SUBURBANIZATION AND HIGHWAYS IN SPAIN WHEN THE ROMANS AND THE BOURBONS STILL SHAPE ITS CITIES

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ABSTRACT: We estimate the effects of highways on the suburbanization of Spanish cities. Based on Spain's historical roads – the almost 2,000 years old Roman roads and the 1760 Bourbon roads –, we rely on an instrumental variables (IV) strategy because of the endogeneity of highway provision. Our results show that, first, each highway emanating from central cities caused an 8-9% decline in central city population between 1960 and 2011. Second, each highway ray fostered a 20% population growth in the suburbs, in particular in suburban municipalities where ramps were located. Finally, we confirm the increasing role of highways on shaping urban form: each additional kilometer closer to the nearest highway ramp increased municipal density growth by an 8%.

Key words: suburbanization, highways, transportation infrastructure
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1 Introduction

Over the last fifty years Spain has dedicated huge amounts of money to fund public investment in the highway system. These efforts mean that today Spain has the longest highway network in Europe and the fifth in the world. Clearly, this scale of investment has had many implications for the country's economy over the following decades. One of these implications is related to the changes in the urban form of its metropolitan areas. What impact did highways have on the suburbanization of Spain's cities between 1960 and 2011? Did they cause the decline of central city population? Did they foster suburban population growth? Did they shape the intrametropolitan pattern of residential location?

Spain's highways have ancient origins and we use this history to investigate the above questions. In particular, we estimate the relationship between the growth in population and highways in three separate equations – one for central cities, one for the suburbs, and one for the overall urban spatial structure. Because of the endogeneity of highway provision, we use the old Roman roads and the 1760 Bourbon roads as sources of exogenous variation. The Roman roads formed a mesh-like network designed to accomplish military and commercial goals, and were the main road infrastructure in Spain for nearly 1,700 years. The 1760 Bourbon roads were funded by the new Bourbon dynasty to satisfy the needs of the new absolutist state: the road network was dramatically changed by abandoning most of the old Roman roads and building a new radial system of post roads centered on Madrid. Because these historical roads were not placed randomly and some of the factors that influenced their location may have also influenced modern highways, instrument exogeneity hinges on satisfying the exclusion restriction by controlling for physical geography and history.

We find that each highway contributed to an 8-9% decline in central city population between 1960 and 2011. This result is only related to highway rays (i.e., emanating from central cities), and not to the expansion of the highway network in the suburbs. We also find that each of these highway rays fostered a 20% population growth in the suburbs, in particular in suburban municipalities where highway ramps were located. As predicted by theory, this ramp effect is larger in more distant suburban municipalities (31%) than the ones close to the center (18%). Finally, we confirm the increasing role of highways on the intrametropolitan patterns of residential location: each additional kilometer closer to the nearest highway ramp increased municipal density growth by an 8%.

Our findings are relevant for three reasons. First, they provide interesting evidence that was needed for Europe. As far as we know, there are only two comparable papers studying the effect of highways on suburbanization in terms of central city population decline: the pioneering paper by Baum-Snow (2007a) for US metropolitan areas, and Baum-Snow et al. (2014)'s analysis for China's prefectures. For the case of Spain, we find similar results to the ones for the US and China: highways cause central city population decline. As in Baum-Snow et al. (2014), only highways connecting central cities to the suburbs (and not the overall suburban network) cause suburbanization. In other words, despite differences in city population size and density, land-use planning, or the use of public transit between US, Chinese and European cities, our results show that population suburbanization is also an ongoing phenomenon in Europe and that it is also influenced by the construction and the intrametropolitan location of highways.

Second, some of our findings are new in the literature and some of them verify theoretical predictions. While the above papers only estimate the effect of highways on central city population, we also study the effect on the suburbs and on the overall urban spatial structure. As above mentioned, we find that highways also foster suburban population growth, in particular in municipalities with ramps. These ramp effects are heterogeneous and increase with distance to the central business district (CBD). Our findings also confirm that highways influence the spatial pattern of suburbanization by spreading population out along these highways.

Finally, although the use of historical instruments is not new in the literature, we are among the first to use 2,000 years old instruments based on the whole Roman road network in Hispania (Spain) and 250 years old instruments based on the whole 1760 Bourbon network in the absolutist Spain. We provide empirical evidence that both the Roman and the Bourbon roads still shape Spanish cities by influencing the construction and location of modern highways.

Our study is also related to recent empirical literature that has examined other aspects of transportation infrastructure and dealt with the aforementioned simultaneity problem. Sharing our intrametropolitan approach, Baum-Snow (2010) investigates the effect of highway improvements on commuting patterns within and between central cities and suburbs. At a county level, Michaels (2008) analyzes the relation between highways and workers' earnings, and Jiwattanakulpaisarn et al. (2009) study the effect of highway infrastructure investment on employment growth. Duranton and Turner (2011) and Hsu and Zhang (2014) provide intermetropolitan evidence for the effect of highway improvements on congestion in the US and Japan, respectively. Duranton and Turner (2012) find that the stock of highways has a positive impact on urban growth in US metropolitan areas. In the development economic literature there are some recent papers analyzing the effect of infrastructures on different city outcomes. Banerjee et al. (2012) examine the effects of access to transportation networks on economic outcomes in Chinese counties. They find that proximity to these networks have a moderate positive effect on per capita GDP levels but no effect on per capita GDP growth. Faber (2012) studies the impact of the Chinese National Trunk Highway System on city growth. Finally, Donaldson (forthcoming) analyzes the incidence of Indian railroads in late 19th and early 20th century and finds big effects on trade and welfare.

The rest of our investigation is organized in six more sections. In Section 2, we summarize the main characteristics of the Roman roads, the 1760 Bourbon roads, and modern highways in Spain. In Section 3, we analyze whether these two historical networks still influence the construction and location of modern highways. In Section 4, we study whether highways cause central city population decline and how. In Section 5, we explore whether highways foster suburban growth and through which type of highways. In Section 6, we investigate whether highways shape cities causing changes in their urban spatial structure. Finally, we present our main conclusions in Section 7.

2 From Hispania's Roman roads to Spain's modern highways

2.1 All roads lead to Rome

The origins of the modern European road infrastructure can be traced to the Roman roads. While pre-Roman peoples built short distance roads to provide mobility within and between local areas, the Romans were the first to built an extensive and sophisticated network of paved and crowned roads. As a whole, they built over 85,000 km of main roads, which radiated from Rome and connected the different parts of the Empire, from Britain to Syria (O'Flaherty, 1996).

The Romans first landed in Iberia in 218 BC to fight against the Carthaginians (Second Punic War), but they still took another two centuries to bring the entire peninsula under their control. Caesar Augustus completed the conquest of Iberia, then Hispania, after the Cantabrian wars in 19 BC. In common with other European countries, road construction in Hispania responded to economic and administrative needs. First, roads were built to promote Rome's military goals, the conquest and defense of Hispania. These strategic roads passed through mountains and avoided valleys. Later, during the Pax Romana, some of the military roads were abandoned, others were modified as engineers found less steep and faster routes, and new ones were built. As a result, Hispania's accessibility was improved and its administrative and commercial relations within the province and with the rest of the Roman Empire were expanded.

Figure 1: Roman roads in Spain

Source: Atlas Nacional de España ©Instituto Geográfico Nacional (2008).

The Roman road system in Hispania (Figure 1) was based on nearly 7,000 km of main roads (10,500 km including local roads) forming a decentralized mesh-like network. According to Carreras and de Soto (2010), there were four main routes. First, the Via Augusta (also known as Via Herculea) crossed all Hispania from the Pyrenees in the northeast to Gades (Cádiz) in the south. It ran 1,500 km along the Mediterranean coast linking cities such as Tarraco (Tarragona), Dertosa (Tortosa), Valentia (Valencia) and Cartago Nova (Cartagena) and then inland through Granada, Corduba (Córdoba), Astig (Écija) and Hispalis (Sevilla) to Gades (Cádiz). Second, the Vía de la Plata (900 km) ran vertically from south to north, from Gades (Cádiz), via Hispalis (Sevilla) and Emerita Augusta (Mérida) to the gold mines of Las Médulas, close to Asturica (Astorga). Third, it was also important the route that linked northwest Hispania with the Ebro valley and the Mediterranian basin in the northeast. This route ran horizontally 1000 km from Braccara Augusta (Braga in Portugal) and Lucus Augusti (Lugo) to Caesaragusta (Zaragoza) and Tarraco (Tarragona). Finally, less important was the route (700 km) that diagonally linked Caesaragusta (Zaragoza) in the northeast with Emerita Augusta (Mérida) in the southwest, through Toletum (Toledo) in the center of Hispania.

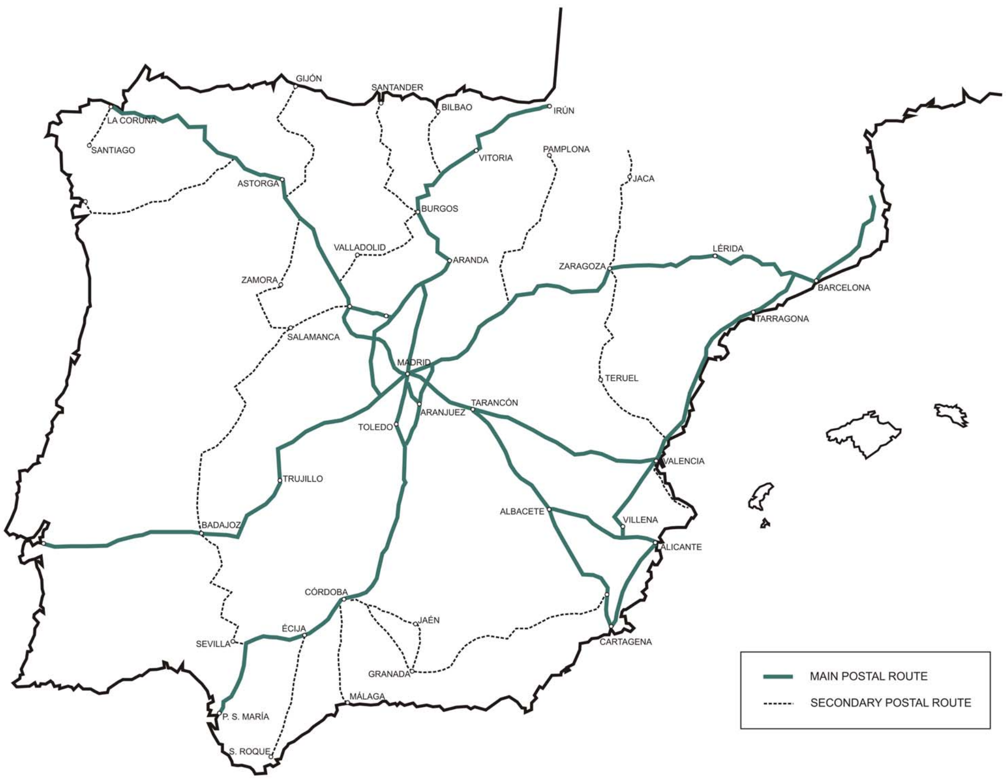
2.2 The new Bourbon dynasty and the new roads

For centuries, the Roman roads were the ones used in Spain. First, by the Visigoths after the decline and fall of the Roman Empire (5ht to 8th century AD). Later, by the Muslim and the Christian kingdoms (8th to 15th century). Finally, by the unification of Spain with a dynastic union between the Castile and the Crown of Aragon (and Catalonia) in one kingdom, but remaining distinct territories with their own traditional institutions, parliaments and laws (15th to 17th century). At the end of the 17th century, the road network of Hapsburg Spain still presented the basic characteristics of the Roman network: a decentralized network based on routes from east to west that ran through the large river valleys, routes from north to south linked to the east-west ones, and some diagonal routes also connected with the roads above (Bel, 2011).

In 1700, the Bourbon dynasty came to power in Spain with Philippe de Bourbon, Duke of Anjou, and grandson of Louis XIV, the Sun King. After the War of the Spanish Succession (1702-1715) between the Bourbons (supported by Castile and France) and the Hapsburgs (supported by Catalonia, Austria, England, Holland, Denmark and Portugal), the new king, known as Philip V, changed Spain's political system from a federation of kingdoms to that of an absolutist state. Following the example of Paris, all political power of the newly unified kingdom became centralized in the city of Madrid, capital of Castile since 1563. Taking into account only political reasons and not economic ones, a new road network funded by the crown was designed to turn Madrid into the new geographical center of Spain (Figure 2): a predominantly radial network that neglected most of the earlier Roman roads. Via the postal service, this radial system improved communications between Madrid and the rest of the kingdom (Menéndez-Pidal, 1992; Bel, 2011).

Based on some 8,000 km of post roads, the 1760 Bourbon network was designed with 6 main routes that radiated from Madrid. First, two routes connected with France. A 500 km post road that ran vertically to the north, to Burgos, and then to the northeast, via Irún to Bayonne. A longer route heading Perpignan ran 800 km to the northeast of Spain linking cities such as Zaragoza, Lleida and Barcelona with the Pyrenees. Also linking with the Mediterranean coast, there was a 450 km post route leading to Cartagena that branched off to Alicante (from Albacete 170 km) and to Valencia (from Tarancón 275 km). Along the Mediterranean coast, all three cities were also linked with Tarragona and Barcelona (600 km). Finally, three routes led to the Atlantic Ocean. Heading south, there was a 700 km post route to Cádiz that crossed the former capital of Castile, Toledo, and other important Roman and Muslim cities such as Córdoba and Sevilla. Connecting with Portugal, a 630 km post road linked with Badajoz, close to the Portuguese border, and Lisbon. Going to the northwest of Spain, there was a connection between Madrid and La Coruña (600 km), via Astorga.

Figure 2: 1760 post roads in Spain



Source: Edited from the map of Tomás López "Mapa de las carreras de Postas de España" (1760), Real Academia de la Historia.

2.3 Building a modern highway system

After the Spanish Civil War (1936–1939) and years of stagnation (1939–1959), Spain experienced strong economic growth accompanied by a rapid increase in car ownership and road traffic. The first modern highways were built in the late 1960s and 1970s in the Ebro valley corridor and along the tourism zones of the Mediterranean coast. The country's growth process was, however, interrupted by the oil crises of the 1970s, which brought to a halt the brief investment process in the highway network. At the beginning of the 1980s, Spain had roughly 2,000 km of highways (Table 1, Figure 3), which were primarily toll highways. Compared to other European countries, Spain showed a clear deficit in road infrastructure and, in particular, in highways (Holl, 2011).

During the next three decades, Spain undertook a highly ambitious expansion of its highway network through different national road construction plans partially funded by the European Union. Based on the regional development rationale, huge amounts of European funds, first EU Regional Funds and later EU Cohesion Funds, were earmarked for highway construction and conditioned the spatial distribution of infrastructure investment in Spain towards less developed regions (Solé-Ollé, 2013).

The 1984–1991 National Road Plan involved nearly 4,500 km of toll-free highways, 70% were the upgrade of a main road by a doubling of existing lanes and 30% were newly built segments. The first important highway links in this major road building program were opened to traffic at the end of the 1980s and the proposed highway connections were completed by the end of 1993. Overall, the proposed highways closely followed the radial outline of the 1760 Bourbon network, including the above mentioned six radial routes emanating from Madrid.

The national government continued its investment program with the 1993–2007 Infrastructure Master Plan, which envisaged a highway system of around 11,000 km by the end of that period, and with the 2000–2007 Infrastructure Plan, which sought to extend the highway system to 13,000 km by 2010 and to facilitate the integration of the high capacity network in the trans-European road network with new connections to Portugal and France.

The current 2005–2020 Strategic Plan for Infrastructures and Transportation also includes more than 5,000 km of new highways mainly through the provision of a complementary finer mesh network that is aimed to break the strongly radial nature of the existing network by giving priority to the completion of connections that link cities without going through Madrid (Holl, 2011).

Besides these national plans, the regional governments also implemented their own plans at the region and province level. National plans focused on linking the largest Spanish cities, relieving the traffic situations of the most congested corridors, and guaranteeing interregional and international connections (Holl, 2011). Regional plans centered on intrarregional connections linking cities in order to improve their levels of accessibility (Garcia-López, 2012).

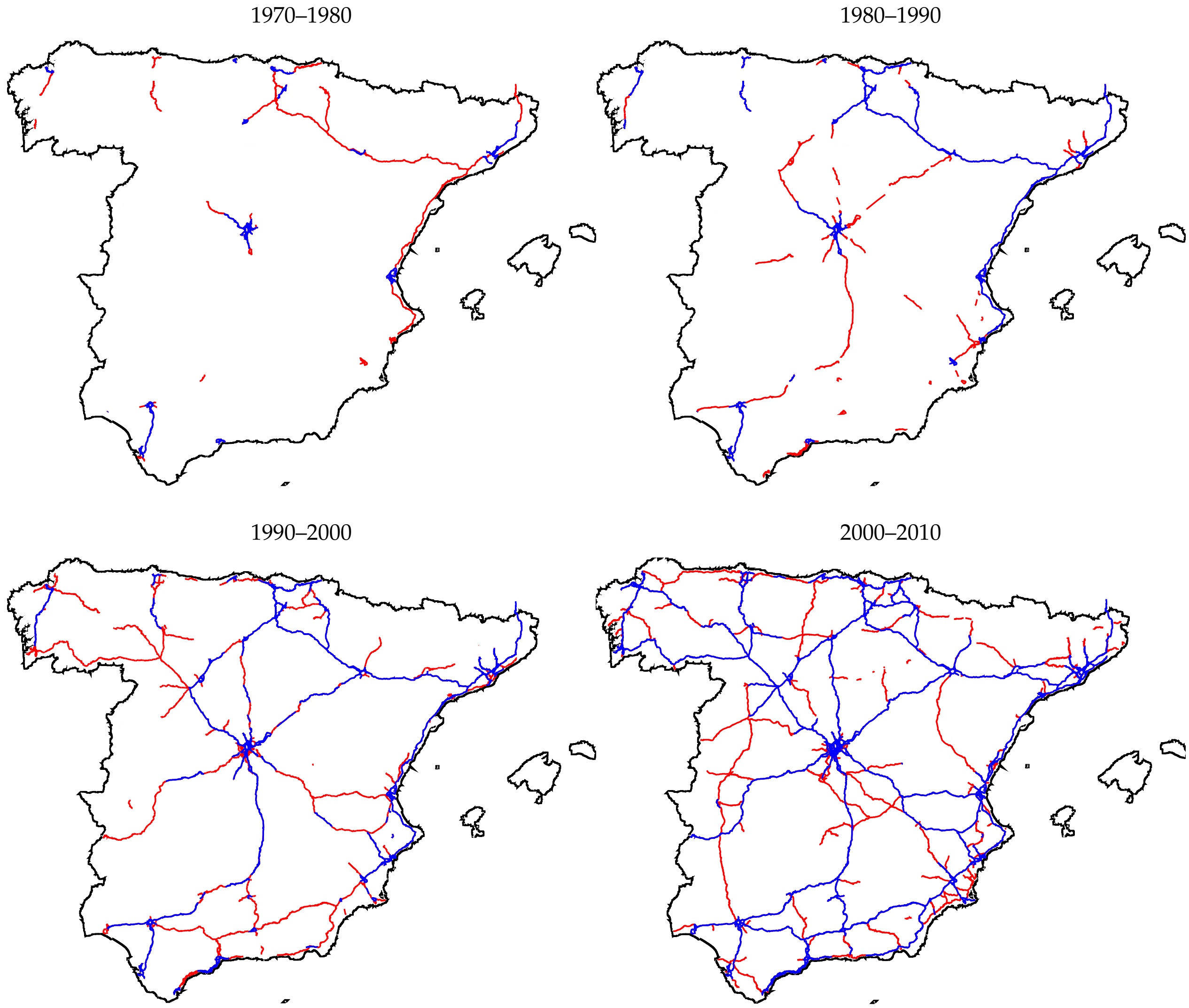
Today the Spanish highway system comprises more than 14,000 km: 11,000 km of toll-free highways and over 3,000 km of toll highways (Table 1, Figure 3). After the US, China, Russia and Canada, it is the fifth longest network in the world. Among EU countries, it is the first. Furthermore, no other European country has experienced such massive highway construction in such a short period of time.

Table 1: The construction of Spain's highway system

	1970	1975	1980	1985	1990	1995	2000	2005	2010
Total kilometers	203	888	1,933	2,296	4,693	6,962	9,049	11,432	14,262
Km of toll highways	82	619	1,530	1,798	1,887	2,023	2,202	2,648	2,991
Km of toll-free highways	121	269	403	498	2,806	4,939	6,847	8,784	11,271
Kilometers managed by:									
National government	203	888	1,933	1,978	3,952	5,632	6,982	8,736	10,630
Regions				318	649	1,176	1,578	2,011	2,869
Provinces					92	154	489	685	763

Source: Anuario Estadístico (several years), Ministerio de Fomento (http://www.fomento.es).

Figure 3: Spain's highway system, 1970–2010



Source: Anuario Estadístico (several years), Ministerio de Fomento (`http://www.fomento.es`). *Note:* Blue lines are highways in year *t-1*. Red lines are new highways built between years *t-1* and *t*.

3 Do historical roads explain modern highways?

In the previous section, we claimed that, nowadays, the Roman roads and the 1760 Bourbon roads still influence modern highways. We now turn to empirically testing this affirmation in the largest Spanish metropolitan areas. Our sample includes 77 metropolitan areas with a central city with at least 50,000 inhabitants based on 1991 Population Census. In the year 2011, 27 million Spaniards (58% of Spain's population) lived in these 77 metropolitan areas. We use the definitions of metropolitan areas by Ruiz (2010), which combines land use continuity and commuting criteria at the municipal level. To calculate highway and historical road variables, we create digital vector maps with polylines (segments) and points (ramps) based on information collected from the Ministry of Public Works (highways) and based on Carreras and de Soto (2010) (Roman roads) and Holl (2011, 2012) (Bourbon roads). Finally, we also use the official Population Censuses to calculate our population control variables and a GIS software to compute distances, land areas and physical geography variables.

Our first goal is to estimate the effect of these two historical roads on central city and suburban highways. We present OLS regressions grouped in three panels in Table 2. The dependent variables include the number of central city highway rays (Panel A), the number of suburban highway ramps (Panel B) and kilometers of suburban highways (Panel C) in 2006. As in Baum-Snow (2007a), highway rays refer to limited access highways connecting the CBD of the central city to the suburbs and serving a significant part of them. The main explanatory variables are the number of central city Roman rays and of central city Bourbon roads (Panel A), the number of suburban municipalities crossed by Roman roads and by Bourbon roads (Panel B) and kilometers of suburban Roman roads and of suburban Bourbon roads (Panel C). To calculate the number of Roman and Bourbon rays we adapt highway rays definition. Finally, we also include central city and MA control variables such as land area, 1960–2011 population growth, 1960 population, geography and history.

Results in Table 2 clearly show that historical roads matter for modern highway construction. In Panel A, both historical central city rays positively influence the number of central city ramps of modern highways in 2006. The overall R^2 of our preferred specification in column 3 is 58%. At the suburban level (Panels B and C), only the 1760 Bourbon variables (ramps and kilometers) are significant and with the expected positive sign. Our preferred specifications are in columns 5 and 8 and show an overall R^2 around a 66%.

Table 2: Modern highways as a function of historical roads

Panel A Central city highways

	2006 CC rays		
	OLS [1]	OLS [2]	OLS [3]
Rays of CC Roman roads	0.475^a (0.109)		0.326^b (0.119)
Rays of CC 1760 Bourbon roads		0.564^a (0.131)	0.474^a (0.152)
ln(Land area)	Y	Y	Y
ln(MA land area)	Y	Y	Y
1960 ln(MA pop.)	Y	Y	Y
1960–2011 Δln(MA pop.)	Y	Y	Y
Geography	Y	Y	Y
History	Y	Y	Y
Adjusted R^2	0.52	0.56	0.58
First-stage statistic	19.00	18.61	22.91
Overid. p-value			0.82

Panel B Suburban highways: Access

	2006 Suburban ramps		
	OLS [4]	OLS [5]	OLS [6]
Suburbs with Roman roads	0.200 (0.263)		-0.198 (0.262)
Suburbs with 1760 Bourbon roads		0.732^a (0.224)	0.828^b (0.323)
ln(Land area)	Y	Y	Y
ln(MA land area)	Y	Y	Y
1960 ln(MA pop.)	Y	Y	Y
60–11 Δln(MA pop.)	Y	Y	Y
Geography	Y	Y	Y
History	Y	Y	Y
Adjusted R^2	0.53	0.67	0.67
First-stage statistic	0.58	10.65	8.02
Overid. p-value			0.03

Panel C Suburban highways: Length

	2006 Suburban km		
	OLS [7]	OLS [8]	OLS [9]
Km of suburban Roman roads	-0.016 (0.364)		-0.179 (0.292)
Km of suburban 1760 Bourbon roads		1.216^a (0.316)	1.237^a (0.335)
ln(Land area)	Y	Y	Y
ln(MA land area)	Y	Y	Y
1960 ln(MA pop.)	Y	Y	Y
60–11 Δln(MA pop.)	Y	Y	Y
Geography	Y	Y	Y
History	Y	Y	Y
Adjusted R^2	0.49	0.66	0.66
First-stage statistic	0.00	14.85	10.61
Overid. p-value			0.16

Notes: 77 observations for each regression. Geography variables are distance to coast, altitude, central city and MA indexes of terrain ruggedness, and central city and MA elevation ranges. History variables are decennial MA population growth rates between 1900 and 1960, and, for Panel A, also a dummy variable for central cities with a cathedral built before 1700, a dummy variable for central cities with a university built before 1700, and the age of the city. Robust standard errors are clustered by region of the MA and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

We now look within metropolitan areas, and focus on the relationship between the location of the two historical roads and the location of modern highways (Table 3). Conditional on distance to CBD, land area, 1960 population, geography, history and MA dummy variables, we study whether suburban municipalities crossed by Roman and/or Bourbon roads receive more suburban highway ramps (Panel A). We find that only the coefficient for the presence of Bourbon roads is positive and significant. The overall R^2 of our preferred specification in column 2 is 61%. In Panel B, we estimate the effect of municipality proximity to historical roads on the municipality proximity to the nearest highway ramp. Since the spatial distribution of the Roman and Bourbon networks are quite different (see Figures 1 and 2), our main explanatory variable is the distance to the nearest of these two historical roads, instead of the two separate distances to the nearest of each historical road. Conditional on control variables, the estimated coefficient for our preferred proximity variable is positive and highly significant, and the overall R^2 of this regression is 93%. As a whole, results in Panels A and B confirm that historical roads also matter for modern highway location.

Table 3: Location of modern highways as a function of historical roads

Panel A Highways in suburban municipalities				**Panel B** Intrametropolitan highway location	
	2006 Suburban ramps				2006 Distance to the nearest ramp
	OLS [1]	OLS [2]	OLS [3]		OLS [4]
Dummy=1 if municipality is crossed by Roman road	0.241 (0.197)		0.172 (0.185)	Dist to the nearest Roman or 1760 road	0.195[a] (0.050)
Dummy=1 if municipality is crossed by 1760 Bourbon road		0.915[a] (0.183)	0.897[a] (0.182)		
Distance to CBD	Y	Y	Y	Distance to CBD	Y
ln(Land area)	Y	Y	Y	ln(Land area)	Y
1960 ln(Population)	Y	Y	Y	1960 ln(Population)	Y
Geography	Y	Y	Y	Geography	Y
History	Y	Y	Y	History	Y
MA fixed effects	Y	Y	Y	MA fixed effects	Y
Adjusted R^2	0.59	0.61	0.61	Adjusted R^2	0.93
First-stage statistic	1.49	24.85	12.96	First-stage statistic	15.23
Overid. p-value			0.51		
Observations	774	774	774	Observations	851

Notes: Geography variables are distance to coast, altitude, index of terrain ruggedness, and elevation range. History variables are decennial municipal population growth rates between 1900 and 1960. Robust standard errors are clustered by MA and are in parentheses. [a], [b], and [c] indicates significant at 1, 5, and 10 percent level, respectively.

It is important to notice that the above results are first-stage results, in which we study the use of historical roads as instruments for modern highways. The use of historical instruments is not new in the literature (see, for example, Duranton and Turner, 2011). However, we are among the first to use 2,000 years old instruments based on the Roman roads. While Garcia-López (2012) considers the Roman roads only in the metropolitan area of Barcelona, we use the whole Roman network in Hispania (Spain). Furthermore, this is the second attempt to instrument with the 1760 Bourbon network. While Holl (2012) instruments market potential at a municipal level, we instrument modern highway variables at different spatial levels (central cities, the overall suburbs, and municipalities).

Our instruments need to be relevant, and they seem to fulfill this requirement. First, common sense suggests that modern highways are not built in isolation of previous historical road networks. On the contrary, new infrastructures are easier and cheaper to build close to old infrastructures (Duranton and Turner, 2012). Second, our preferred specifications in Tables 2 and 3 show positive and significant effects for our selected instruments, and high overall R^2 of their regressions. Finally, they also show first-stage statistic values that are above the Stock and Yogo (2005)'s rule of thumb (F>10) and near or above the Stock and Yogo (2005) critical values for the size test in the context of TSLS estimation.

Our instruments need to be exogenous. Historical roads may be exogenous because of the length of time since they were built and the significant changes undergone by society and economy in the intervening years (Duranton and Turner, 2012). Furthermore, neither of them were built to anticipate population growth and the current suburbanization process in Spanish cities 2,000 and 250 years later, respectively. As discussed in the previous Section 2, while the Roman roads were built to achieve military, administrative, and commercial goals with the rest of the Roman Empire (Carreras and de Soto, 2010), the 1760 Bourbon roads were designed as a central government tool for nation building without following the requirements of Spain's economy in the 18th century (Bel, 2011).

However, it is also true that other factors, in particular the suitability of geography, could have influenced both the construction and location of our two historical road networks. Furthermore, these factors may have also affected modern highways. As a result, to fulfill with the exogeneity condition, it is important to control for physical geography. As above mentioned, we include geography variables such as distance to coast, altitude, central city and MA indexes of terrain ruggedness, and central city and MA elevation ranges.

Finally, the two historical roads have surely mattered in other ways. In particular, since cities with more Roman and/or Bourbon roads tend to be larger than other cities, our instruments predict our dependent variables (central city, suburban, and municipality population growth) directly as well indirectly by predicting modern highway variables. According to Duranton and Turner (2011, 2012), the exclusion restriction requires the orthogonality of the dependent variable and the instrument/s conditional on control variables. In other words, the exogeneity of our instruments also hinges on having an appropriate set of population controls. In our case, we consider decennial MA population growth rates between 1900 and 1960 in regressions in Table 2 and their municipal counterparts in regressions in Table 3. In the central city analysis (Table 2 Panel A), we also include controls for the age of the central city and the presence of historic structures such as cathedrals and universities built before 1700. We have also experimented with the number of churches older than 300 years and the number of historic monuments, but they are not included because their high partial correlations with the other history variables.

In summary, according to the above first-stage results, the two historical networks considered in this study, the Roman roads and the 1760 Bourbon roads, provide us with a set of non-weak and relevant instruments. According to the above comments, we believe that these instruments are also exogenous.

4 Do highways cause suburbanization in Spain?

Between 1960 and 2011, Spain's overall population grew from 30 million to 47 million. An 83% of this growth took place in our sample of 77 metropolitan areas, which doubled their population from 13 million to 27 million. At the intrametropolitan level, Spanish cities experienced a process of relative suburbanization, in which population (density) increased in central cities (70% as a whole and an average 79% in our 77 CCs sample) but at lower rates than in the suburbs (200% as a whole and average 86% in our 77 suburbs sample). As a result, the share of metropolitan population living in central cities decreased from 76% in 1960 to 65% in 2011.

In the following sections, we study 1) whether highways caused Spain's suburbanization and how, 2) whether they fostered suburban growth and through which type of highways, and 3) whether they shaped cities causing changes in their urban spatial structure.

We begin with analyzing the role of highways on central city population decline. We use 1960–2011 population data and 1960–2006 highway data to estimate the following regression:

$$\begin{aligned}\Delta\ln(\text{CC population}) = \alpha_0 + \alpha_1 \times \Delta(\text{rays of CC highways}) \\ + \sum_i (\alpha_{2,i} \times \text{CC and MA control variables}_i)\end{aligned} \quad (1)$$

where CC highway rays are computed following Baum-Snow (2007a)'s definition, i.e., limited access highways connecting the CBD of the central city to a significant part of the suburbs. Since the Spanish highway stock was zero in 1960, our main explanatory variable is the number of CC highway rays in 2006. We control for CC and MA characteristics related to the theoretical model (CC and MA land area, 1960–2011 MA population growth and the initial MA population outside CC), to the suitability of geography (distance to coast, altitude, CC and MA indexes of terrain ruggedness, and CC and MA elevation ranges), and to history (decennial MA population growth rates between 1900 and 1960, a dummy variable for central cities with a cathedral built before 1700, a dummy variable for central cities with a university built before 1700, and the age of the city).

Under the assumption that the random element of population growth is uncorrelated with highways, we can estimate Eq. (1) by ordinary least squares (OLS). However, as Baum-Snow (2007a), Duranton and Turner (2011, 2012) and Garcia-López (2012) point out, highways are not placed randomly. On the contrary, their location is expected to be endogenous to population growth: planners may want to serve areas with high predicted population growth or, alternatively, with poor prospects. In both cases, reverse causation would be at work. To try to correct this problem, we rely on an instrumental variables strategy which uses the historical instruments discussed in Section 2.

Table 4 Panel A shows our main OLS and IV results in columns 1 to 5. The OLS regression in column 1 has a high R^2 of 92%. However, the estimated coefficient of interest shows that highway rays have no significant effect on the decentralization of population.

In columns 2 to 5, we instrument highway rays with Roman rays (columns 2 and 3), Bourbon rays (column 4), and with both historical instruments (column 5). In general, all TSLS results clearly show that highway rays have a significant effect on population suburbanization. It is important to notice that the estimated coefficient is quite stable across the different TSLS specifications, even when we include geography and history control variables to secure the exogeneity of our instruments. According to the included control variables, the first-stage statistic and the overidentification p-value, our preferred specification is in column 5 and its results indicate that each additional ray causes an 8% decline in central city population. Since, on average, Spain's central cities experienced relative declines in population, i.e., they grew but at lower rates than the suburbs, this result should be interpreted as showing that radial highways discouraged central city growth both by promoting relocations from central cities to the suburbs and by attracting new population (immigrants) to the suburbs. We confirm this second effect in section 5.

Table 4: Central city population decline as a function of modern highways

Panel A
Highway rays

	1960–2011 Δ ln(Central city population)						
	Main results					Robustness	
						Endog	10-year
	OLS [1]	TSLS [2]	TSLS [3]	TSLS [4]	TSLS [5]	TSLS [6]	TSLS [7]
CC rays in 2006	-0.011	-0.079^b	-0.072^b	-0.082^a	-0.079^a	-0.087^a	-0.074^b
	(0.016)	(0.034)	(0.032)	(0.028)	(0.021)	(0.032)	(0.034)
ln(Land area)	Y	Y	Y	Y	Y	Y	Y
ln(MA land area)	Y	Y	Y	Y	Y	Y	Y
60–11 Δln(MA pop.)	Y	Y	Y	Y	Y	Inst.	Y
1960 ln(MA pop.)	Y	Y	Y	Y	Y	Y	Y
Geography	Y	N	Y	Y	Y	Y	Y
History	Y	N	Y	Y	Y	Y	Y
Adjusted R^2	0.92						
First-stage statistic		7.09	19.00	18.61	22.91	15.38	22.27
Overid. p-value					0.82	0.61	0.51
Instruments							
Roman rays		✓	✓		✓	✓	Weighted
Bourbon rays				✓	✓	✓	Weighted
60–11 Δln((Spain-MA) pop.)						✓	
Observations	77	77	77	77	77	77	385

Panel B
Alternative highway variables

	1960–2011 Δ ln(CC pop.)	
	Suburban	
	Length	Ramps
	TSLS [8]	TSLS [9]
2006 Km sub. highways	0.003	
	(0.004)	
2006 Suburban ramps		0.006
		(0.018)
ln(Land area)	Y	Y
ln(MA land area)	Y	Y
60–11 Δln(MA pop.)	Y	Y
1960 ln(MA pop.)	Y	Y
Geography	Y	Y
History	Y	Y
First-stage statistic	15.33	10.06
Overid. p-value		
Instruments		
Km of suburban Bourbon roads	✓	
Suburban municipalities crossed by Bourbon roads		✓
Observations	77	77

Notes: Geography variables are distance to coast, altitude, central city and MA indexes of terrain ruggedness, and central city and MA elevation ranges. History variables are decennial MA population growth rates between 1900 and 1960, a dummy variable for central cities with a cathedral built before 1700, a dummy variable for central cities with a university built before 1700, and the age of the city. Panel regression in column 7 also includes MA fixed effects. The weighted instruments are computed as (rays of central city historical road) × (kilometers of highways running through the central city at time t)/(kilometers of highways running through the central city in 2006). Robust standard errors are clustered by region of the MA and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

The difference between our preferred TSLS coefficient (-0.079) and its OLS counterpart in column 1 (-0.011) suggests that the 1960–2006 construction of highways in Spain was endogenous. As in the United States (see Baum-Snow, 2007a) and China (see Baum-Snow et al., 2014), more highways have been built in Spain's central cities that present rapidly growing populations. Although not reported for reasons of space, first-stage results confirm this through a significant estimated coefficient of 0.964 for 1960–2011 MA population growth in Table 2 column 3.

In Table A.1 in Appendix A, we investigate whether our preferred estimate is stable across different types of metropolitan areas by grouping them according to their MA and CC population, CC density, coastal-inland location, CC industrial mix, MA income, and CC political status. None of these regressions show that highway effects are heterogeneous in those cases.

In columns 6 and 7, we check the robustness of the above result. First, since there is evidence that highways also foster metropolitan growth (e.g., Duranton and Turner, 2012), we address this potential endogeneity problem in column 6 by instrumenting 1960–2011 MA population growth with the national 1960–2011 population growth (excluding the MA). With this instrument, we rule out the possibility that differences in highway endowments are produced by differences in metropolitan population growth rates. The TSLS coefficient on rays when instrumenting both for rays and MA population growth is -0.087, less than one standard deviation of our preferred coefficient in column 5. Both instruments are still valid, with a first-stage statistic of 15.4, and the regression passes the overidentification test. Although with a first-stage statistic bellow 10, we obtain similar results when instrumenting with the expected MA population growth computed *à la* Bartik (1991).

We also compare our preferred long difference result with that obtained from a panel regression version of Eq. (1) that includes information for five periods of ten years: 1960–1970, 1970–1981, 1981–1991, 1991–2001, and 2001–2011. Besides adapting time-variant variables to these periods, we also include the above mentioned time-invariant control variables. To account for unobserved metropolitan area characteristics, we include MA fixed effects. Following Baum-Snow (2007a), we instrument highway rays in each decade with the weighted versions of Roman rays and Bourbon rays that are time variable. They are computed as (rays of central city historical road) $\times$ (kilometers of highways running through the central city at time t)/(kilometers of highways running through the central city in 2006). Results in column 7 show that both weighted instruments are valid and the TSLS regression passes the overidentification test. Furthermore, the estimated coefficient of highway rays (-0.074) is very close to our preferred estimate (-0.079).

One concern to our approach is that ray results might be driven by the expansion of the highway network in our selected metropolitan areas, in particular in their suburbs. In Table 4 Panel B, we explore this possibility by estimating our preferred specification in column 5 using two alternative explanatory variables: the length (kilometers) of suburban highways in 2006 (column 8) and, because we only consider limited access highways, the number of suburban ramps in 2006 (column 9). According to the first-stage results reported in Table 2 Panels B and C, we instrument suburban highway length with the length (km) of suburban 1760 Bourbon roads, and the number of suburban ramps with the number of suburban municipalities crossed by 1760 Bourbon roads. The TSLS estimated coefficients of both variables are very close to zero and statistically insignificant. As a result, CC population decline in Spain is only related to the construction of CC highway rays and not to the expansion of highways in the suburbs.

Confirmed that only highway rays matter for suburbanization, we test the validity of our identification strategy in Table B.1 in Appendix B. In column 1 Panel A, we estimate the effect of 2006 highway rays on 1900–1960 CC population growth, while controlling for CC and MA land areas, 1900–1960 MA population growth, 1900 MA population, and geography and history variables. Instrumenting with both Roman and Bourbon rays, the TSLS estimated coefficient for rays is -0.001 and statistically insignificant. As expected, this result indicates that rays in 2006 predict a (non significant) zero population suburbanization between 1900 and 1960. Furthermore, this result also validates our identification strategy because, conditional on control variables, our two instruments, Roman roads and Bourbon roads, are not correlated with unobservables that drive CC population decline.

As far as we know, there are only two comparable papers studying the effect of highways on suburbanization in terms of central city population decline: the pioneering paper by Baum-Snow (2007a) for US metropolitan areas between 1950 and 1990, and Baum-Snow et al. (2014)'s analysis for China's prefectures between 1990 and 2010. Interestingly, our preferred estimate (-0.08) is very similar to the ones obtained for the US (-0.09) and China (-0.05).

With this said, we should treat this similarity with caution: differences between the MAs of these countries affect their estimates. For example, one might expect a larger effect in China because its cities are more populated and dense. However, changes in residential location from Chinese central cities to their suburbs were modest and highways only contributed to suburbanization both by retarding relocations from the suburbs to central cities and by attracting immigrants to the suburbs (Baum-Snow et al., 2014). On the contrary, radial highways promoted suburban relocations in Spain and, as we show in the following section, suburban growth.

The estimates are also affected by commuting trends. In this sense, highways might have a larger effect in the US because commuting by private vehicle was already prevalent after World War II (68% of workers commuted in a car, truck, or van in 1960) and it is still dominant (86% commuted in private vehicle and 5% in public transportation in 2009) (see McKenzie and Rapino, 2011). Alternatively, the effect might be smaller in Spain because of more use of public transit (57% commuted in car and 16% in bus, subway or train in 2001) (see Ministerio de Fomento, 2013).

Despite all three studies consider the construction of their highway networks from the very beginning, the length of the study period may have also influenced their estimates. Since residential location responses to highway construction might take years, we should expect to find larger effects in Spain and the US, with the longest time periods (i.e., 60 and 50 years, respectively), and smaller in China (30 years).

Bearing in mind the above comments and admitting that other factors might have influenced the estimates, the results of all three papers show that suburbanization is an ongoing phenomenon clearly influenced by transportation infrastructure and, in particular, by highways.

5 Do highways foster population growth in Spain's suburbs?

We now turn to the suburbs. Following an empirical strategy similar to the one used for central cities, we regress 1960–2011 suburban population growth on 1960–2006 changes in the number of suburban ramps:

$$\Delta\ln(\text{SUB population}) = \beta_0 + \beta_1 \times \Delta(\text{ramps of SUB highways}) + \sum_i (\beta_{2,i} \times \text{SUB and MA control variables}_i) \quad (2)$$

where the number of ramps of suburban highways include both ramps on radial highways connecting the CBD of the central city with the suburbs and ramps on non-radial highways serving only the suburbs. Since the Spanish highway stock was zero in 1960, our main explanatory variable is the number of SUB highway ramps in 2006. As previously, we control for characteristics related to the theoretical model, to the suitability of geography and to history.

Since we fear that highways and their ramps are not allocated randomly, but following an endogenous process based on past and future trends of population growth, we estimate Eq. (2) by two-stage least squares (TSLS). According to first-stage results in Table 2 Panel B, we instrument 2006 suburban ramps with the number of suburban municipalities crossed by the 1760 Bourbon roads. As in the previous section, we validate our identification strategy with a falsification test (Table B.1 Panel B in Appendix B), in which we regress 1900–1960 suburban population growth on 2006 suburban ramps. As expected, the estimated coefficient is zero and insignificant.

The first two columns of Table 5 Panel A report our main TSLS results for ramps. In column 1, we only include control variables related to the theoretical model and the first-stage statistic of this regression is 12.36. In column 2, we also add geography and history variables and the first-stage statistic is still over the Stock and Yogo (2005)'s rule of thumb (F>10). Results in both cases are similar: each ramp caused a 7% growth in suburban population between 1960 and 2011.

In columns 3 and 4 Panel A, we study the effects of two alternative explanatory variables: 2006 central city rays (column 3) and 2006 length (km) of suburban highways (column 4). Based on their first-stage results in Table 2 Panels A and C, the former is instrumented with the number of central city rays of Roman roads and of Bourbon roads, and only the length (km) of suburban 1760 Bourbon roads instruments the latter. While both regressions pass all weak instrument tests and the overidentification test, the estimated coefficient is only significant and positive for highway rays (column 3). This result implies that each central city highway ray caused a 20% population growth in the suburbs.

Since the ray variable includes information only for radial highways whereas the ramp variable includes information for both radial and non-radial highways, the question that arises is whether ramp results are driven by ray results and, accordingly, by radial highways. In column 5 Panel A, we investigate this possibility by regressing simultaneously 1960–2011 suburban population growth on 2006 ramps and 2006 rays, which are instrumented by the three above mentioned instruments[1]. While the TSLS estimated coefficient for rays does not change (0.21) and remains sig-

[1]An alternative approach would be to use two ramp variables, one for radial highways and another for non-radial highways. However, this empirical strategy would be more difficult to implement because the need of more valid instruments that, at the same time, would be too similar in their construction. Our selected empirical strategy resembles the one used for central cities in Panel B of Table 4, and, in particular, allow us to take advantage of two sets of explanatory variables and unrelated instruments without losing first-stage power.

nificant at a 10% level, the coefficient for ramps significantly reduces to -0.03 and is insignificant. As a result, we confirm that each radial highway caused a 20% growth in suburban population.

It is important to notice that, as Redding and Turner (forthcoming) point out, this 20% estimate is the compound effect of relocation and growth and our cross-sectional empirical strategy does not allow us to separately estimated both effects. However, we can approximate them by using the estimated effect on CC population (i.e., each highway ray displaced 8% of CC population) and by considering that CC population is, on average, 1.8 times suburban population. In this sense, the relocation effect on suburban population is around 14.4% (=8%×1.8) and the remaining 5.6% is the growth effect. As a result, we confirm that radial highways cause not only relocation from central cities to the suburbs, but also population growth in their suburbs. The latter result is consistent with Duranton and Turner (2012)'s findings that highways foster urban growth.

Table 5: Suburban population growth as a function of modern highways

Panel A
The suburbs

	1960–2011 Δln(Suburban population)				
	Ramps		Other variables		Both
	TSLS [1]	TSLS [2]	TSLS [3]	TSLS [4]	TSLS [5]
2006 Suburban ramps	0.065^b (0.026)	0.066^b (0.027)			-0.028 (0.025)
2006 Central city rays			0.196^b (0.099)		0.211^c (0.116)
2006 Km of suburban highways				0.003 (0.003)	
ln(Land area)	Y	Y	Y	Y	Y
ln(MA land area)	Y	Y	Y	Y	Y
60–11 Δln(MA pop.)	Y	Y	Y	Y	Y
1960 ln(MA pop.)	Y	Y	Y	Y	Y
Geography	N	Y	Y	Y	Y
History	N	Y	Y	Y	Y
First-stage statistic	12.36	10.65	20.08	14.85	11.57
Overid. p-value			0.63		0.54
Instruments					
Number of suburban municipalities crossed by Bourbon roads.	✓	✓			✓
Roman and Bourbon CC rays.			✓		✓
Km of suburban Bourbon roads.				✓	
Observations	77	77	77	77	77

Panel B
Suburban municipalities

	1960–2011 Δln(Muni. pop.)		
	Ramps		Hetero
	TSLS [6]	TSLS [7]	TSLS [8]
2006 Suburban ramps	0.246^a (0.072)	0.219^a (0.085)	0.176^a (0.069)
× Dummy=1 if dist to CBD ≥ 10 km			0.129^c (0.074)
Distance to CBD	Y	Y	Y
ln(Land area)	N	Y	Y
1960 ln(Population)	N	Y	Y
Geography	N	Y	Y
History	N	Y	Y
MA fixed effects	Y	Y	Y
First-stage statistic	46.49	24.85	25.43
Instruments			
Dummy=1 if suburban municipality is crossed by a Bourbon road.	✓	✓	✓
× CBD Dummy			✓
Observations	774	774	774

Notes: Geography variables are distance to coast, altitude, indexes of terrain ruggedness, and elevation ranges. History variables are decennial MA (Panel A) and municipal (Panel B) population growth rates between 1900 and 1960. Regression in column 8 also includes its dummy variable. Robust standard errors are clustered by region of the MA (Panel A) and by MA (Panel B) and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

We now turn our attention to a look inside the suburbs and explore the effect of highways within the suburbs themselves. In Table 5 Panel B, we consider the 774 municipalities that form the suburbs of our 77 MAs. In column 6, we regress 1960–2011 suburban municipality growth on the number of municipal ramps in 2006, while controlling only for the distance to CBD and MA fixed effects. In column 7, we also add controls for land area, 1960 population, geography and history variables. According to first-stage results in Table 3 Panel A, we instrument our main explanatory variable with a dummy variable for suburban municipalities crossed by a Bourbon road. This instrument passes all weak instrument tests, and, according to the falsification test in Table B.1 Panel C, instruments are not correlated with unobservables that drive suburban municipality growth. In general, both TSLS results show that municipal ramps have a positive and significant effect on municipal population growth in the suburbs. In particular, our preferred specification is in column 7 and its results indicate that each ramp causes a 22% population growth in suburban municipalities where they are located.

Since land use theory suggests that highway effects are heterogeneous in terms of distance to CBD (see, for example, Baum-Snow, 2007b), we compare suburban municipalities located less than 10 km from the CBD with those located beyond 10 km. In column 8, we include a dummy variable for suburban municipalities located beyond 10 km from the CBD and its interaction with the ramp variable. To instrument the interacted ramp variable, we interact the dummy variable for Bourbon roads with the dummy variable for CBD distance. This regression passes all weak instrument tests. The TSLS estimated coefficients for the two ramp variables show smaller effects for the municipalities close to the CBD (18%) and significant higher effects for the ones located far from the CBD (31%).

6 Do highways shape Spanish cities?

While previous results show that highways cause population decline in central cities and population growth in the suburbs, we do not know how the urban spatial structure of these metropolitan areas has evolved according to the new transportation infrastructure, the highways. In this section, we focus on this question by examining the role of highways location on the intrametropolitan pattern of residential location.

We depart from the traditional linearized negative exponential density to regress 1960 and 2011 population densities on distance to CBD and on distance to the nearest highway ramp in 2006:

$$\begin{aligned}\ln(\text{Population density}) = {} & \gamma_0 + \gamma_1 \times \text{distance to CBD} \\ & + \gamma_2 \times \text{distance to the nearest highway ramp} \\ & + \sum_i (\gamma_{3,i} \times \text{control variables}_i) + \text{MA fixed effects}\end{aligned} \tag{3}$$

where the unit of observation is the municipality, whether it is a central city or a suburban municipality. Population density refers to inhabitants per square kilometer, and distances are in kilometers. The coefficients γ_1 and γ_2 are the so-called density gradients and capture the extent to which density falls with distance to CBD and distance to the nearest highway ramp, respectively.

Table 6 Panel A reports results for Eq. (3). In columns 1 and 3, we consider the traditional monocentric urban form by regressing population density only on distance to CBD. The OLS estimated coefficients are negative and significant, verifying the reduction in population density as we move away from the CBD. Furthermore, since the absolute value of the 2011 CBD gradient (-0.17) is larger than its 1960 counterpart (-0.12), we also verify that there is a process of population suburbanization in which more people is moving to the suburbs, reducing the differences in densities between the central city and the suburbs. Furthermore, while the overall R^2 of both regressions is high (91% in 1960, and 83% in 2011), its reduction also points out the increasing role of other factors that affect the urban spatial structure. In columns 2 and 4, we add the distance to the nearest highway ramp in 2006. The TSLS coefficients for the distance to CBD remain unchanged and follow the same dynamics than their OLS counterparts: population density reduces with distance to CBD and, as a result of the suburbanization process, this reduction is larger in 1960 than in 2011.

Table 6: Urban spatial structure as a function of modern highways

Panel A
Intrametropolitan location of population

	ln(Population density) 1960		ln(Population density) 2011	
	OLS [1]	TSLS [2]	OLS [3]	TSLS [4]
2006 Dist to the nearest ramp		-0.055 (0.084)		-0.220^b (0.110)
Distance to CBD	-0.168^a (0.013)	-0.170^a (0.016)	-0.127^a (0.011)	-0.124^a (0.016)
Geography	Y	Y	Y	Y
History	N	N	N	N
MA fixed effects	Y	Y	Y	Y
Adjusted R^2	0.91		0.83	
First-stage statistic		15.52		15.31
Instrument: Distance to the nearest Roman road or 1760 Bourbon road.		✓		✓

Panel B
The spatial pattern of suburbanization

	1960–2011Δ ln(Pop density)			
	OLS [5]	TSLS [6]	TSLS [7]	TSLS [8]
2006 Dist to the nearest ramp		-0.006 (0.041)	-0.102^a (0.036)	-0.081^b (0.040)
Distance to CBD	0.020^a (0.005)		0.036^a (0.014)	-0.021^c (0.012)
1960 ln(Population)				-0.288^a (0.032)
Geography	N	N	N	Y
History	N	N	N	Y
MA fixed effects	Y	Y	Y	Y
Adjusted R^2	0.49			
First-stage statistic		26.96	15.12	15.23
Instrument: Distance to the nearest Roman road or 1760 Bourbon road.		✓	✓	✓

Notes: 851 observations for each regression (77 are central cities and 774 are suburban municipalities). Geography variables are land area, distance to coast, altitude, index of terrain ruggedness, and elevation range. History variables are decennial population growth rates between 1900 and 1960. Regressions are weighted by the share of 1960 and 2011 MA population in the municipality in columns 1, 2 and 5 to 8, and in Columns 3 and 4, respectively. Robust standard errors are clustered by MA and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Because we fear that location of highways is endogenous to the intrametropolitan location patterns, we estimate Eq. (3) in columns 2 and 4 by TSLS. Based on first-stage results in Table 3 Panel B, we instrument the highway distance with the distance to the nearest Roman or Bourbon road. First-stage statistics for these regressions are above the Stock and Yogo (2005)'s rule of thumb. As we expected, the 1960 and 2011 estimated coefficients for the highway distance are significantly different. While the estimated gradient is -0.05 but not significant in 1960, its value becomes significant and changes to -0.22 in 2011. In other words, the intrametropolitan location of population is not related to the location of (future) highways[2], whereas in 2011 population density significantly

[2] A qualifier is important here. The 1960 regression in column 2 Table 6 is not a falsification test to validate our identification strategy. Although conditional on distance to CBD, geography and MA fixed effects, we regress past density (1960) on the location of future highways (2011) without controlling for history. As commented in Section 3, the exogeneity condition hinges on having an appropriate set of history variables. When we include, for example, past levels of decennial populations from 1900 to 1950, the estimated coefficient for highway distance becomes zero. This regression would be different from the traditional density functions that we regress in columns 1 to 4 of Table 6.

reduces a 22% if we move one kilometer away from the nearest highway ramp.

The above results clearly show that population lived closer to the highways in 2011 than in 1960. Since there was any highway in 1960, these results indirectly suggest that population spread out along the new highways between 1960 and 2011. We test this suggestion regressing a growth version of Eq. (3):

$$\begin{aligned}\Delta\ln(\text{Population density}) = {} & \delta_0 + \delta_1 \times \text{distance to CBD} \\ & + \delta_2 \times \text{distance to the nearest highway ramp} \\ & + \sum_i (\delta_{3,i} \times \text{control variables}_i) + \text{MA fixed effects}\end{aligned} \tag{4}$$

where the coefficients δ_1 and δ_2 are the so-called growth gradients and capture the extent to which the growth of density (or population) increases, when they are positive, or decreases, when they are negative, with distance to CBD and distance to the nearest highway ramp, respectively.

Table 6 Panel B reports results for Eq. (4). With the exception of column 5, all other regressions in columns 6 to 8 are estimated by TSLS. As in Panel A, we instrument our endogenous explanatory variable, the distance to the nearest highway ramp, with the distance to the nearest Roman or Bourbon road. First-stage statistics for these regressions are above the Stock and Yogo (2005)'s rule of thumb. Based on our preferred specification in column 8, we validate our identification strategy with an estimated zero effect of 2006 proximity to highways on 1900–1960 municipal (population) density growth (Table B.1 Panel D in Appendix B).

The first two columns of Table 6 Panel B include MA fixed effects and one main explanatory variable. In column 5, we only include distance to CBD and the overall R^2 is high (49%). The OLS estimated coefficient for the CBD distance is significant and positive, verifying the suburbanization process: municipalities located far from the CBD grew more quickly, a 2% faster per kilometer, between 1960 and 2011. In column 6, we regress municipal density growth only on distance to the nearest ramp. Although the TSLS estimated coefficient for the highway distance is a negative but insignificant -0.01, this result is unsurprising since its an average between the opposite effects of highways on population growth in central cities and suburban municipalities.

When we jointly estimate the effects of proximity to CBD and to highways in column 7, the TSLS estimated coefficient for the CBD distance remains significant and positive whereas the coefficient for the highway distance increases its absolute value and becomes highly significant. In other words, once we control for the suburbanization process, in which population growth is faster per kilometer when we move away from the central cities, we find that population growth is higher the closer we move to the nearest highway ramp.

Column 8 is our preferred specification because we also control for the 1960 log population and log land area (i.e., the 1960 density), other geography variables and history variables. The TSLS results of this regression confirm our previous intuition that population spread out along the new highways between 1960 and 2011. In particular, each additional kilometer closer to the nearest highway ramp increases population growth by an 8%.

Another interesting result is related to the CBD distance: its estimated coefficient becomes negative (-0.02). This conditional (on 1960 density) effect complements the unconditional findings in previous columns: on average, each additional kilometer closer to the CBD reduces population growth (columns 2 and 7), but conditioning out the fact that nearly everything around the CBD (and central city) is dense and developed and that high population (density) municipalities grow more slowly, proximity to CBD still has a positive effect on nearby growth (column 8).

One concern to our intrametropolitan analysis is the presence of spatial correlation. Following McMillen (2004), this problem appears because of functional form misspecification and we try to minimize it by including as many variables as possible related to the urban spatial structure (distances to CBD, highways, and coast, geography variables, ...). However, since spatial correlation in the error terms still might be a concern, we check the robustness of our results estimating Eq. (3) and (4) by Conley (1999)'s two-step spatial GMM. For three cutoffs, Table C.1 in Appendix C show that the spatial GMM results are very similar to our preferred TSLS ones.

7 Conclusions

Today the Spanish highway system is highly developed and comprises more than 14,000 km. Although the first highways were built in the late 1960s, the construction accelerated since 1986, when the country joined the EU and huge amounts of European funds were earmarked for highway construction. While Spain had roughly 2,400 km of highways in 1986, the stock of highways increased in 12,000 km between 1986 and 2011. No other European country has experienced such massive highway construction in such a short period of time.

In this paper we investigate the effect of this highway construction on the process of population suburbanization of Spain's cities between 1960 and 2011. Because of the potential endogeneity problem of highway provision, we first study whether the construction and location of highways are influenced by historical roads. According to the first-stage results and our own considerations, the two historical road networks considered in this study are the Roman roads and the 1760 Bourbon roads. This first stage analysis allows us concluding that historical roads explain modern highways.

We look at central cities to confirm that highways do cause suburbanization in Spain. In particular, our estimates indicate that each highway ray contributed to an 8-9% decline in central city population between 1960 and 2011. We also find that this result is only related to highway rays (i.e., emanating from central cities), and not to the expansion of the highway network in the suburbs. Furthermore, this result holds when grouping metropolitan areas according to their population size, density, coastal-inland location, industrial mix, income, and central city political status.

When looking at the suburbs, we find that highways do foster population growth in Spain's suburbs. However, the effect is only related to radial highways connecting central cities with their suburbs: each highway ray built between 1960 and 2006 caused a 20% growth in suburban population between 1960 and 2011. Based on our computations, we separate this compound effect in a relocation effect (i.e., each highway ray displaced population from central cities to the suburbs rising suburban population around 14.4%) and in a net growth effect (i.e., each highway ray attracted around 5.6% of new population to the suburbs). At a municipal level, we link the above effect with suburban municipalities where ramps are placed: these municipalities grew an additional 20% for each ramp built inside their boundaries between 1960 and 2006. As predicted by theory, this ramp effect is larger in more distant municipalities (31%) than close to the center (18%).

Finally, we look within metropolitan areas to study the relationship between the urban spatial structure and the location of highways. Departing from the traditional linearized exponential density function, the static estimates for 1960 and 2011 confirm the increasing role of highways on the intrametropolitan patterns of residential location whereas the "dynamic" ones confirm that 1960—2011 municipal population growth was faster the closer to the highways. As a result, we provide evidence that highways do shape Spanish cities.

The contribution of the paper is relevant because it provides evidence that was needed for Europe. While the other two comparable papers are centered on the US and China, ours is centered on Spain, the European country with the longest highway network in the EU and the fifth in the world. Furthermore, our results for Spain complement Baum-Snow (2007a)'s and Baum-Snow et al. (2014)'s results and show that, despite differences in city population size and density, land-use planning, or the use of public transportation in these three countries, suburbanization is an ongoing phenomenon clearly influenced by the highways construction. Compared to the above papers studying the highway effects only on central city population decline, our findings for the suburbs and the urban spatial structure are new in the literature. It is important to note that some of our suburban and intrametropolitan results verify theoretical predictions. First, we confirm that highway effects are heterogeneous in CBD distance. Second, we also provide evidence that the suburbanized population is not evenly distributed across suburbs; on the contrary, population spreads out along the highways.

Our work has some limitations. First, we do not explore the effects of other transportation infrastructures such as railroads. However, while railroad lines link our 77 cities via long-distance services, only some of the largest have a railroad network that connects the central city with other metropolitan municipalities (for the case of Barcelona, see Garcia-López, 2012). Second, we do not investigate the effect of highways on employment or GDP outcomes. Unfortunately, none of these variables are available at the municipal or metropolitan area level. Finally, although the paper also studies the effects of highways on changes in the urban spatial structure, we neglect the effects on changes in residential land consumption patterns. Since these data is only available for 1990, 2000 and 2006, we leave this issue for future research.

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Appendix A Heterogeneous results for central cities estimates

In Table A.1, we present regressions which test for heterogeneity in our preferred results by grouping MAs according to different criteria. First, we consider a more restricted definition of MA and CC: MAs under/over 100,000 inhabitants in 1960 (column 1) and CCs under/over 50,000 inhabitants in 1960 (column 2). In column 3 we investigate whether highway effect varies with density: CCs under/over 603 inhabitants per square kilometer in 1960 (median). Since ancient civilizations such as the Greeks, the Romans, and the Tartessians, among others, first settled on the coast, we compare coastal with inland cities in column 4. We also study the effect of CC industrial mix by grouping cities according to their sectoral specialization: CCs with a manufacturing employment share over/under the median share of all cities (23%) in 1991 (column 5) and CC with a construction share over/under the median (10%) in 1991 (column 6). In column 7, we also examine whether MA income levels affect our results: MAs belonging to a province with an income over/under Spain's mean income in 1955. Finally, we analyze whether the political status of some cities as province capitals affect their process of suburbanization (column 8).

Departing from our preferred regression in column 5 Table 4, we add the dummy variables of each subsample and their interaction with the ray variable. To instrument the interacted ray variable, we use interacted Roman rays and interacted Bourbon rays. It is important to notice that we use all four instruments (two for rays and two for the interacted rays) only in regressions in columns 1 to 4. , According to their first-stage and reduced-form results, the other regressions only use three instruments (columns 5 and 7) and two instruments (columns 6 and 8).

The IV estimated coefficients for the interacted ray variables are positive, but not significant. These results indicate that, although the effect of highways rays seems to be smaller in smaller MAs and CCs, less dense CCs, inland MAs, cities specialized in manufacturing and construction, richer metropolitan areas, and non-capital central cities, the differences between these effects and those estimated through the highway ray variables are not significant. In other words, highway effects on CC population decline are not heterogeneous in these cases.

Finally, Table A.1 also reports first-stage statistic values and overidentification p-values. With the exception of regressions in column 6 and 8, which are exactly identified, the other regressions pass their overidentification tests. According to Stock and Yogo (2005)'s critical values, most regressions pass the size test in the context of LIML estimation (columns 1 to 3 and 5, 7 and 8) and in the context of TSLS estimation (column 4). Since its first stage stastistic value is between the 10% and 15% critical values, results in column 6 should be interpreted with caution.

Table A.1: Central city population decline as a function of modern highways: Heterogeneity

Dependent variable:	1960–2011 Δln(Central city population)							
Type of heterogeneity:	Population size		Geography		Industrial mix		Income	Political status
	Small vs. large MAs	Small vs. large CCs	More vs. less dense CCs	Inland vs. coastal MAs	Manufacturing vs. other CCs	Construction vs. other CCs	Rich vs. poor MAs	Capital vs. non-capital CCs
	LIML [1]	LIML [2]	LIML [3]	TSLS [4]	LIML [5]	LIML [6]	LIML [7]	LIML [8]
2006 (=1960–2006 Δ) CC rays	-0.079^{b}	-0.085^{a}	-0.102^{b}	-0.134^{c}	-0.076^{a}	-0.102^{a}	-0.110^{b}	-0.080^{a}
	(0.040)	(0.040)	(0.051)	(0.077)	(0.020)	(0.036)	(0.050)	(0.027)
× Dummy	0.039	0.018	0.043	0.090	0.010	0.076	0.035	0.009
	(0.051)	(0.074)	(0.038)	(0.055)	(0.040)	(0.084)	(0.055)	(0.042)
ln(Land area)	Y	Y	Y	Y	Y	Y	Y	Y
ln(MA land area)	Y	Y	Y	Y	Y	Y	Y	Y
1960–2011 Δln(MA pop.)	Y	Y	Y	Y	Y	Y	Y	Y
1960 ln(MA suburban pop.)	Y	Y	Y	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y	Y	Y	Y
History	Y	Y	Y	Y	Y	Y	Y	Y
Dummy = 1 if	1960 MA pop<100,000	1960 CC pop.< 50,000	1960 CC Den inh/km^2 ≥ 603	Inland MA	1991 CC Man. $\geq 23\%$	1991 CC Const. $\geq 10\%$	1955 Rich province	Province non-capital CC
First-stage statistic	13.10	11.70	6.48	23.45	6.19	6.51	9.70	10.52
Overidentification p-value	0.30	0.12	0.89	0.87	0.54		0.71	
Instruments								
Rays of CC Roman roads	✓	✓	✓	✓	✓		✓	
× Dummy	✓	✓	✓	✓			✓	✓
Rays of CC Bourbon roads	✓	✓	✓	✓	✓	✓	✓	✓
× Dummy	✓	✓	✓	✓	✓	✓		
Observations	77	77	77	77	77	77	77	77
× Dummy	49	30	39	38	39	39	30	38

Notes: Geography variables are distance to coast, altitude, central city and MA indexes of terrain ruggedness, and central city and MA elevation ranges. History variables are decennial MA population growth rates between 1900 and 1960, a dummy variable for central cities with a cathedral built before 1700, a dummy variable for central cities with a university built before 1700, and the age of the city. All regressions also include their dummy variables. Robust standard errors are clustered by region of the MA and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Appendix B Falsification tests to validate our identification strategies

We run placebo regressions to check the validity of our identification strategies. Conditional on control variables, we estimate the effect of contemporary highway variables on past dependent variables. By doing so, we test whether our instruments are still correlated with unboservables that affect our dependent variables.

Table B.1 reports TSLS results for our four main specifications. In column 1 Panel A, we run the falsification test for regression in column 5 Table 4 by estimating the effect of 2006 highway rays on 1900–1960 CC population growth. In column 2 Panel B, we regress 1900–1960 suburban population growth on 2006 suburban ramps, and testing instrument validity for specification in column 2 Table 5. Falsification test for regression in column 7 Table 5 is in column 3 Panel C, in which we estimate the effect of 2006 suburban ramps on 1900–1960 suburban municipality growth. Finally, column 4 Panel D shows TSLS results of regressing 2006 distance to the nearest highway ramp on 1900–1960 municipal density growth. All four regressions include the same control variables than their originals specifications, but referred to 1900–1960 and 1900 when needed. Because lack of population data prior to 1900, decennial MA past population growth rates are not included. In column 1 we add the other history variables: a dummy for central cities with a cathedral built before 1700, a dummy for central cities with a university built before 1700, and the age of the city.

Table B.1: Additional robustness checks: Placebo regressions

Panel A Central cities		**Panel B** The suburbs		**Panel C** Suburban municipalities		**Panel D** Urban spatial structure	
1900–1960 Δln(CC pop.)		1900–1960 Δln(Sub. pop.)		1900–1960 Δln(Muni. pop.)		1900–1960 Δln(Pop. Den.)	
	TSLS [1]		TSLS [2]		TSLS [3]		TSLS [4]
2006 CC rays	-0.001 (0.043)	2006 Suburban ramps	-0.001 (0.012)	2006 Suburban ramps	0.006 (0.176)	2006 Dist to ramp	-0.005 (0.027)
ln(Land area)	Y	ln(Land area)	Y	Distance to CBD	Y	Distance to CBD	Y
ln(MA land area)	Y	ln(MA land area)	Y	ln(Land area)	Y	ln(Land area)	Y
1900–1960 Δln(MA pop.)	Y	1900–1960 Δln(MA pop.)	Y	1900 ln(Population)	Y	1900 ln(Population)	Y
1900 ln(MA sub. pop.)	Y	1900 ln(MA sub. pop.)	Y	Geography	Y	Geography	Y
Geography	Y	Geography	Y	MA fixed effects	Y	MA fixed effects	Y
First-stage statistic	18.21	First-stage statistic	38.67	First-stage statistic	24.96	First-stage statistic	16.89
Overid. p-value	0.22						
Instrument: Rays of CC Roman roads and rays of CC 1760 Bourbon roads.		Instrument: Suburban municipalities with 1760 Bourbon roads.		Instrument: Dummy=1 if municipality with 1760 Bourbon roads.		Instrument: Distance to the nearest Roman or 1760 roads.	
Observations	77	Observations	77	Observations	774	Observations	851

Notes: Geography variables are distance to coast, altitude, indexes of terrain ruggedness, and elevation ranges. In column 1 we also include history variables such as a dummy variable for central cities with a cathedral built before 1700, a dummy variable for central cities with a university built before 1700, and the age of the city. Regressions are weighted by the share of 1960 MA population in the municipality in columns 3 and 4. Robust standard errors are clustered by region of the MA (columns 1 and 2) and by MA (columns 3 and 4) and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Instrumenting with the same historical variables, the TSLS estimated coefficient for the four 2006 highway variables are near zero and insignificant. As expected, these results show that 2006 highway variables predict a zero 1900–1960 CC population decline (column 1 Panel A), a zero

1900–1960 suburban population growth (column 2 Panel B), a zero 1900–1960 suburban municipality growth (column 3 Panel C), and a zero 1900–1960 municipal density growth closer to this infrastructure (column 4 Panel D). As a result, these results also validate our identification strategies because, conditional on control variables, Roman and/or Bourbon instruments are not correlated with unobservables that drive CC population decline, suburban population growth, suburban municipality growth, or municipal density growth, respectively.

Table B.1 also reports first stage statistic values that are above Stock and Yogo (2005)'s critical values. Regression in column 1 Panel A also passes the overidentification test.

Appendix C Robustness to spatial correlation

We check the robustness of our intrametropolitan results to spatial correlation. We use the two-step spatial GMM procedure developed by Conley (1999) to correct the standard errors. The Stata code to implement the spatial robust standard errors can be found on `http://economics.uwo.ca/people/conley_docs/code_to_download_gmm.html`. Since our MAs are very different in their spatial size, we use three cutoffs: 8.5 km, 25 km, and 45 km, which roughly correspond to the minimun area of 71 km^2, to the average area of 580 km^2, and to the maximum area of 2075 km^2, respectively. We find that our preferred estimates in Table 6 are robust and very similar to the spatial GMM estimates in Table C.1.

Table C.1: Urban spatial structure as a function of modern highways: Spatial GMM

Panel A Intrametropolitan location of population							**Panel B** The spatial pattern of suburbanization			
	ln(Pop density)							1960–2011Δ Δ ln(Pop density)		
	1960			2011						
Cutoff	8.5 km	25 km	45 km	8.5 km	25 km	45 km	Cutoff	8.5 km	25 km	45 km
Two-Step Spatial GMM	[1]	[2]	[3]	[4]	[5]	[6]	Two-Step Spatial GMM	[7]	[8]	[9]
2006 Dist to the ramp	-0.063	-0.059	-0.061	-0.245^{b}	-0.243^{b}	-0.245^{b}	2006 Dist to the ramp	-0.091^{a}	-0.092^{a}	-0.093^{a}
	(0.086)	(0.097)	(0.096)	(0.104)	(0.113)	(0.115)		(0.035)	(0.034)	(0.035)
Distance to CBD	-0.169^{a}	-0.168^{a}	-0.178^{a}	-0.120^{a}	-0.120^{a}	-0.120^{a}	Distance to CBD	-0.018^{b}	-0.017^{c}	-0.016^{c}
	(0.016)	(0.018)	(0.017)	(0.014)	(0.016)	(0.016)		(0.009)	(0.009)	(0.010)
							1960 ln(Population)	-0.281^{a}	-0.279^{a}	-0.279^{a}
								(0.028)	(0.028)	(0.030)
Geography	Y	Y	Y	Y	Y	Y		Y	Y	Y
History	N	N	N	N	N	N		Y	Y	Y
MA fixed effects	Y	Y	Y	Y	Y	Y		Y	Y	Y
Instrument	Distance to the nearest Roman or 1760 Bourbon road.									

Notes: 851 observations for each regression (77 are central cities and 774 are suburban municipalities). Geography variables are land area, distance to coast, altitude, index of terrain ruggedness, and elevation range. History variables are decennial population growth rates between 1900 and 1960. Regressions are weighted by the share of 1960 and 2011 MA population in the municipality in Columns 1 to 3 and 7 to 9, and in Columns 4 to 6, respectively. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Appendix D Summary statistics

Table D.1: Summary statistics

	Mean	Stand. Dev.	Minimum	Maximum
Panel A. Central city population decline (Table 4) and suburban growth (Table 5 Panel A): Eq. (1) and (2) – 77 obs.				
1960–2011 Δln(Central city population)	0.79	0.78	-0.50	4.26
1960–2011 Δln(Suburban population)	0.86	0.77	-0.74	3.06
2006 Central city highway rays	2.79	1.90	0	9
2006 Suburban highway ramps	5.17	5.34	0	32
2006 Kilometers of suburban highways	32.56	29.61	0	179.90
Rays of central city Roman roads	1.18	1.21	0	4
Rays of central city 1760 Bourbon roads	1.03	1.28	0	7
Suburban municipalities crossed by 1760 Bourbon roads	1.99	3.25	0	18
Kilometers of suburban 1760 Bourbon roads	7.14	11.38	0	67.53
ln(Central city land area) (km^2)	4.70	1.13	1.95	7.47
ln(MA land area) (km^2)	6.17	0.68	4.26	7.64
1960–2011 Δln(MA population)	0.79	0.63	-0.45	3.43
1960 ln(Suburban population)	10.15	0.90	8.38	12.97
1960 ln(MA population)	11.51	0.88	9.43	14.64
Distance to coast (km)	76.46	102.65	0.09	342.21
Altitude (m)	264.25	283.79	3.00	1002.00
Central city index of terrain ruggedness	40.12	27.79	2.52	148.07
MA index of terrain ruggedness	46.56	32.18	5.92	170.75
Central city elevation range (m)	429.51	321.80	16	1491
MA elevation range (m)	681.31	473.25	67	2816
1900–1910 Δln(MA population)	0.09	0.08	-0.15	0.29
1910–1920 Δln(MA population)	0.11	0.10	-0.15	0.53
1920–1930 Δln(MA population)	0.13	0.12	-0.48	0.38
1930–1940 Δln(MA population)	0.16	0.11	-0.16	0.39
1940–1950 Δln(MA population)	0.11	0.10	-0.13	0.47
1950–1960 Δln(MA population)	0.17	0.12	-0.08	0.58
Dummy for CC with a cathedral built before 1700	0.51	0.50	0	1
Dummy for CC with a university built before 1700	0.14	0.35	0	1
Age of central city	414.21	800.54	-1104	1870
Panel B. Urban spatial structure (Table 6 Panel A) and its changes (Table 6 Panel B): Eq. (3) and (4) – 851 obs.				
1960 ln(Population density)	4.71	1.42	1.38	9.67
2011 ln(Population density)	5.53	1.68	1.98	9.96
1960–2011 Δln(Population density)	0.82	0.92	-0.91	4.51
2006 Distance to the nearest highway ramp (km)	4.34	5.18	0.11	54.40
Distance to the nearest Roman or 1760 Bourbon road (km)	4.30	6.18	0.01	59.70
Distance to CBD (km)	8.89	5.12	0	53.22
ln(Land area) (km^2)	3.16	1.21	-3.51	7.47
Distance to coast (km)	83.75	102.53	0.02	352.75
Altitude (m)	331.24	304.79	3	1152
Index of terrain ruggedness	41.73	34.66	0	183.90
Elevation range	300.14	296.14	0	2537
1900–1910 Δln(Population)	0.11	0.53	-0.35	8.12
1910–1920 Δln(Population)	0.51	0.13	-0.36	0.78
1920–1930 Δln(Population)	0.12	0.36	-0.75	6.90
1930–1940 Δln(Population)	0.05	0.17	-1.53	0.93
1940–1950 Δln(Population)	0.06	0.15	-0.84	1.05
1950–1960 Δln(Population)	0.12	0.45	-0.36	8.87