example through the attraction of industrial investments and FDI, the facilitation of international trade, innovation and R&D, etc. Another relevant aspect is the residual importance given to tourism in the 1945 plan, as touristic areas were served by 3rd class roads, the least important national-level roads. This stands in great contrast with the importance of tourism in the modern Portuguese economy.[10]

These arguments suggest that the main 1945 roads should not display, conditional on control variables, a significant correlation with the *growth* of population between 1981 and 2011 (other than through their correlation with the geography of motorways) and, therefore, can

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[9] For comparison, motorisation rates in recent years are around 500 cars per 1,000 inhabitants.
[10] In 2017, the travel and tourism sector represented a direct (total) contribution of 6.8% (17.3%) of GDP. For comparison, in the European Union this share was 3.9% (11.7%) (WTTC, 2018).

be excluded from Equation (1). The fact that the Estado Novo almost "insulated" the country from the socioeconomic development and modernisation trends that were observed in the democratic West in the post-war period provides, in the context of our research, a plausible source of identification, since the 1945 plan was conceived for a country with very low levels of motorisation, a rural and illiterate society, and a largely closed economy, drastically different from the society and economy that developed after the democratic 1974 Revolution and the accession to the European Community in 1986.

4.3. Baseline results

The first two columns in Table 1 report OLS estimates of Equation (1). The difference between them is that in column 1 we impose $\delta = 0$ 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 55% in the size of the estimated coefficient. This is a clear, if unsurprising, indication that omitted variable bias is of an important magnitude. However, as discussed above, OLS estimates may still be significantly biased due to reverse causality 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 3.2, 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 clearly weaker than the others, as the first-stage Kleibergen and Paap (2006) rk Wald F statistic is only slightly above the usual threshold of 10. This may explain why the coefficient of interest is estimated in an imprecise way in the second-stage regression reported in column 6. We can use the critical values associated to the Montiel Olea and Pflueger (2013) "effective F-statistic" to obtain some additional indication about the relative weakness of this instrument (in just-identified models the effective F-stat coincides with the Kleibergen-Paap Wald statistic). The null hypothesis is that the bias in TSLS exceeds a fraction τ of a "worst-case" benchmark. As we can see in column 6, we cannot reject the null (at a 5% significance level) for a τ as high as 20%, and only marginally for a τ of 30%. With the other instruments we are able to reject the null for a τ of 5% or 10%.

The point estimates of the coefficient of interest across these four second-stage regressions range from 0.596 to 1.027, always larger than the OLS estimate in column 2. 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 0.38 (0.19).[11] That is, we use different sources of plausible exogenous variation of motorway length and obtain results that point in the same direction, which gives us additional confidence that the estimated associations reflect, probably, 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, 0.71) into a single instrument, the average length of the two historical road networks. This composite instrument displays by far the highest first-stage F-statistic, leading to the most precise estimate of the coefficient of interest, with a t-statistic of 3.64 (this stronger instrument will be useful to construct a compact set of strong instrumental variables for models with more than one endogenous regressor; more on this below).

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 0.699 in column 3, we find that an increase of one standard deviation in motorways between 1981 and 2011 (approximately 13.03 km) leads population to increase by about 9.5% over the same period. For perspective, note that total population in mainland Portugal grew by no more than 7.6% in this period, and that the observed mean population growth per municipality was actually negative, around minus 3.1%[12] (with a standard deviation of 29.1%, which means that a standard deviation increase in motorway kms causes as much as about one third of a standard deviation in population growth).

In the remainder of our analysis, we do not use the weaker instrument of the model reported in column 6, i.e., the distance to the nearest 1st class 1945 road, as a way of avoiding possible bias. 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 similar, ranging narrowly from 0.689 to 0.871, 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 (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.

4.4. 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

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

[12] As noted in section 3.3, 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 experienced massive population losses).

[13] Andrews et al. (2019) recommend the effective F-stat of Montiel Olea and Pflueger (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 Pflueger (2013) and Pflueger and Wang (2015) or to the rule-of-thumb value of 10. There is no equivalent procedure for the case of more than one endogenous variable.

Table 1
Expansion of the motorway network and population growth.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A							
Δ Motorways 2011–1981	1.000***	0.451***	0.699***	0.656**	1.027***	0.596	0.826***
	(8.69)	(3.31)	(2.98)	(2.41)	(3.13)	(1.45)	(3.64)
Estimation method:	OLS	OLS	TSLS	TSLS	TSLS	TSLS	TSLS
Control variables:	N	Y	Y	Y	Y	Y	Y
R^2	0.280	0.642					
Kleibergen-Paap F-statistic			51.52	24.28	35.74	13.15	66.01
Critical values, worst-case bias of 5%/10%			37.42/23.11	+	+	+	+
Critical values, worst-case bias of 20%/30%			15.06/12.04	+	+	+	+
Panel B							
IV1: length of 1800 itineraries			0.242***				
			(7.18)				
IV2: log of dist. to 1800 itinerary				−2.647***			
				(−4.93)			
IV3: length of 1945 NRP 1st class roads					0.270***		
					(5.98)		
IV4: log of dist. to 1945 NRP 1st class road						−1.671***	
						(−3.63)	
Composite IV = (IV1+IV3)/2							0.347***
							(8.12)

Notes. The dependent variable is 100 times 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). + stands for "equal to column 3". Critical values for the 5% significance level sourced from Pflueger and Wang (2015). Panel B reports first-stage coefficients of the instrumental variables.

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 range of variation is slightly tighter.

Second, we consider as the endogenous explanatory variable a measure of accessibility gains, i.e., the reduction in the road time-distance from each municipality centroid to the nearest motorway access node (as described in section 4.1). Again, to avoid repetition, in columns 3 and 4 of Table 3 we report only the minimum and the maximum estimated *β*. Our results suggest that reducing the travel time to a motorway access node has a causal effect on population growth. Using the minimum estimate of column 3, we find that an increase of one standard deviation in our accessibility measure (about 1.20 log points) leads to a population growth of 11.4% 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 0.47. 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 some of the more recent corridors was redundant and resulted in a situation of over-investment in this type of infrastructure. According to Pereira et al. (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 0.979 and 1.535, higher than all but one of the estimates 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 had on population growth.

Changes to the dependent variable: 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 show that motorways have an important effect on employment growth. According to these estimates, an increase of a standard deviation in motorways between 1981 and 2011 would cause an increase of respectively 13.4% and 16.3% in employment between 1991 and 2011, i.e., about 0.6–0.7 of a standard deviation of employment growth. The comparison based on standard deviations shows a sizeable effect; interestingly, this magnitude is similar to what Duranton and Turner (2012) report for employment growth in US metropolitan areas between 1983 and 2003 (also a 20-year period). Yet, this apparent resemblance should be seen with caution, as there are important differences between the two studies, which prevent direct comparability. For example, our explanatory variable is the difference between motorway kms at the end and the beginning of the period of analysis, while Duranton and Turner (2012) consider motorway kms in 1983, i.e., at the beginning of their period of analysis. Also, the geographical units of analysis are very different. While we consider all the municipalities in mainland Portugal, a small country, Duranton and Turner (2012) focus on a specific sample – metropolitan areas – within a very large country.

We also estimate the effect of motorways on population growth for the same period using the same combinations of instrumental variables –

Table 2
Expansion of the motorway network and population growth.

	(1)	(2)	(3)	(4)	(5)
Panel A					
Δ Motorways 2011–1981	0.689***	0.810***	0.872***	0.797***	0.791***
	(3.27)	(3.61)	(3.79)	(3.93)	(3.91)
Kleibergen-Paap F-statistic	28.87	33.06	25.94	23.66	35.60
Effective F-statistic	27.37	28.61	28.06	20.31	35.71
Critical values, worst-case bias of 5%	6.060	9.523	7.209	18.52	5.354
Hansen J-statistic	0.0222	1.040	0.819	1.120	0.309
Hansen J-statistic p-value	0.882	0.308	0.365	0.571	0.579
Correlation between used IVs	−0.375	0.705	−0.188		−0.321
Panel B					
IV1: length of 1800 itineraries	0.203***	0.188***		0.143***	
	(5.15)	(4.53)		(2.86)	
IV2: log of dist. to 1800 itinerary	−1.213**		−2.180***	−1.322**	−1.291**
	(−2.08)		(−4.31)	(−2.23)	(−2.43)
IV3: length of 1945 NRP 1st class roads		0.152***	0.235***	0.159***	
		(2.86)	(5.36)	(2.91)	
Composite IV = (IV1+IV3)/2					0.300***
					(6.57)

Notes. The dependent variable is 100 times 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). Critical values for the 5% significance level sourced from Pflueger and Wang (2015). Panel B reports first-stage coefficients of the instrumental variables.

see columns 3 and 4, which show that the estimated β for population is smaller than that for employment.[14] To further detail this 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 5, an increase of one standard deviation in motorways between 1981 and 2011 leads to an increase in the jobs to population ratio of around 0.022 between 1991 and 2011. Such an effect is of a substantial magnitude, as the standard deviation of the difference of this ratio is 0.057. This is to say that the extent to which a municipality's employment market grew relative to the size of its 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.

5. Heterogenous effects: suburbanisation and population agglomeration

5.1. Estimation framework

As noted above in section 2, 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 the 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 studied with econometric techniques. In the case of the Netherlands, a relatively small country, Levkovich et al. (2020) identify 20 central cities with at least 50,000 inhabitants[15] 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. These authors emphasise the link between the lack of medium-sized urban centres and the low rate of urbanisation in Portugal in the second half of the 20th century.[16]

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). 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). The large area of Portuguese municipalities is an important specificity in this context. In 1981, mainland Portugal had 275 municipalities, with an average area of around 324 km². For comparison, Levkovich et al. (2020) consider 811 municipalities in the Netherlands, with an average area of 42 km² approximately. Municipalities in Spain are also much smaller than in Portugal – mainland Spain has 7,974 municipalities, with an average area of around 63 km².

The municipalities of Coimbra and Braga had in 1981 a population of respectively 138,930 (for an area of 319.4 km²) and 125,472 (183.2 km²), implying that around half of the population of these municipalities lived in areas that were suburban or even 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 sub-

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[14] Ciani et al. (2022) provide similar results for Calabria. The effect of the proximity to the freeway is larger for employment than for population.

[15] This is also the reference threshold used in Baum-Snow (2007) and Garcia-López et al. (2015) to identify central cities in respectively the US and Spain.

[16] 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 km² 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 vs. 108.3 inhabitants per km² in 1990).

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	0.719***	0.865***				
	(3.28)	(3.68)				
Δ- log of travel time to access node 2011–1981			8.985***	10.52***		
			(3.29)	(3.61)		
Δ length of motorways 2001–1981					0.979***	1.535***
					(2.78)	(2.96)
Kleibergen-Paap F-statistic	23.70	27.35	23.41	24.72	18.70	13.43
Effective F-statistic	20.86	21.65	17.17	23.11	20.68	13.85
Critical values, worst-case bias of 5%	10.23	11.94	14.30	7.410	11.27	7.714
Hansen J-statistic	0.184	0.479	0.0255	0.357	0.128	0.553
Hansen J-statistic p-value	0.668	0.498	0.873	0.550	0.720	0.457
Panel B						
IV1: length of 1800 itineraries	0.174***	0.158***	0.155***		0.164***	
	(3.84)	(3.36)	(4.12)		(4.81)	
IV2: log of dist. to 1800 itinerary	−1.519**		−0.0969	−0.163***	−0.370	−1.264***
	(−2.45)		(−1.56)	(−3.31)	(−0.87)	(−3.30)
IV3: length of 1945 NRP 1st class roads		0.180***		0.0217***		0.131***
		(3.07)		(5.36)		(3.46)
Composite IV = (IV1+IV3)/2						

Notes. The dependent variable is 100 times 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; estimations (3) and (4) control, in addition, for the log of travel time by road to the nearest motorway access node in 1981 (not reported to save space). Panel A reports for each endogenous variable the minimum and the maximum estimates of their respective coefficient. Critical values for the 5% significance level sourced from Pflueger and Wang (2015). Panel B reports first-stage coefficients of the instrumental variables.

Table 4
Expansion of the motorway network and employment growth.

Dependent variable:	(1)	(2)	(3)	(4)	(5)	(6)
	Employment growth (100*log-difference), 2011–1991		Population growth (100*log-difference), 2011–1991		Difference in employment/ population ratio, 2011–1991	
Panel A						
Δ length of motorways 2011–1981	0.963***	1.159***	0.476***	0.600***	0.00171**	0.00193***
	(3.87)	(4.63)	(2.99)	(3.45)	(2.46)	(3.03)
Kleibergen-Paap F-statistic	28.87	33.06	+	++	+	++
Effective F-statistic	27.37	28.61	+	++	+	++
Critical values, worst-case bias of 5%	6.065	9.536	+	++	+	++
Hansen J-statistic	0.570	1.593	0.246	1.535	0.592	0.0586
Hansen J-statistic p-value	0.450	0.207	0.620	0.215	0.442	0.809
Panel B						
IV1: length of 1800 itineraries	0.203***	0.188***	+	++	+	++
	(5.15)	(4.53)				
IV2: log of dist. to 1800 itinerary	−1.213**		+		+	
	(−2.08)					
IV3: length of 1945 NRP 1st class roads		0.152***		++		++
		(2.86)				
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. + and ++ stand respectively for "equal to column 1" and "equal to column 2". Critical values for the 5% significance level sourced from Pflueger and Wang (2015). Panel B reports first-stage coefficients of the instrumental variables.

urbanisation dynamics that occurred in Portugal in the period of analysis. As seen in section 3.3, 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 by road of no more than 45 or 60 minutes to their central city. These criteria identify 38 and 50 suburban municipalities, respectively. That is, we identify a minimum and a maximum of 13.8% and 18.2% of suburban municipalities in mainland Portugal, a proportion broadly in line with the 9.7% reported for Spain (García-López et al., 2015) and the 16.4% reported for the Netherlands (Levkovich et al.,

Table 5
Expansion of the motorway network and suburbanisation.

Dependent variable:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Population growth (100*log-difference), 2011–1981		Employment growth (100*log-difference), 2011–1991		Population growth (100*log-difference), 2011–1991		Difference in employment/population ratio, 2011–1991	
Δ length of motorways 2011–1981								
if non-suburban	0.643***	0.630**	1.201***	1.257***	0.471**	0.465**	0.00250***	0.00280***
	(2.66)	(2.56)	(4.07)	(4.13)	(2.45)	(2.41)	(3.28)	(3.67)
if suburban	1.333***	1.152***	0.943**	0.828**	1.082***	0.934***	−0.000327	−0.000211
	(2.60)	(2.82)	(2.24)	(2.25)	(2.66)	(2.80)	(-0.33)	(-0.20)
Suburban definition:	≤45m	≤60m	≤45m	≤60m	≤45m	≤60m	≤45m	≤60m
Conditional F-statistics for:								
Δ length of motorways 2011–1981	60.52***	60.38***	+	++	+	++	+	++
interaction with suburban dummy	61.66***	73.76***	+	++	+	++	+	++

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 (50) 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 and Windmeijer (2016) 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.

2020). We consider the following nonlinear version of Equation (1) (for convenience we omit the time subscript for Δ, which stands for the difference between 2011 and 1981 values):

$$100^*\Delta\ln Y_i = \alpha + \beta\Delta H_i + \beta_S\Delta H_i S_i + \beta_P\Delta H_i\ln Pop70_i + \gamma A_i + X_i'\delta + \theta_S S_i$$
$$+ \theta_C C_i + \varphi_d + \varepsilon_i,$$
(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 and 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 $Z \times \ln Pop70$.

5.2. Results

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. As explained above, the instrumentation strategy consists of employing the instruments used in section 4 and their interactions with the suburban dummy. Because this results in a maximum of six instruments, we implement the just-identified case with the strongest instruments to avoid weak IV bias.[17] 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 a 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 maximum travel time to their central city (Lisbon or Porto) of 45 or 60 minutes. To guard against possible endogeneity, travel times were calculated using the 1981 road network (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 that this effect is clearly larger for the group of suburban municipalities.[18] Using the point estimates reported in column 1, which were obtained with the 45-minute threshold, we find that an increase of 13.03 km (one standard deviation) in motorways leads ceteris paribus to a population growth of 8.7% and 19.0% in non-suburban and suburban municipalities respectively. With the 60-minute threshold (column 2), the effect in non-suburban and suburban municipalities is respectively 8.6% and 16.2%.

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[17] 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 to the just-identified case and the Hansen J-stat is always statistically nonsignificant. These results are available upon request.

[18] An alternative could be to use the official membership of the two Metropolitan Areas, i.e., 31 suburban municipalities. Results are 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 their membership could be, to some extent, endogenous to the expansion of the motorway network.

These results suggest that motorways have contributed to sub-urbanisation in Portugal.[19] 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 section 4.4 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 two 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 effect on jobs is actually slightly smaller than the effect on population. 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 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. 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 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 augment our analysis with an additional interaction term of motorway expansion and the logarithm of the population in 1970, i.e., 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 (ii) in municipalities that had more population in 1970. Fig. 4 summarises our results considering both groups of 38 and 50 suburban municipalities (the estimates in Panel A are less precise for suburban municipalities due probably to the smaller number of municipalities).[20] 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 1.155 (with a p-value of 0.025) and 0.706 (p-value of 0.005) respectively. Yet, it is interesting to note that hypothesis (ii) is also supported by the data, as

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

Panel B. with 50 suburban municipalities (within 60m to central city)

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

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 1.407 (p-value of 0.008).

6. Conclusion

This paper investigates the effects of the construction of the Portuguese motorway network on the growth of population and employment at the local level. 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 13.03 km (i.e., one standard deviation) in motorways between 1981 and 2011 leads, on average, to an additional population growth of about 9.5% 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.

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[19] 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.

[20] As with Table 5, we estimated an over-identified version of Fig. 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 quantitatively almost identical and the Hansen J-stat is statistically nonsignificant in both cases A and B. These results are available upon request.
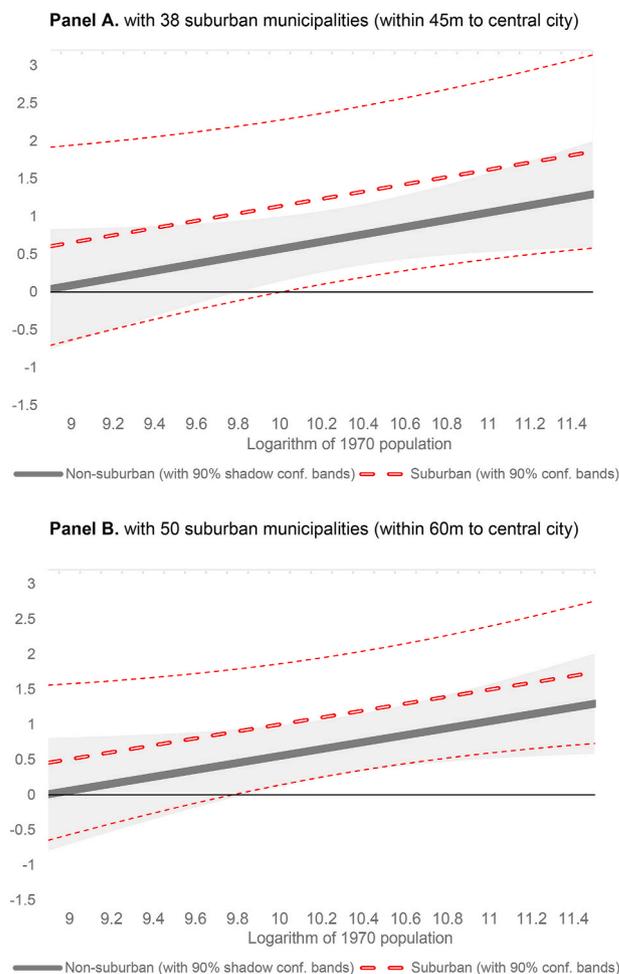
While average effects are estimated with considerable precision, with point estimates being located within relatively tight ranges, we provide evidence that motorways have effects of different magnitudes in suburban municipalities vis-à-vis the rest of the country. They are positive and substantial in both cases, but the effect on population is considerably larger for suburban municipalities (the effect on employment is, conversely, smaller for these 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 motorways can influence the onset of population agglomeration dynamics.

These are findings with relevant policy implications. As large investments in transport infrastructure are being implemented or discussed in many developing and emerging economies, policymakers should ponder the possibility that motorways may stimulate the concentration of population in vast suburban areas, a substantial increase in car-based commuting flows around central cities (and resulting CO_2 emissions), and, at the same time, contribute to the loss of population in both central cities and low-density rural regions. The "policy experiment" that was carried out in Portugal strongly suggests that these are real risks. Therefore, while certainly necessary for long-run economic growth and development, large-scale investments in motorway networks may require the consideration of complementary region-specific policies that mitigate risks of this nature, for example the careful design of land development restrictions in areas around central cities or the development of housing policies and programmes in central cities.

Finally, we plan to extend this research in a number of ways. For example, the construction of detailed urban sprawl measures based on satellite images from the CORINE Land Cover inventory will allow us to investigate the effects of motorways on urban sprawl across the whole of the country's territory. This will include a fine-grain analysis of the small-scale (intra-municipal) suburbanisation dynamics that, we suspect, have occurred around relatively small cities in the regions outside Portugal's two metropolitan areas. Also, we would like to emphasise that the growth effects identified in this paper occur at the local level. That is, we remain silent about the extent to which these effects reflect "new" growth or the relocation of economic activity from municipalities that did not receive motorways. We expect to be able to shed light on this important issue in future research.

Author statement

Rocha: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualization; Writing – original draft; Writing – review & editing. **Melo**: Conceptualization; Data curation; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Writing – review & editing. **Afonso**: Data curation; Investigation; Project administration; Resources; Software; Visualization. **de Abreu e Silva**: Conceptualization; Data curation; Funding acquisition; Investigation; Project administration; Resources; Validation; Supervision; Visualization; Writing – review & editing.

Declarations of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Web Appendix. Supplementary material

Supplementary material to this article can be found online at https ://doi.org/10.1016/j.ecotra.2023.100302.

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