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Cities and Innovation

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SUBURBANIZATION AND HIGHWAYS: WHEN THE ROMANS, THE BOURBONS AND THE FIRST CARS STILL SHAPE SPANISH CITIES [*]

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ABSTRACT: We estimate the effects of highways on the suburbanization of Spanish cities. First, we extend previous findings for the US and China by providing evidence for Europe: each additional highway ray built between 1991 and 2006 produced a 5 per cent decline in central city population between 1991 and 2011. Second, our main contribution is at the intrametropolitan level. We find that highway improvements influence the spatial pattern of suburbanization: suburban municipalities that were given improved access to the highway system between 1991 and 2006 grew 4.6% faster. The effect was most marked in suburbs located at 5–11 km from the central city (7.1%), and concentrated near the highways: population spreaded out along the (new) highway segments (4.7%) and ramps (2.7%). To estimate the causal relationship between population growth and highway improvements, we rely on an IV estimation. We use Spain’s historical road networks – Roman roads, 1760 main post roads, and 19th century main roads – to construct our candidates for use as instruments.

JEL Codes: R4, O2

Keywords: Suburbanization, highways, transportation infrastructure.

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[*] We are very grateful to Pau de Soto for their very helpful historical GIS maps. Financial support from the Ministerio de Ciencia e Innovación (research projects ECO2009-12234 and ECO2010-20718 (M.A. Garcia-López) and ECO2009-12680 and ECO2010-16934 (E. Viladecans-Marsal)), Generalitat de Catalunya (research projects 2009SGR478 (M.A. Garcia-López) and 2009SGR102 (E. Viladecans-Marsal)), and the ‘Xarxa de Referència d’R+D+I en Economia Aplicada’ is gratefully acknowledged.

1. Introduction

Over the last twenty years the population of Spanish cities has grown and suburbanized intensively (Solé-Ollé and Viladecans-Marsal, 2004). At the same time, the Spanish highway system has been extended by about 10,000 km, making it the longest network in the European Union (Holl, 2011). In this paper, we investigate the impact of highways on the suburbanization process of Spanish cities between 1991 and 2011. We find that highways cause Spanish suburbanization and influence its spatial pattern by spreading population out along these new, improved highways. More specifically, each additional highway ray (i.e., emanating from the central city) built between 1991 and 2006 contributed to a 5 per cent decline in central city population between 1991 and 2011. Municipalities that improved their access to the highway system grew faster (2.5%) and this effect was most marked in suburban municipalities (4.6%) and increased with distance to the central city, in particular in suburbs located 5.4–11.1 km (7.1%). We also verify theory's prediction that the impact on population growth concentrates in suburban municipalities near highways (3.7% in suburbs within 2.4 km) and, in particular, in those with new highway segments/ramps inside their boundaries (4.7 and 2.7%, respectively).

This study is of interest for three reasons. First, it helps to explain the role played by highways in changing the urban form of modern cities. Baum-Snow (2007a) shows that highway improvements can cause absolute suburbanization in which central cities lose population. Baum-Snow et al. (2012) verify these results for China in a context of relative suburbanization in which central cities gain population but at lower rates than their suburbs. Our results confirm these two findings with a sample of cities that not only includes those undergoing suburbanization processes, but also those exposed to centralization processes.

Second, we find that these highway improvements also influence the spatial pattern of this suburbanization process. While Garcia-López (2012) shows that highway improvements foster suburban population growth in Barcelona, we verify and extend this result to the whole Spanish urban system. These findings provide a basis for analyzing potential policy interventions that can help to redirect urban form and mitigate the negative consequences of the suburbanization process, such as greater resource consumption and CO_2 emissions (Glaeser and Kahn, 2010), the inefficient supply of public goods (Carruthers and Ulfarsson, 2003) or the reduction in social interaction and the increase in segregation (Glaeser and Kahn, 2004), among others.

Finally, this study is important because it provides evidence for Europe. Despite the differences between US, Chinese and European cities, our results confirm that the suburbanization process in Europe is also influenced by highways.

Conditional on controls, we estimate the relationship between the growth in population and highway improvements in two separate equations – one to study the effect on central city population decline and the other to study the effect on changes in people's intrametropolitan location patterns. In both cases, our primary identification problem is the simultaneous determination of population growth and highway improvements: planners may wish to build highways in places in which population growth is expected to be strong or, alternatively, where such prospects are poor (Baum-Snow, 2007a; Duranton and Turner, 2012). To solve this reverse causation problem we rely on historical instruments – Roman roads, 1760 main post roads, and 19th century main roads – as our sources of exogenous variation.

This study contributes to the existing literature in several ways. Our main contribution is to undertake an intrametropolitan analysis of the suburbanization process. At the municipal level and for different samples, our results show that highway improvements influence the spatial pattern of this suburbanization process by attracting population to those municipalities that have improved their access to the highway system. Furthermore, we find that the effects are heterogeneous in terms of distance to the central city (central cities vs. suburban municipalities) and in terms of distance to the highway system (linked vs. non-linked suburban municipalities).

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 (2011) provide intermetropolitan evidence for the effect of highway improvements on congestion in the US and Japan, respectively. Finally, Duranton and Turner (2012) and Holl and Viladecans-Marsal (2012) find that the stock of highways has a positive impact on urban growth in both the US and Spain. Most of these studies rely on historical instruments as sources of exogenous variation.

The remainder of the paper is structured as follows. In Section 2, we present the related theory and our empirical strategy for estimating the effects of highway improvements on suburbanization and its spatial pattern. In Section 3, we characterize suburbanization and centralization processes in Spanish cities, the Spanish highway system and its more recent improvements, and the Spanish historical roads and our selected instruments. We present the results in Section 4 and conclusions in Section 5.

2. Theory and Estimation

2.1. Theory

Transportation Improvements and Suburbanization

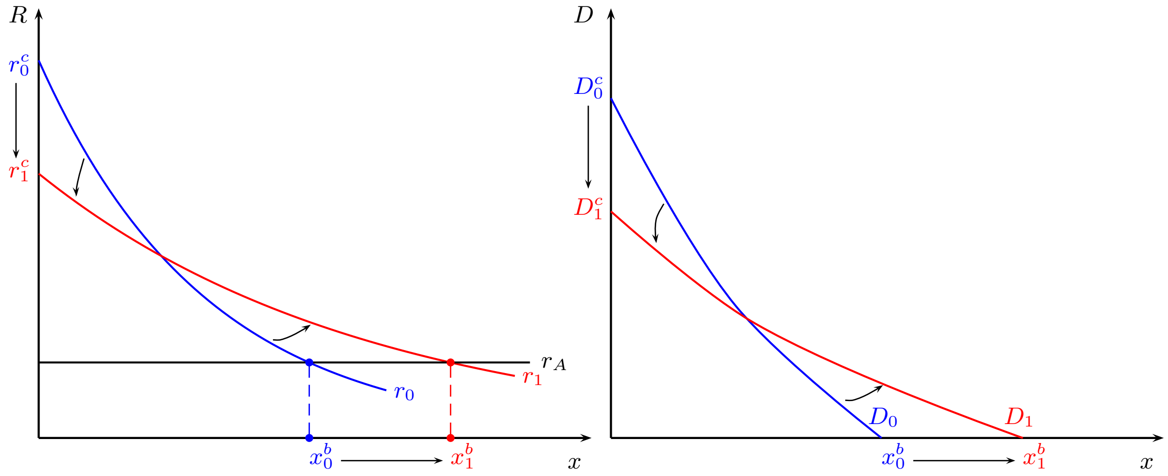
Based on the classical monocentric land use theory developed by Alonso (1964), Mills (1967) and Muth (1969), the comparative static analyses conducted by Wheaton (1974) and Brueckner (1987) show that suburbanization may be the result of transportation improvements.

Consider the *closed* city absentee landlord version of the monocentric model, in which metropolitan population size is exogenous and the level of utility is endogenous. Now consider that metropolitan population is constant. As Baum-Snow (2007b) shows, by decreasing the marginal cost of travel, more land is accessible for each given commuting distance. At the center, land rent decreases and, via a price effect, land consumption increases. Since average net income rises, land consumption also increases through a wealth effect, pushing people towards the suburbs. Both effects push some people away from the center, lowering central density. In the suburbs, the arrival of new people increases land rent and population density. Holding the agricultural land constant, the metropolitan boundary expands and the residential land area rises. In other words, when transportation improvements increase transport speed, (1) rent and density gradients flatten; (2) rent and population (density) decline at the center; and (3) rent and population (density) increase in the suburbs (Figures 1a and 1b). This spatial process is what is commonly known as suburbanization or *absolute* suburbanization.

Now consider a closed city with a simultaneous change in transportation and population. Wheaton (1974) shows that a greater metropolitan population also expands the metropolitan boundary, and raises densities everywhere in the city without changing rent and density gradients. Since metropolitan growth is also exogenous, the aforementioned transportation effect still holds. Combining both population growth and transportation effects, (1) rent and density gradient flatten; and (2) rent and density increase in the suburbs. The net effect at the center depends on the magnitude of each partial effect: (3.1) central rent and population (density) decrease when the transportation effect is greater than the population growth effect; (3.2) central rent and density increase (but less than in suburban areas) or do not vary when the transportation effect is lower or equal to the growth effect. That is, transportation improvements combined with exogenous population growth may cause the aforementioned *absolute* suburbanization process Figure 2a), in which central rent and population (density) decline at the center while they increase in suburban areas, or a *relative* suburbanization process (Figure 2b), in which central rent and population (density) increase but at lower rates than in the suburbs.

A qualifier is important here. Suburbanization may also be the result of changes in income levels. As McMillen (2006) points out, an increase in income raises the demand for land (housing), which leads people to prefer suburban areas where land rents (housing prices) are lower. However, it also increases the aversion to time spent commuting, which makes central locations more valuable. As a result, an increase in income causes suburbanization processes analogous to those described in this section when the former effect dominates. For simplicity, we have considered income levels to be constant.

Figure 1: Transportation Improvements in a *Closed* City Without Population Growth

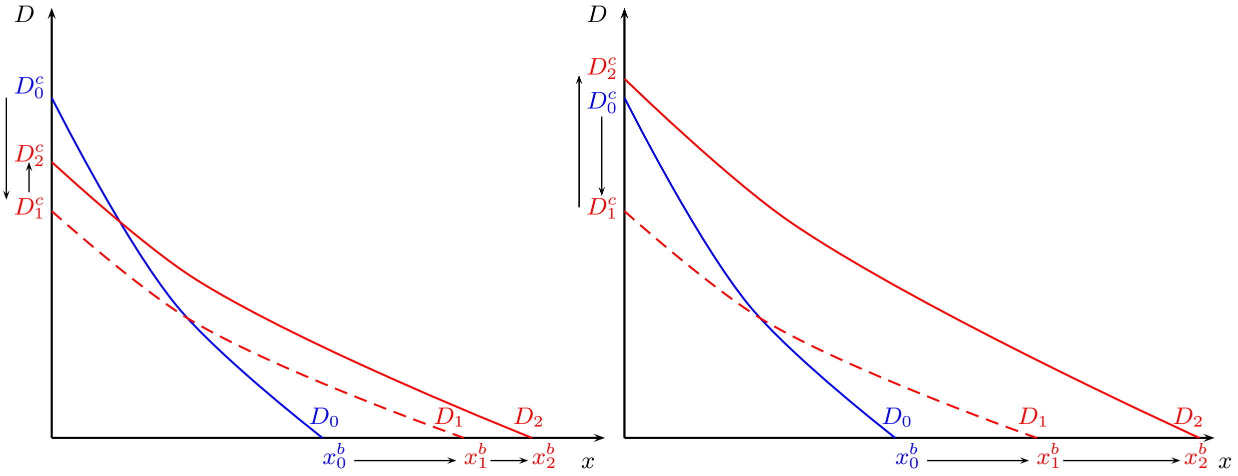


(a) Rents and Absolute Suburbanization

(b) Densities and Absolute Suburbanization

Notes: R is land rent, r_A is agricultural land rent, r_0 and r_1 are land rent functions, and r_0^c and r_1^c are land rents at the center. D is population density, D_0 and D_1 are population density functions, and D_0^c and D_1^c are population densities at the center. x is distance to central city, and x_0^b and x_1^b are metropolitan boundaries. 0 and 1 indicates initial values and values after transportation improvements, respectively.

Figure 2: Transportation Improvements in a *Closed* City With Population Growth



(a) Densities and Absolute Suburbanization

(b) Densities and Relative Suburbanization

Notes: 0, 1 and 2 indicates initial values, values after transportation improvements, and values after an increase in metropolitan population, respectively.

Highway Improvements and (the Spatial Pattern of) Suburbanization

Baum-Snow (2007b) extends the closed city version of the classical monocentric model by considering two alternative transportation infrastructures that introduce heterogeneity in transport speeds: a slower dense network of streets and a highway system based on faster sparse radial highways. The population commutes to the center (1) using the dense network of streets directly (as in the classical model), (2) using this network to access the highway system and then the center, or (3) using the nearest radial highway directly[1].

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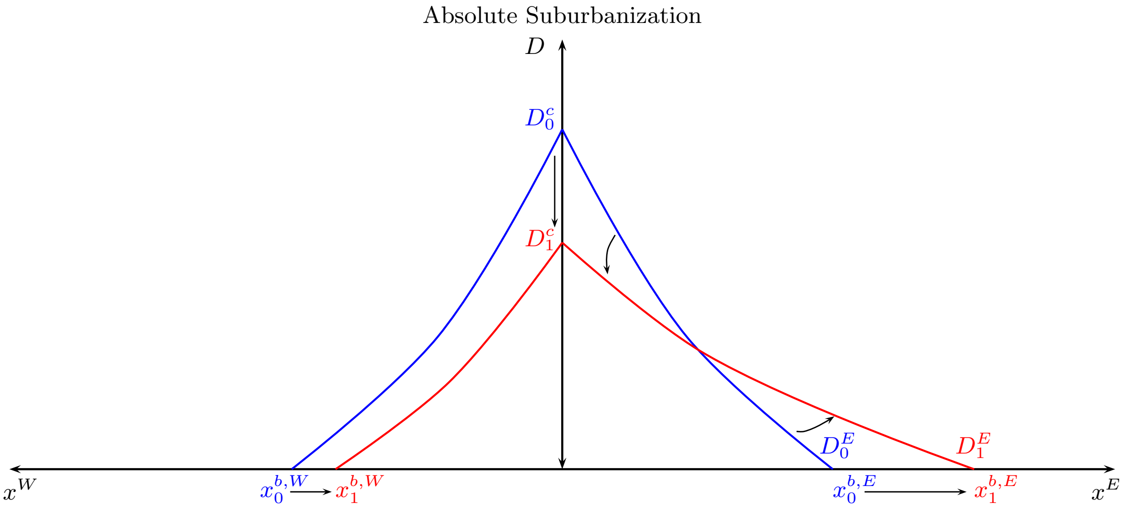
[1] Anas and Moses (1979) include a high speed transit system based on sparse radial corridors. Baum-Snow (2007b) extends their approach by allowing for different technologies to access the radial corridors from the dense network of streets.

Using comparative static analyses and simulations, Baum-Snow (2007b) confirms the aforementioned general effect on population (density) near the center: the construction of (new) highways contributes to central city population decline (Figure 3). Moreover, he also qualifies the aforementioned effect on suburban population (densities): the suburbanized population is not evenly distributed across suburbs; on the contrary, population spreads out along the (new) highways and, as a result, population (density) only increases in suburban areas near highways[2].

Figure 3: A New Highway Ray in a *Closed* City Without Population Growth


Absolute Suburbanization

Notes: E and W indicates values for the eastern and western part of the city, respectively.

2.2. Estimation

Our empirical investigation is in two parts. In the first, we investigate the effect of highway improvements on the suburbanization process of Spanish cities. In the second, we study the effect on the spatial pattern of this suburbanization process.

Econometric Strategy (I): Suburbanization and Highway Improvements

Based on Baum-Snow (2007a) and Baum-Snow et al. (2012), we study the effect of highway construction on central city population (density) decline by estimating the following first-difference equation:

$$\Delta ln(P_{it}^{cc}) = A_0 + A_1 \Delta hwy_{it} + A_2 \Delta X_{it}^{cc} + A_3 \Delta X_{it} + \epsilon_{it} \tag{1}$$

where $\Delta ln(P_{it}^{cc}) = ln(P_{it}^{cc}) - ln(P_{it-1}^{cc})$ measures central city population (density) growth between t and *t-1* for metropolitan area i. X_{it}^{cc} and X_{it} are vectors of observed central city and metropolitan characteristics, respectively. Since some of them are time-invariant (e.g., geography), we include them in levels. ϵ is the error term.

Δhwy_{it} measures highway improvements between t and *t-1*. Depending on the specification, we consider three types of improvement: changes in the number of rays of *central city* highways, changes in the length (kilometers) of *metropolitan* highways, and changes in the length (kilometers) of *suburban* highways. Following Baum-Snow (2007a), we use "changes in rays" to estimate the effect of central city highway penetration. Following Baum-Snow et al. (2012), we use "changes in metropolitan kilometers" and "changes in suburban kilometers" to control that these improvements are not driving highway-penetration effects.

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[2] Baum-Snow (2007b) also studies the effects on metropolitan boundaries and on size: (1) Since metropolitan population is constant, boundaries shrink in suburban areas that do not use the new highway, while they increase in suburban areas close to the new highway; (2) the overall residential land area increases.

Econometric Strategy (II): The Spatial Pattern of Suburbanization and Highway Improvements

The second part of the empirical investigation is our main contribution. To study the effect of highway construction on changes in the intrametropolitan pattern of residential location of Spanish cities, we estimate the first-difference equation of a linearized negative exponential density function derived from a quasilinear utility:

$$\Delta ln(P_{jit}) = B_0 + B_1 \Delta d_{hwy,jit} + B_2 \Delta X_{jt} + \eta_{it} \tag{2}$$

where $\Delta ln(P_{jit}) = ln(P_{jit}) - ln(P_{jit-1})$ measures population (density) growth between t and *t-1* for municipality j that belongs to metropolitan area i. X_{jt} denotes a vector of observed municipality characteristics. Since some of these are time-invariant (e.g., geography, history), we include them in levels. This vector also includes some $t-1$ characteristics (e.g., initial population, socioeconomic variables). By so doing, we account for the possibility that initial municipal conditions may determine population (density) growth and correlate with highway improvements. Finally, we include metropolitan area fixed-effects to control for shocks that are common to all municipalities within a metropolitan area.

$\Delta d_{hwy,jit}$ are the changes in distance to the nearest highway ramp in municipality j and measure highway improvements between t and *t-1*. Following Garcia-López (2012), we use this variable to estimate the effect of proximity to highway improvements. That is, we investigate whether population spreads out along new highways and increases in municipalities that have improved access to the highway system.

Identification Issues

Under the assumption that the random element of population (density) growth is uncorrelated with highways, we can estimate Eq. ((1) and Eq. (2) by ordinary least squares (OLS). However, as Baum-Snow (2007a), Baum-Snow et al. (2012), 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 (density) growth. For the case of highway improvements, 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 resolve this problem, we rely on instrumental variables estimation and model highway improvements explicitly in Eq. (3) and Eq. (4):

$$\begin{aligned} \Delta hwy_{it} &= C_0 + C_1 \Delta X_{it}^{cc} + C_2 \Delta X_{it} + C_3 Z_{it} + \mu_{it} \\ \Delta ln(P_{it}^{cc}) &= A_0 + A_1 \widehat{\Delta hwy_{it}} + A_2 \Delta X_{it}^{cc} + A_3 \Delta X_{it} + \epsilon_{it} \end{aligned} \tag{3}$$

$$\begin{aligned} \Delta d_{hwy,jit} &= D_0 + D_1 \Delta X_{jt} + D_2 Z_{it}^{d} + \nu_{it} \\ \Delta ln(P_{jit}) &= B_0 + B_1 \widehat{\Delta d_{hwy,jit}} + B_2 \Delta X_{jt} + \eta_{it} \end{aligned} \tag{4}$$

where $\widehat{\Delta hwy_{it}}$ are predicted changes in highways (i.e., rays, length) and $\widehat{\Delta d_{hwy,jit}}$ are predicted changes in distance to the nearest highway ramp, both estimated in the first-stage. Z_{it} and Z_{it}^{d} are the exogenous instruments which, conditional on controls, predict our endogenous variables and being otherwise uncorrelated with population (density) growth. That is, instruments have to satisfy the relevance,$C_3 \neq 0$ and $D_2 \neq 0$, and the exogeneity, $C_3 \neq 0$ and $D_2 \neq 0$, conditions.

3. Data

Spain is a convenient case study for three reasons. First, Spanish cities are undergoing four spatial processes that are changing their urban spatial structure. More specifically, some cities are experiencing a decline in their central city population (absolute suburbanization), while others are seeing their central city population rise, but at a slower rate than that of their suburbs (relative suburbanization). Furthermore, population centralization is also an ongoing phenomenon in a third of Spanish cities: most of them are experiencing relative centralization (with their population growing at higher rates in central cities), and only a few of them are experiencing absolute centralization (population growing in the central city and decreasing in the suburbs).

Second, the country's overall population has grown from 39.4 million to 47.1 million between 1991 and 2011. Almost all this growth occurred in the last decade as a result of international immigration flows. Furthermore, most growth took place in cities and fostered relative suburbanization processes.

Finally, the main transportation infrastructure of most Spanish cities is based on a highway system, while railroad lines only link these cities via long-distance services[3]. The main improvements to the transportation infrastructure have been undertaken on the highway system, which was extended by about 10,000 km over this 20-year period.

3.1. Population in Spain: Urban Growth and Suburbanization

Spain has more than 8,100 municipalities serving as separate political and administrative units. Except for the largest metropolitan areas, there is no strict administrative definition of a metropolitan area in Spain. Recently Ruiz (2010) defines what he terms *urban areas* by combining land use continuity and commuting criteria at the municipal level. As in Holl and Viladecans-Marsal (2012), here we consider the largest 129 of these and exclude one of them because its central city had fewer than 20,000 inhabitants in 1991, three because they do not include a suburban municipality, and two because they presented no employment information for 1991. As a result, our sample comprises 123 *metropolitan areas* made up of 1,300 municipalities: 123 central cities (of at least 20,000 people) and 1,177 suburban municipalities. These metropolitan areas (MAs) accounted for almost 70% of the Spanish population in 2011 (Table 1). In Appendix A Table A.1 reports summary statistics for our main variables in Eq. (3) and (4).

We use population data from the 1991 and 2001 Population Censuses and from the 2011 Municipal Register, all produced by the National Statistics Institute of Spain. According to Eq. (3) and (4), we construct our two dependent variables as the 1991–2011 changes in log central city population, $\Delta ln(P^{CC}_{1991-2011}) = ln(P^{CC}_{2011}) - ln(P^{CC}_{1991})$, and the 1991–2011 changes in log population, $\Delta ln(P_{1991-2011}) = ln(P_{2011}) - ln(P_{1991})$. Since municipal land area did not change during this time period, these variables can also be interpreted in terms of population density growth.

Table 1 documents the evolution of Spanish population between 1991 and 2011. Specifically, Panel A presents trends in aggregate population growth in our selected 123 MAs and their central cities and suburban municipalities (suburbs). As discussed above, most of the growth in Spain took place in our MAs, which grew 24%. This urban growth was not homogeneous over the 20-year period. On the contrary, it concentrated in the last decade (17%), while the population only grew by 7% between 1991 and 2001. Furthermore, the factors that influenced growth also differed between the two subperiods: while the 1991–2001 growth was related to rural-urban migration, the 2001–2011 growth was the result of international migration flows from Latin America, Eastern Europe and North Africa.

At the intrametropolitan level, the population is highly centralized: central cities accounted for 68% of the metropolitan population in 1991. However, Table 1 also shows major changes in residential location patterns between 1991 and 2011: most population growth took place in the suburbs, which grew 46%, while the central cities only grew 14%. Influenced by the international immigration flows, a *relative* suburbanization process was fostered during the 2001–2011 period.

Despite these average counts, Panel B shows that there were cities that indeed experienced processes of *absolute* suburbanization. Some of them even experienced both suburbanization processes. This is case of Spain's two largest cities, Barcelona and Madrid: while they lost central population between 1991 and 2001, both cities recorded population gains between 2001 and 2011 as a result of their role as ports of entry for immigrants. At the end of the 20-year period, Barcelona had lost 29,000 inhabitants and Madrid had gained 255,000 inhabitants.

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[3] Only some of the largest Spanish cities have a railroad network that connects the central city with other metropolitan municipalities. See Garcia-López (2012) for the Barcelona case.

Finally, it is important to note that 30% of our MAs underwent processes of population centralization in which the share of metropolitan population located in their central cities increased. Most of these central cities gained population due to rural and intermetropolitan migratory flows that also benefited their suburbs, but at lower rates (relative centralization). Only a few of them attracted population from their own suburbs (absolute centralization).

Table 1: Population Growth and Suburbanization in Spain, 1991–2011

Panel A:	**Population and its growth**					
	1991	2001	2011	1991–2001	2001–2011	1991–2011
Spain	39,434	41,117	47,190	1,683 (4%)	6,073 (15%)	7,756 (20%)
Metropolitan areas	25,577	27,253	31,751	1,676 (7%)	4,498 (17%)	6,174 (24%)
Central cities	17,341	17,695	19,693	354 (2%)	1,998 (11%)	2,352 (14%)
Suburbs	8,236	9,558	12,058	1,322 (16%)	2,499 (26%)	3,822 (46%)

Panel B:	**Suburbanization and centralization**		
	1991–2001	2001–2011	1991–2011
Absolute suburbanization			
Number of central cities	28	11	16
ΔPopulation	-385	-33	-176
Top 5 cities	Barcelona, Madrid Cádiz, Bilbao, Granada	Cádiz, Ferrol Mieres, Valladolid, Basauri	Cádiz, Barcelona Valladolid, Bilbao, Granada
Relative suburbanization			
Number of central cities	58	77	70
ΔPopulation	425	1629	1803
Top 5 cities	Murcia, Colmenar Collado, Zaragoza, Alacant	Madrid, Barcelona Murcia, Zaragoza, Valencia	Madrid, Murcia Zaragoza, Alacant, Marbella
Absolute centralization			
Number of central cities	10	4	7
ΔPopulation	51	11	35
Top 5 cities	Gijón, Lugo Teruel, Durango, Puertollano	Gijón, Lugo Barakaldo, Puertollano, Durango	Gijón, Lugo Teruel, Durango, Puertollano
Relative centralization			
Number of central cities	27	31	30
ΔPopulation	263	390	691
Top 5 cities	Fuenlabrada, Torrevieja Dos Hermanas, Roquetas, Albacete	Terrassa, Roquetas Orihuela, Mijas, Ejido	Torrevieja, Roquetas Terrassa, Dos Hermanas, Mijas

Notes: Absolute values are thousands of inhabitants.

3.2. Highways in Spain: Improvements and Historical Roads

Our main explanatory variables include several measures of highway improvements. In Eq. (3) we follow Baum-Snow (2007a) and Baum-Snow et al. (2012) and use the 1991–2006 changes in the number of rays[4] of central city highways. In some regressions we also use the 1991–2006 changes in highway length (kilometers). In Eq. (4) we follow Garcia-López (2012) and use the 1991–2006 changes in distance to the nearest highway ramp.

To calculate these variables, we create digital vector maps with polylines (highway segments) and points (ramps) based on information collected from the Ministry of Public Works and described in more detail in Holl (2007, 2011). Using GIS software, we compute the number of rays, the length of highways (km), and the straight-line distance (km) between each municipal centroid and the nearest highway ramp in 1991 and 2006. For descriptive purposes we also compute the 2001 distance.

The Spanish Highway System

Although the first highways in Spain were built during the 1960s when the country underwent considerable economic growth, the crisis of the following decade brought their construction to a halt. At the beginning of the 1980s, Spain had roughly 2,000 km of highways, concentrated mostly in the north-east and along the Mediterranean coastal corridors. Most major MAs were not linked by highway and the main road network was unable to accommodate the rise in car ownership and traffic (Holl, 2011).

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[4] We define rays as in Baum-Snow (2007a), i.e., limited access highways connecting central cities to the suburbs (and serving a significant part of them).

The 1984–1991 National Road Plan involved upgrading approximately 3,250 km of main itineraries, including the six radial routes emanating from the capital city of Madrid, to toll-free highways. Overall, the proposed highways closely followed the radial outline of the road network that can be dated back to the 18th century. 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. In 1993, the 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. In 2000, the 2000–2007 Infrastructure Plan sought to extend the highway system to 13,000 km by 2010. The current 2005–2020 Strategic Plan for Infrastructures and Transportation also includes more than 5,000 km of new highways[5].

Today, the Spanish highway system comprises more than 11,000 kilometers of toll-free highways and over 3,000 kilometers of toll highways (Holl, 2011). We center our analysis on the 1991–2006 period because the main and most intensive highway improvements were made in this 15-year period – 7,638 km of highways were built in Spain, with approximately 35% of them being located in our sample of 123 MAs (Table 2).

Table 2: The Construction of the Spanish Highway System, 1991–2006

Panel A:	**Kilometers of highways**					
	1991	2001	2006	1991–2001	2001–2006	1991–2006
Spain	4,435	9,571	12,073	5.136 (116%)	2,502 (26%)	7,638 (172%)
Metropolitan areas	2,909	4,480	5,553	1.571 (54%)	1,073 (24%)	2,644 (91%)
Central cities	1,228	1,940	2,359	712 (58%)	419 (22%)	1,131 (92%)
Suburbs	1,681	2,540	3,194	859 (51%)	654 (26%)	1,513 (90%)

Panel B:	**Rays and distance to ramps**		
	1991	2001	2006
Highway ramps			
Central cities with rays	62	86	99
Number of Rays	156	239	290
Top 5 cities	Barcelona, Madrid Valencia, Bilbao, Sevilla	Madrid, Valencia Barcelona, Sevilla, Bilbao	Madrid, Valencia Barcelona, Sevilla, Murcia
Average distance to the nearest ramp (km)			
Metropolitan areas	17.27	7.22	5.28
Central cities	20.31	7.66	5.04
Suburbs	16.95	7.18	5.30

At the intrametropolitan level, highways penetrated deeper in both central cities and suburbs. Inside central cities, highways were extended with the construction of 134 new rays amounting to 1,131 km. Furthermore, the number of central cities with rays increased from 62 in 1991 to 99 in 2006. In the suburbs, the highway network was almost doubled with 1,513 kilometers of new highways.

As a result of this highway construction, the municipalities belonging to our MAs improved their access to the highway system. During the 15-year period, the distance from the municipality centroid to the nearest highway ramp fell by 12.0 km for the sample of MAs, by 15.3 km in central cities, and by 11.7 km in the suburbs. Finally, it should be stressed that most of the distance reduction took place in the 1991–2001 period.

Historical Roads as Instruments

In common with most European countries, the origins of the Spanish transportation infrastructure can be traced to the Roman roads. Although earlier roads had been built, the Romans were the first to develop a sophisticated system of paved and crowned roads. Initially, they were built to promote Rome's military goals: first, in the conquest of Hispania and, later, in its defense. These strategic roads passed through mountains and avoided valleys. During the Pax Romana some of

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[5] Besides these national plans, the regional governments also implemented their own plans. National plans focused on linking the largest Spanish cities and relieving the traffic situations of the most congested corridors (Holl, 2011). Regional plans centered on connecting cities inside their territory in order to improve levels of accessibility (Garcia-López, 2012).

the military roads were abandoned, while others were modified as engineers found less steep and faster routes. New roads were also built in order to improve the accessibility of Hispania. The resulting road system (Figure 4) formed a decentralized mesh-like network that allowed Hispania to expand its administrative and commercial relations with the rest of the Empire (Garcia-López, 2012).

A major overhaul of the transportation system was undertaken during the 18th century. In 1700, the Bourbon dynasty came to power in Spain, succeeding the Habsburgs, and the new monarch, Philip V, changed Spain's political system from a federation of kingdoms to that of an absolutist state as all political power became centralized in the capital. Adopting the Paris city model, the new road network funded by the crown was designed to turn the city of Madrid into the new geographical center of Spain (Figure 5): 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 newly unified kingdom (Menéndez-Pidal, 1992; Bel, 2011; Garcia-López, 2012).

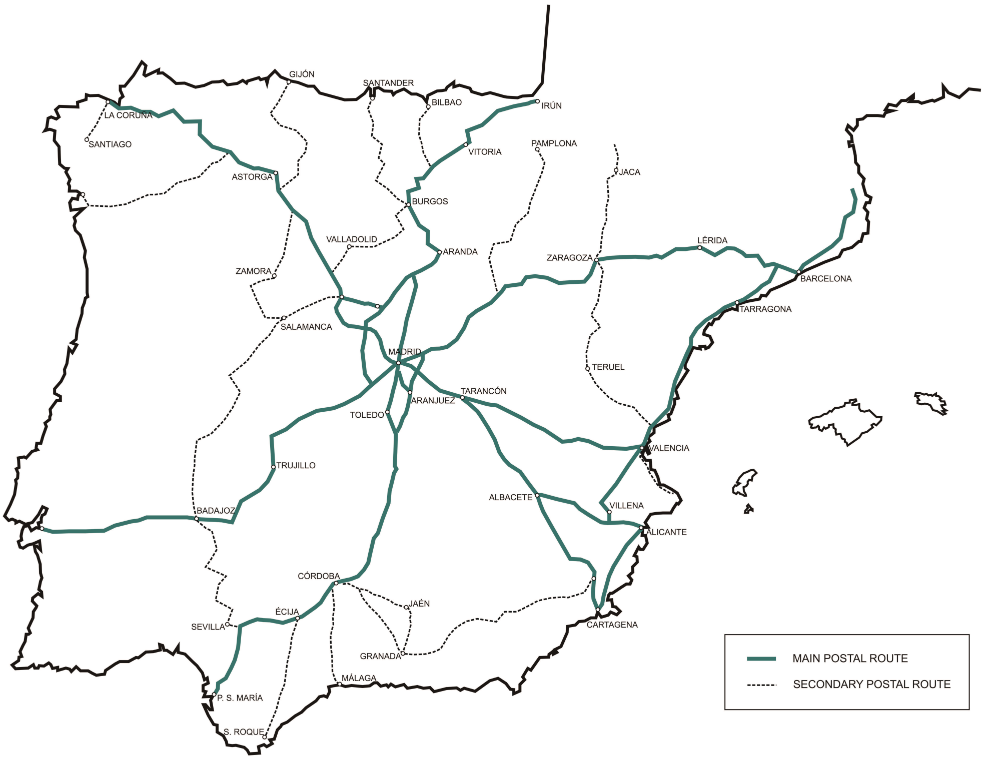
Land transportation and its corresponding infrastructure were radically changed with the development of the internal combustion engine and its use in the automobile. During the late 19th century, existing roads were improved and new roads were designed in keeping with the radial system of the 18th century (Figure 6) (Garcia-López, 2012).

In the spirit of Duranton and Turner (2011, 2012), Holl and Viladecans-Marsal (2012), Hsu and Zhang (2011), Baum-Snow et al. (2012), and Garcia-López (2012), we use these three historical networks to construct our candidates for use as instruments. In Eq. (3) our candidates are the number of rays associated with each historical road. In Eq. (4) we use the straight-line distances in kilometers from each municipal centroid to the nearest segment of each historical road. In these computations, we use digital vector maps based on Carreras and de Soto (2010) (Roman roads, 19th century main roads), and Holl (2011, 2012) (1760 main post roads).

Figure 4: Roman Roads in Spain

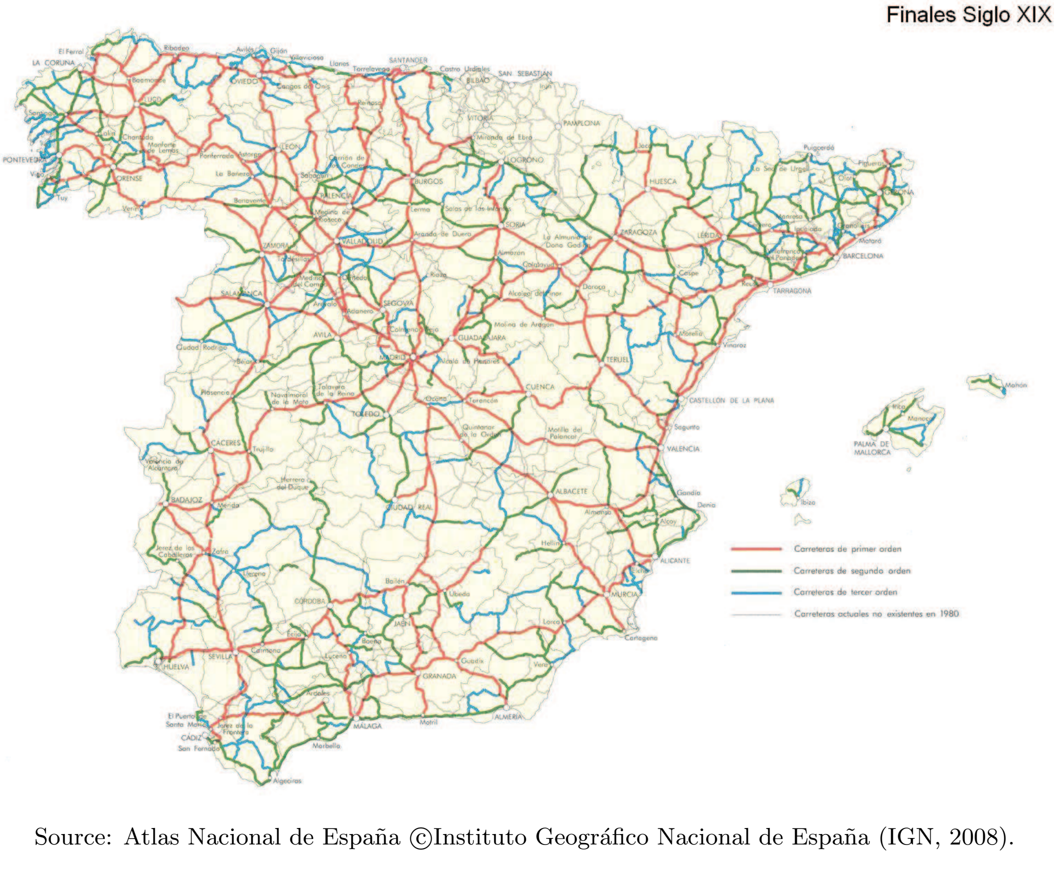
Source: Atlas Nacional de España ©Instituto Geográfico Nacional de España (IGN, 2008).

Figure 5: 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.

Figure 6: 19th Century Main Roads in Spain



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

Our instruments need to be exogenous. And in this respect, historical roads are exogenous because of the length of time that has passed since they were built and the significant changes undergone by society and the economy in the intervening years. More specifically, it is self-evident that Roman roads were not built to anticipate the current process of suburbanization in Spain's MAs. As discussed above, they satisfied military, administrative, and commercial objectives. In the case of the other two historical networks, Bel (2011) claims that Spain's transportation infrastructure, designed after the 18th century, served as a central government instrument for nation building and was not motivated by the requirements of the economic system. These claims should, however, be qualified. Since all three networks were not randomly located and given that some of the factors that influenced their location may also have influenced improvements to modern transportation systems, instrument exogeneity hinges on having at our disposal an appropriate set of controls - above all, for Spain's physical geography and its historical demographic behavior.

Our candidates also need to be relevant. Common sense suggests that modern highways are not built in isolation of existing historical road networks. On the contrary, modern highways are more easily and cheaply built if they adhere to the existing infrastructure (Duranton and Turner, 2012). However, it might also be the case that modern and historical networks do not coincide because of differences in the reasons that motivated their construction (economic vs. political decisions) (Garcia-López, 2012). Furthermore, historical networks might not be sufficiently extensive to allow modern infrastructure to be predicted statistically (Baum-Snow et al., 2012). To test the relevance of our candidate instruments econometrically, we run regressions predicting modern highways as a function of all three historical roads.

Columns 1-3 in Table 3 present OLS regressions predicting the length (kilometers) of MA highways in 2006 as a function of the length (kilometers) of Roman roads, 1760 main post roads and 19th century main roads, and other controls. Column 1 includes just our three historical roads, their coefficients all being significant and presenting the expected positive sign. These unconditional results indicate that historical roads do indeed shape modern highways. As we gradually add controls for physical geography[6] (column 2) and 2006 MA population (column 3) only the coefficient for the 1760 main post roads remains significant.

Table 3: Metropolitan Highways and Historical Roads

	Ordinary least squares (OLS)					
Dependent variable:	Kilometers of metropolitan highways in 2006			1991–2006 ΔKilometers of highways		
	[1]	[2]	[3]	[4]	[5]	[6]
Kilometers of Roman roads	0.312^c (0.158)	0.158 (0.162)	0.033 (0.147)	0.142 (0.121)	0.066 (0.125)	0.036 (0.147)
Kilometers of 1760 main post roads	1.131^c (0.541)	1.190^c (0.572)	0.836^b (0.283)	0.438^c (0.252)	0.464^c (0.265)	0.371^c (0.174)
Kilometers of 19th c. main roads	0.241^c (0.134)	0.378^b (0.153)	0.077 (0.101)	0.135 (0.102)	0.172 (0.109)	0.084 (0.117)
ln(Central city land area)	N	Y	Y	N	Y	Y
ln(MA land area)	N	Y	Y	N	Y	Y
Geography	N	Y	Y	N	Y	Y
ln(2006 MA population)	N	N	Y	N	N	N
1991–2011 Δln(MA population)	N	N	N	N	N	Y
ln(1991 MA population)	N	N	N	N	N	Y
Adjusted R^2	0.45	0.48	0.77	0.33	0.35	0.45

Notes: 123 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. Robust standard errors are clustered by region of the MA central city and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

In columns 4-6, we estimate the effect of the length (kilometers) of historical roads on the change in the number of kilometers of MA highways from 1991 to 2006. We first include our

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[6] We use GIS software to compute/obtain most of our control variables: land area, longitude and latitude coordinates, straight-line distance to coast, and straight-line distance to central city. We also compute altitude, the elevation range and the terrain ruggedness index developed by Riley et al. (1999) using the Spanish 200-meter digital elevation model (`http://www.ign.es/ign/layoutIn/modeloDigitalTerreno.do`). These variables are the average values for each municipality and MA.

three candidates (column 4) and we gradually augment the regression with further controls for physical geography (column 5) and the 1991–2011 population growth[7] (column 6). Unconditional and conditional results indicate that the length of the 1760 network predicts changes in the length of modern highways.

Table 4 presents OLS regressions predicting the number of rays of central city highways in 2006 (columns 1-3) and the change in the number of rays of central city highways from 1991 to 2006 (columns 4-6)[8] as a function of the number of central city rays of Roman roads, 1760 main post roads and 19th century main roads, and other controls. The format of the table is similar to that employed in Table 3. Columns 1 and 4 only include our three candidate instruments and then we gradually add controls for physical geography (columns 2 and 5), and 2006 MA population (column 3) and 1991–2011 population growth (column 6). The results indicate that only the number of rays of the 19th century main roads predicts changes in the number of modern central city rays.

Table 4: Central City Highways and Historical Roads

	Ordinary least squares (OLS)					
Dependent variable:	Rays of central city highways in 2006			1991–2006 ΔRays of central city highways		
	[1]	[2]	[3]	[4]	[5]	[6]
Rays of Roman roads	0.073	0.073	0.047	0.034	0.039	0.039
	(0.128)	(0.118)	(0.095)	(0.097)	(0.113)	(0.119)
Rays of 1760 main post roads	0.483^b	0.555^a	0.393^a	-0.022	0.016	0.001
	(0.194)	(0.172)	(0.097)	(0.102)	(0.097)	(0.077)
Rays of 19th c. main roads	0.265^b	0.442^a	0.271^a	0.158^c	0.196^b	0.180^b
	(0.097)	(0.093)	(0.062)	(0.092)	(0.077)	(0.081)
ln(Central City land area)	N	Y	Y	N	Y	Y
ln(MA land area)	N	Y	Y	N	Y	Y
Geography	N	Y	Y	N	Y	Y
ln(2006 MA population)	N	N	Y	N	N	N
1991–2011 Δln(MA population)	N	N	N	N	N	Y
ln(1991 MA population)	N	N	N	N	N	Y
Adjusted R^2	0.24	0.35	0.62	0.05	0.20	0.20

Notes: 123 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. Robust standard errors are clustered by region of the MA central city and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Finally, we test whether the location of these historical roads affects the location of the modern highways (Table 5). In columns 1-3, we estimate the effect of municipality proximity to historical roads on the municipality proximity to the nearest highway ramp in 2006. Column 1 only includes the distances to the nearest Roman road, the nearest 1760 main post road, and the nearest 19th century main road. Column 2 adds controls for municipality land area, distance to the central city, and physical geography. Column 3 augments the regression with past population levels every 10 years from 1900 to 1991[9]. The results indicate that only the distances to the 1760 main post road and to the 19th century main road predict the distance to the modern highways, i.e., modern highways are located close to these historical roads.

In columns 4-6 of Table 5, we estimate the effect of these distances to the three historical roads on the changes in distance to the nearest highway ramp from 1991 to 2006. As in Table 4, we first include the three historical distances and then we gradually add controls for land area, distance to central city and physical geography (column 5), and past populations and 1991 socioeconomic characteristics[10] (column 6). The results show that only distance to the nearest 1760 main post road is relevant, i.e., modern highways have been improved at some distance from the routes taken

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[7] We include 1991–2011 changes in log MA population because columns 4-6 are the results of first-stage estimates of Eq. (3) when highway improvements are measured as changes in the length (kilometers) of highways.

[8] These are the results of first-stage estimates of Eq. (3) when highway improvements are measured as changes in the number of central city rays.

[9] Past populations are drawn from the 1900, 1910, 1920, 1930, 1940, 1950, 1960, 1970, and 1981 Population Censuses produced by the National Statistics Institute of Spain (`http://www.ine.es`).

[10] 1991 socioeconomic variables are computed using information from the 1991 Population Census.

by the 1760 main post roads.

Table 5: Intrametropolitan Location of Modern Highways and Historical Roads

	Ordinary least squares (OLS)					
Dependent variable:	Distance to the nearest ramp in 2006			1991–2006 ΔDistance to the nearest ramp		
	[1]	[2]	[3]	[4]	[5]	[6]
Distance to the nearest Roman road	0.006	-0.001	0.000	-0.001	-0.003	0.003
	(0.007)	(0.007)	(0.007)	(0.006)	(0.007)	(0.010)
Distance to the nearest 1760 main post road	0.105^{a}	0.069^{a}	0.075^{a}	-0.160^{a}	-0.165^{a}	-0.163^{a}
	(0.028)	(0.026)	(0.024)	(0.032)	(0.031)	(0.031)
Distance to the nearest 19th c. main road	0.167^{a}	0.169^{a}	0.168^{a}	0.039	0.024	0.015
	(0.032)	(0.033)	(0.032)	(0.029)	(0.030)	(0.032)
ln(Land area)	N	Y	Y	N	Y	Y
Distance to central city	N	Y	Y	N	Y	Y
Geography	N	Y	Y	N	Y	Y
ln(Populations)	N	N	Y	N	N	Y
1991 Socioeconomic controls	N	N	N	N	N	Y
Adjusted R^2	0.91	0.92	0.93	0.99	0.99	0.99

Notes: 1300 observations for each regression (123 are central cities and 1177 are suburban municipalities). All regressions include MA fixed effects. Geography variables include distance to coast, altitude, index of terrain ruggedness, latitude, and longitude. Socioeconomic controls include unemployment and employment rates, share of manufacturing population, share of population over 25 years old, share of population with university degree, and share of foreign-born population. Population variables include contemporaneous population and levels of population every 10 years from 1900 to 1991. Regressions are weighted by 2006 population (columns 1-3) and 1991 population (columns 4-6). Analogous unweighted regressions produce historical distance coefficients that are larger in absolute value. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

4. Results

4.1. Suburbanization and Highway Improvements

As discussed in Section 2.2, we first study the effect of highway construction on the growth in central city population (density). Our unit of observation is a central city $_{i}^{cc}$ that belongs to metropolitan area i.

Highway Rays in Central Cities

Table 6 presents ordinary least squares (OLS) and two-stage least squares (TSLS) estimates for Eq. (3). In columns 1 and 6, we estimate the effect of the 1991–2006 changes in the number of central city rays on the changes in log central city population (density) between 1991 and 2011. Columns 2 and 7 add controls for central city and MA land area and other additional geography variables. Columns 3 and 8 augment the regression with MA population growth and initial MA population. Since an increase in income may also cause suburbanization, columns 4 and 9 add the growth of MA simulated income computed *à la* Baum-Snow (2007a), i.e., interacting 1991 shares of sectoral employment in the MA and the national salary growth rate of each sector[11]. In columns 5 and 10 we repeat the same regression as in column 8 but excluding the physical geography controls. By so doing, this specification is closer to Baum-Snow (2007a)'s preferred specification. Based on the first-stage results in Table 4 columns 4-6, TSLS regressions use the number of rays of central city 19th century main roads as an instrument for 1991–2006 changes in central city highway rays. We report first-stage F-statistics for the selected instrument.

Estimated OLS coefficients (columns 1-5) on highway rays are negative, but near 0, and mostly insignificant. We restrict our attention to significant results only. For our preferred OLS specification in column 3, each additional ray causes a 1.5% decline in central city population. For Baum-Snow (2007a)'s specification (column 5), from which we exclude the additional geography variables, the estimated coefficient is slightly lower at -0.012.

Estimated TSLS coefficients (columns 6-10) on highway rays differ from their OLS counterparts in magnitude and significance. The unconditional estimate in column 6 shows an (insignificant) 9% reduction. This coefficient becomes significant when controlling for geography (column 7).

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[11] National growth rates are computed using national average salaries by one-digit industry excluding the regions that encompass each MA. Salary data are taken from the 1995 and 2006 Salary Structure Survey.

When we add controls for MA population growth and initial MA population (column 8), the absolute value of the coefficient is reduced to 5%. In column 9, the inclusion of simulated MA income growth, which is insignificant[12], slightly reduces this estimate to 4.7%. The exclusion of additional geography variables (column 10) increases the absolute value of this estimate to 12.6%.

Based on the significance of the explanatory variables and first-stage F-statistics, we select the specification in column 8 as our preferred specification. Compared to the specification *à la* Baum-Snow (2007a) in column 10, our preferred specification passes the weak instrument test. Compared to the specification in column 7, specification 8 includes relevant explanatory variables that are significant. We do not select specification 9 because simulated MA income growth is insignificant and the coefficients are very similar to those of our preferred specification.

Table 6: Central City Population Decline and Highway Improvements: Rays

Dependent variable:	1991–2011 Δln(Central city population (density))									
	Ordinary least squares (OLS)					Two-stage least squares (TSLS)				
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
1991–2006 ΔCentral city rays	0.013	-0.030	-0.015^{c}	-0.012	-0.012^{c}	-0.091	-0.098^{c}	-0.050^{a}	-0.047^{a}	-0.126^{c}
	(0.025)	(0.018)	(0.007)	(0.009)	(0.006)	(0.126)	(0.058)	(0.015)	(0.017)	(0.070)
ln(Central city land area)		0.033	0.053^{a}	0.059^{a}	0.062^{a}		0.047	0.061^{a}	0.063^{a}	0.110^{a}
		(0.036)	(0.010)	(0.009)	(0.010)		(0.037)	(0.011)	(0.009)	(0.030)
ln(MA land area)		-0.214^{b}	-0.066^{b}	-0.072^{a}	-0.086^{a}		-0.226^{a}	-0.078^{a}	-0.080^{a}	-0.131^{a}
		(0.076)	(0.023)	(0.023)	(0.016)		(0.072)	(0.021)	(0.020)	(0.034)
1991–2011 Δln(MA population)			0.982^{a}	0.977^{a}	0.965^{a}			0.976^{a}	0.974^{a}	1.024^{a}
			(0.085)	(0.085)	(0.064)			(0.081)	(0.081)	(0.123)
ln(1991 MA population)			-0.025^{b}	-0.021^{c}	-0.024^{a}			-0.018^{a}	-0.016^{b}	0.007
			(0.010)	(0.010)	(0.008)			(0.006)	(0.007)	(0.026)
1991–2006 Δln(MA simulated income)				1.075					0.477	
				(0.688)					(0.642)	
Geography	N	Y	Y	Y	N	N	Y	Y	Y	N
Adjusted R^2	0.01	0.29	0.88	0.88	0.88					
Kleibergen-Paap first-stage statistic						9.40	11.45	9.72	11.38	2.42

Notes: 123 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. Based on first-stage results in Table 4 columns 4-6, TSLS regressions use the number of rays of central city 19th c. main roads as instrument for 1991–2006 changes in central city highway rays. Robust standard errors are clustered by region of the MA central city and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

To sum up, our preferred TSLS specification in column 8 gives a value of -0.050 for the parameter of highway improvements in Eq. (3). This value implies that each additional highway ray built between 1991 and 2006 led to a 5 per cent decline in central city population between 1991 and 2011. The difference between this value and its OLS counterpart (-0.015) suggests that the 1991–2006 construction of highway rays was endogenous. As in the US (Baum-Snow, 2007a; Duranton and Turner, 2012) and China (Baum-Snow et al., 2012), more highways have been built in Spain's central cities that present rapidly growing populations (Holl and Viladecans-Marsal, 2012) and, at the same time, these highways cause the population to suburbanize[13].

Metropolitan and Suburban Highway Length

Following Baum-Snow et al. (2012), we are concerned that our results are driven by the construction of highways in our MAs and, in particular, in their suburbs. Table 7 presents TSLS estimates for our preferred specification using the 1991–2006 changes in highway kilometers as the explanatory variable. In columns 1 and 2, we consider all metropolitan highways. Columns 3 and 4 consider only suburban sections of these highways. Columns 2 and 4 also add changes in highway rays. Table 7 also reports individual Angrist-Pischke and global Kleibergen-Paap first-stage F-statistics for our selected instruments. Based on the first-stage results in Table 3 columns 4-6, the length (kilometers) of the 1760 main post roads instruments for changes in highway kilometers. As in Table 6, the number of rays of central city 19th century main roads instruments

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[12] Since we use simulated incomes to account for the potential endogeneity, this result shows that income growth did not cause suburbanization in Spain. Baum-Snow (2007b) finds a similar result in the US.

[13] Control variables also affected this spatial process. More spacious central cities with more rapidly growing MA populations grew more quickly. Central cities of MA with more land and larger 1991 populations grew more slowly.

for changes in central city highway rays.

Table 7: Central City Population Decline and Highway Improvements: Length

Dependent variable:	1991–2011 Δln(Central city population (density))			
	Two-stage least squares (TSLS)			
	[1]	[2]	[3]	[4]
1991–2006 ΔCentral city rays		-0.056^{a} (0.017)		-0.047^{b} (0.023)
1991–2006 ΔKilometers of metropolitan highways	0.001 (0.001)	0.001 (0.001)		
1991–2006 ΔKilometers of suburban highways			0.002 (0.002)	0.001 (0.002)
Angrist-Pischke first-stage statistic ΔRays		7.94		9.47
Angrist-Pischke first-stage statistic ΔKilometers		8.43		9.86
Kleibergen-Paap first-stage statistic	10.32	4.36	9.24	2.41

Notes: 123 observations for each regression. All regressions include the same non-transport control variables as in Table 6 column 8. Based on first-stage results in Table 3 columns 4-6, kilometers of 1760 main post roads instrument for 1991–2006 changes in highway kilometers. As in Table 6, the number of rays of central city 19th c. main roads instruments for 1991–2006 changes in central city highway rays. Robust standard errors are clustered by region of the MA central city and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

In all four specifications, the estimated coefficients on changes in length are positive but insignificant, while the estimated coefficients on rays remain significant and close to the original estimate of our preferred specification in Table 6 column 8 (-0.050). As in Baum-Snow et al. (2012), these results rule out the possibility that these other types of infrastructure were driving previous results[14].

Endogenous Population Growth

There is evidence for the US (Duranton and Turner, 2012) and, in particular, for Spain (Holl and Viladecans-Marsal, 2012) that highways foster MA population growth. We address this potential endogeneity problem in Table 8. We estimate our preferred specification in Table 6 column 8, but instrument separately MA population growth with four instruments. Table 8 also reports individual Angrist-Pischke and global Kleibergen-Paap first-stage statistics.

Table 8: Central City Population Decline and Highway Improvements: Growth Endogeneity

Dependent variable:	1991–2011 Δln(Central city population (density))			
	Two-stage least squares (TSLS)			
Bartik (1991) computation:	1991–2011 Metropolitan	1991–2001 Metropolitan	1991–2011 Suburban	1991–2001 Suburban
	[1]	[2]	[3]	[4]
1991–2006 ΔCentral city rays	-0.037 (0.067)	-0.044 (0.032)	-0.045^{c} (0.027)	-0.046^{b} (0.023)
Angrist-Pischke first-stage statistic ΔRays	10.45	10.64	10.44	10.48
Angrist-Pischke first-stage statistic ΔMA population	0.56	2.66	3.38	8.45
Kleibergen-Paap first-stage statistic	0.24	1.05	1.59	6.12

Notes: 123 observations for each regression. All regressions include the same non-transport control variables as in Table 6 column 8. Based on first-stage results in Table 4 columns 4-6, the number of rays of central city 19th c. main roads instruments for 1991–2006 changes in central city highway rays. We instrument 1991-2011 MA population growth with the expected population growth calculated *à la* Bartik (1991). Robust standard errors are clustered by region of the MA central city and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

We instrument 1991–2011 MA population growth with the expected MA population growth computed *à la* Bartik (1991), i.e., interacting the initial shares of sectoral employment in the MA and the national growth rate of each sector. Because international immigration flows mainly took place between 2001 and 2011 and affected 2001–2011 economic outcomes, some instruments use 1991–2011 national growth rates (columns 1 and 3) whereas others focused on the 1991–2001 period (columns 2 and 4). Furthermore, because some central cities played the role of entrance

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[14] A qualifier is important here. Individual Angrist-Pischke first-stage F-statistics are around 10 and hence instruments pass individual weak tests. However, global Kleibergen-Paap F-statistics are 15% (column 2) and 25% (column 4) below Stock and Yogo (2005)'s critical values. Thus, we should treat these results with caution.

port for immigrants, two instruments use 1991 employment shares in the overall MA (columns 1 and 2) whereas others only use data from the suburbs (columns 3 and 4). Our preferred instrument is in column 4, i.e., the expected MA growth computed interacting 1991 suburban employment shares and 1991-2001 national growth rates.

TSLS results in Table 8 verify our intuition. As in Baum-Snow et al. (2012), endogenous MA population growth introduces bias to our coefficient of interest. However, this bias is small. Since only our preferred instrument in column 4 passes individual and global weak instrument tests, the coefficient on rays only falls to -0.046 (from -0.050).

Heterogeneous Effects?

We also investigate whether our estimate is stable across different types of MAs. Attempts to study cities separately according to their spatial processes (absolute vs. relative suburbanization, or suburbanization vs. centralization) failed due to weak instruments. Thus, we followed Baum-Snow et al. (2012) strategy and studied regional heterogeneity by breaking Spain up into two regions, the Mediterranean coast and the remainder of the country, based on the fact that ancient civilizations (Greeks and Romans) first settled along the coast. Furthermore, the densest and most dynamic Spanish MAs are located on this coast. The results in Table 9 show that for population suburbanization, our estimates for the Mediterranean coast and the remainder of the country do not differ significantly.

Table 9: Central City Population Decline and Highway Improvements: Region Heterogeneity

Dependent variable:	1991–2011 Δln(Central city population (density))
	Two-stage least squares (TSLS)
1991–2006 ΔCentral city rays	-0.042^{b} (0.020)
x Dummy Mediterranean coast	-0.033 (0.034)
Angrist-Pischke first-stage statistic ΔRays	9.05
Angrist-Pischke first-stage statistic ΔRays x Dummy	16.58
Kleibergen-Paap first-stage statistic	7.96

Notes: 123 observations. Regression includes the same non-transport control variables as in Table 6 column 8. Based on first-stage results in Table 4 columns 4-6, the number of 19th c. main roads instruments for 1991–2006 changes in central city highway rays. Similarly, the interacted historical variable instruments for the interacted ray variable. We also include a Mediterranean coast region dummy variable. Robust standard errors are clustered by region of the MA central city and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

A Placebo Exercise (I)

Finally, we evaluate the validity of our identification strategy with a placebo regression in which we estimate the effect of 1991–2006 changes in rays on 1981–1991 central city population growth. As shown in Table 10, the coefficient on rays is insignificant, suggesting that, conditional on controls, our 19th century instrument is not correlated with unobservables that drive population suburbanization.

Table 10: Central City Population Decline and Highway Improvements: Placebo Regression

Dependent variable:	1981–1991 Δln(Central city population (density))
	Two-stage least squares (TSLS)
1991–2006 ΔCentral city rays	-0.260 (0.178)
Kleibergen-Paap first-stage statistic	10.36

Notes: 123 observations. Regression includes the same non-transport control variables as in Table 6 column 8 except 1991–2011 change in ln(MA population) and ln(1991 MA population). Instead, 1981–1991 change in ln(MA population) and ln(1981 MA population) are included as controls. Based on first-stage results in Table 4 columns 4-6, the number of 19th c. main roads instruments for 1991–2006 changes in central city highway rays. Robust standard errors are clustered by region of the MA central city and are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

4.2. The Spatial Pattern of Suburbanization

We now turn our attention to examine the role of highway improvements on changes in the intrametropolitan location patterns of people. We estimate Eq. (4) in which the unit of observation is a municipality j that belongs to metropolitan area i.

Average Effects

Table 11 presents OLS (columns 1-5) and TSLS (columns 6-10) results describing the effect of the 1991–2006 changes in distance to the nearest highway ramp on the changes in log population (density) from 1991 to 2011. Columns 1 and 6 only include our measure of highway improvements. Columns 2 and 7 add controls for 1991 population, land area, and distance to central city. Columns 3 and 8 augment the regression with physical geography variables. Columns 4 and 9 add 1991 socioeconomic controls. In columns 5 and 10, we include past population levels every 10 years from 1900 to 1981. In order to account for the overall population growth between 1991 and 2011 and to control for other shocks that are common to all municipalities within an MA, all specifications include MA fixed effects.

Table 11 also reports first-stage F-statistics for our selected instrument. Based on first-stage results in Table 5 columns 4-6, TSLS regressions use distance to the nearest 1760 main post road as an instrument for 1991–2006 changes in distance to the nearest highway ramp. All five specifications pass the weak instrument test.

Table 11: Changes in Residential Location and Highway Improvements

Dependent variable:	1991–2011 Δln(Population (density))									
	Ordinary least squares (OLS)					Two-stage least squares (TSLS)				
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
1991–2006 ΔDistance to the nearest ramp	-0.006	-0.002	-0.002	-0.002	-0.002	-0.119^a	-0.030^b	-0.038^b	-0.025^b	-0.025^b
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.030)	(0.015)	(0.015)	(0.012)	(0.011)
ln(1991 Population)		-0.142^a	-0.152^a	-0.174^a	-0.165^a		-0.142^a	-0.153^a	-0.178^a	-0.164^a
		(0.010)	(0.012)	(0.011)	(0.014)		(0.010)	(0.012)	(0.011)	(0.013)
ln(Land area)		0.080^a	0.087^a	0.097^a	0.085^a		0.077^a	0.085^a	0.095^a	0.081^a
		(0.011)	(0.013)	(0.012)	(0.013)		(0.011)	(0.013)	(0.012)	(0.012)
Distance to central city	N	Y	Y	Y	Y	N	Y	Y	Y	Y
Geography	N	N	Y	Y	Y	N	N	Y	Y	Y
1991 Socioeconomic controls	N	N	N	Y	Y	N	N	N	Y	Y
ln(Past populations)	N	N	N	N	Y	N	N	N	N	Y
Adjusted R^2	0.36	0.64	0.65	0.72	0.74					
Kleibergen-Paap first-stage statistic						26.54	27.85	29.43	30.96	30.35

Notes: 1300 observations for each regression (123 are central cities and 1177 are suburban municipalities). All regressions include MA fixed effects. Geography variables include distance to coast, altitude, index of terrain ruggedness, latitude, and longitude. Socioeconomic controls include unemployment and employment rates, share of manufacturing population, share of population over 25 years old, share of population with university degree, and share of foreign-born population. Past population variables include past levels of population every 10 years from 1900 to 1981. Based on first-stage results in Table 5 columns 4-6, TSLS regressions use distance to the nearest 1760 main post road as instrument for 1991-2006 changes in distance to the nearest highway ramp. All regressions are weighted by 1991 population. Analogous unweighted regressions produce coefficients that are larger in absolute value (see Appendix A Table A.2). Robust standard errors are in parentheses. When standard errors are clustered by MA, results remain significant. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

If we restrict our attention to the control variables, their estimated coefficients are remarkably stable across the OLS and TSLS specifications. As expected, the results for initial population show mean reversion, i.e., large municipalities grew more slowly. The results for municipal land area indicate that more spacious municipalities also grew more quickly.

OLS and TSLS results differ for our variable of interest: only estimated TSLS coefficients on changes in distance are statistically different from zero and, as expected, show that the population grew in municipalities that in the period 1991–2006 enjoyed improved access to the highway system. Specifically, the unconditional estimate in column 6 is -0.119, while this estimate falls to -0.025 in our preferred conditional specification in column 10. This value implies that each kilometer reduction in distance to the highways between 1991 and 2006 resulted in a 2.5% increase in municipal population between 1991 and 2011. The difference between this value and its OLS counterpart (-0.002) suggests that the 1991–2006 construction and location of highways was endogenous.

Proximity to Central City

Land use theory suggests that effects are heterogeneous in terms of distance to the central city (CBD): small effects at the center, large effects in the suburbs. We examine this type of heterogeneity in Table 12. In column 1, we estimate our preferred specification from Table 11 column 10 with a regression that only includes suburban municipalities. In columns 2-5, we split our sample according to central city proximity: municipalities located less than 5.4 km from the central city (column 2 includes CCs and suburbs; column 3 only includes suburbs), suburban municipalities located 5.4–11.1 km (column 4), and suburban municipalitites located more than 11.1 km (column 5).

Table 12: Changes in Residential Location and Highway Improvements: Distance to Central City

Dependent variable:	1991–2011 Δln(Population (density))				
	Two-stage least squares (TSLS)				
		Distance to central city			
		< 5.4 km	< 5.4 km	5.4–11.1 km	≥ 11.1 km
	Suburbs	CCs and suburbs	Suburbs	Suburbs	Suburbs
	[1]	[2]	[3]	[4]	[5]
1991–2006 ΔDistance to the nearest ramp	-0.046^{a} (0.018)	0.114^{c} (0.060)	0.828 (0.573)	-0.071^{b} (0.030)	-0.005 (0.013)
Kleibergen-Paap first-stage statistic	17.51	0.22	1.34	7.23	6.11
Observations	1177	323	200	644	333

Notes: All regressions include MA fixed effects and the same non-transport control variables as in Table 11 column 10. Based on first-stage results in Table 5 columns 4-6, distance to the nearest 1760 main post road instruments for 1991–2006 changes in distance to the nearest highway ramp. All regressions are weighted by 1991 population. Analogous unweighted regressions produce coefficients that are larger in absolute value. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

The results verify theory's prediction that the effect is larger in suburban municipalities: the coefficient on changes in distance increases in absolute value to -0.046 (from -0.025) in column 1. Although some distance regressions in columns 2-5 suffer from weak first-stages[15] and, thus, they should be treated with caution, their results also seem to verify theory's prediction that the effect on population growth increases with distance to the central city, changing from negative to positive. Specifically, we first find that the coefficient for central cities and their closest suburbs is positive (0.114) and significant (column 2), indicating that each kilometer reduction in distance to the ramps resulted in 11.4% population reduction in those municipalities. This negative effect partly reflects the effect on central city population decline previously studied in Tables 6-9. As shown in column 3, the coeficient remains positive but insignificant for only the most central suburbs. Second, the coefficient becomes negative (-0.071) and significant in municipalities located 5.4–11.1 km from the central city (column 4). Compared to the average estimates for all suburbs (column 1) and for all observations (Table 11 column 10), this positive effect is larger and shows that population grew faster (7.1%) in these outer municipalities. Finally, we also find that the effect of highways dissapear for the most distant municipalities: the coefficient dramatically decreases to -0.005 and becomes insignificant (column 5).

Proximity to Highways

As shown in Section 2.1, land use theory also suggests that the suburbanized population spreads out along highways and, as a result, population growth takes place near highways. In Table 13, we investigate this source of heterogeneity by comparing the results when we only consider suburban municipalities without any highway inside their boundaries (column 1), with at least one highway (column 2), with highway but without ramp (column 3), with ramp (column 4) and with new ramp built between 1991 and 2006 (column 5). Furthermore, we also split our sample of suburban municipalities according to their proximity to highways: less than 2.4 km

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[15] First-stage F-statistics are 15% (column 4), 20% (column 5) and more than 25% (columns 2-3) below Stock and Yogo (2005)'s critical values. We obtain similar insignificant coefficients when instrumenting with Roman roads and 19th century main roads.

from the nearest highway (column 6), between 2.4 and 5.3 km (column 7), and more than 5.3 km (column 8).

Table 13: Changes in Residential Location and Highway Improvements: Proximity to Highways

Dependent variable:	1991–2011 Δln(Population (density))							
	Two-stage least squares (TSLS)							
	Suburban highways					Distance to the nearest highway		
	No	Yes	No ramp	Ramp	New	$<$ 2.4 km	2.4–5.3 km	$\geq$ 5.3 km
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
1991–2006 ΔDistance to the nearest ramp	-0.014 (0.020)	-0.047^a (0.018)	-0.086^c (0.047)	-0.027^c (0.017)	-0.025^c (0.015)	-0.037^a (0.013)	0.002 (0.021)	0.010 (0.018)
Kleibergen-Paap first-stage statistic	6.15	19.68	3.33	10.81	5.91	28.16	4.62	3.92
Observations	574	603	269	334	129	580	299	298

Notes: All regressions include MA fixed effects and the same non-transport control variables as in Table 11 column 10. Based on first-stage results in Table 5 columns 4-6, distance to the nearest 1760 main post road instruments for 1991–2006 changes in distance to the nearest highway ramp. All regressions are weighted by 1991 population. Analogous unweighted regressions produce coefficients that are larger in absolute value. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

The results confirm theory's prediction that population growth concetrates near highways. Among the suburban municipalities that in 1991–2006 enjoyed improved access to the highway system, the population grew only in those with a highway inside their boundaries (columns 2-5 vs. column 1) and, in terms of distance, in those located less than 2.4 km from the nearest highway (column 6 vs. columns 7-8).

Being cautious because some regressions suffer from weak first-stages, we also find heterogeneous effects according to the presence of highway ramps: the effect of highways is smaller (2.5–2.7%) in suburban municipalities with (new) ramps inside their boundaries (columns 4 and 5) and larger (8.6%) in suburbs without ramps (column 3). Since suburban municipalities with ramps provide the fastest access to the highway system, these results may be due to the competition between firms and households for land. Alternatively, since road traffic is more intense in suburbs with ramps, it may be that disamenities such as noise and air pollution generate negative effects and reduce population growth rates in these municipalities.

A qualifier is important here. We now that modern highways are placed and organized to facilitate movement of traffic within MAs, and in particular, into and out of central cities. However, they are also built to connect major central cities and facilitate movements between MAs. As discussed in Section 3.2, this second function is directly associated with the origins of modern highways: historical roads that existed primarily to link large and growing cities, expanding their commercial relations. The question is whether these historical links still influence residential location patterns and make the linked municipalities grow more because they are linked, rather than because they have a highway. We investigate this question in more detail in Appendix A Table A.3. We estimate our preferred specification using only suburban municipalities with highways inside their boundaries (linked suburbs) and interacting our highway improvements measure with a dummy variable that indicates whether or not the linked suburb is also linked through any historical road (historically linked suburb). The results show that estimates are not significantly different in the historically linked and non-linked suburbs.

Initial Highways

Our previous results show that changes in residential location patterns between 1991 and 2011 are related to 1991–2006 highway improvements. However, it is possible that the initial highway system also affect the growth of population (Duranton and Turner, 2012; Holl and Viladecans-Marsal, 2012) and, in particular, the spatial pattern of the suburbanization process. In Table 14 we explore in detail this question by estimating the conditional effect of the 1991 distance to the nearest highway ramp on the changes in log population (density) from 1991 to 2011. We estimate several regressions based on our previous analysis. Specifically, column 1 includes all CC and suburban observations. In column 2 we only use suburban municipalities. We split our sample of suburbs according to their central city proximity: less than 9 km in column 3, and more than 9 km in column 4. In columns 5-12, we explore whether the effect is heterogeneous in highway proximity: first, by only considering suburban municipalities without highways inside their boundaries (column 5), with at least one highway (column 6), with highway but without ramp (column 7), with ramp (column 8), and with new ramp built between 1991 and 2006 (column 9); second, by only using observations located less than 2.4 km (column 10), between 2.4 and 5.3 km (column 11), and more than 2.4 km (column 12) from the nearest highway.

Table 14: Changes in Residential Location and 1991 Highways

Dependent variable:	1991–2011 Δln(Population (density))											
	Two-stage least squares (TSLS)											
	CCs and suburbs	Only suburbs	Distance to CC		Suburban highways					Distance to hwy		
			< 9 km	≥ 9 km	No	Yes	No ramp	Ramp	New	< 2.4 km	2.4–5.3	≥ 5.3 km
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
1991 Distance to ramp	0.014^b	0.022^a	0.068^a	0.001	0.005	0.036^a	0.051^b	0.025^c	0.028^c	0.029^a	-0.005	-0.003
	(0.006)	(0.007)	(0.026)	(0.006)	(0.006)	(0.013)	(0.020)	(0.015)	(0.017)	(0.010)	(0.053)	(0.005)
KP first-stage statistic	72.46	58.32	9.16	40.73	44.79	32.25	8.40	12.96	5.67	47.36	0.67	36.36
Observations	1300	1177	610	567	574	603	269	334	129	580	299	298

Notes: All regressions include MA fixed effects and the same non-transport control variables as in Table 11 column 10. Based on first-stage results in Table 5 columns 1-3 and their reduced-form results (available upon request), distance to the nearest 1760 main post road instruments for 1991 distance to the nearest highway ramp. All regressions are weighted by 1991 population. Analogous unweighted regressions produce coefficients that are larger in absolute value. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

In all specifications, the estimated coefficient on the 1991 distance to the nearest highway ramp is positive, indicating that proximity to the 1991 highway ramps had a negative effect on suburban population growth. On average, a municipality located one kilometer closer to the 1991 ramps reduced its growth by 1.4%. This negative effect is higher for suburban municipalities (2.2%) and, in particular, for those located less than 9 km from the central city (6.8%). As in the case of highway improvements (Table 13), we find that effects are heterogeneous in highway proximity: the effect is only significant in suburban municipalities with highways inside their boundaries and in suburbs located less than 2.4 km from the nearest highway. Furthermore, among these estimates we also find heteregeneity according to the presence of ramps: the negative effect is larger (5.1%) in suburban municipalities without ramps and smaller (2.5-2.8%) in those with (new) ramps.

It is important to note that the effect of the 1991 highways is different than that of the 1991–2006 highway improvements: while highway improvements positively influenced the spatial pattern of the suburbanization process by fostering population growth in suburban municipalities near highways, the above results show that 1991 highways negatively affected the growth of population. Despite being opposite, these two findings are part of the same story: they associate the effect of highways to the length of time since they were built and the degree of land development. Specifically, population increased in municipalities with undeveloped land close to the new highways and far from the old highways where nearby municipalities were fully developed and showed high density levels (Garcia-López, 2012).

A Placebo Exercise (II)

In Tables 15 and 16 we evaluate the validity of our identification strategy with placebo regressions related to previous results in Tables 11-13 and Table 14, respectively. We estimate the effect of 1991–2006 changes in highway distance (Table 15) and the effect of the 1991 distance to the nearest highway ramp (Table 16) on 1981–1991 municipal population growth. Both tables have the same format. In column 1, we use all CC and suburban observations. Regression in column 2 only includes suburban municipalities. Since previous results show that (1) the positive effect of 1991–2006 highway improvements takes place in municipalities located 5.4–11.1 km from the central city, and that (2) the negative effect of 1991 highways affects suburbs within 9 km from the central city, we use their associated observations in columns 3. To test whether pre-construction population growth affected the location of highways, columns 4-7 include suburban municipalities with highways inside their boundaries, with at least a new highway segment built between 1991 and 2006, with new ramps, and, finally, suburbs situated less than 2.4 km from the nearest highway, respectively. In all cases the coefficient on 1991–2006 changes in distance and the coefficient on 1991 distance are insignificant, suggesting that, conditional on controls, our 1760 instrument is not correlated with unobservables that drive population growth.

Table 15: Changes in Residential Location and Highway Improvements: Placebo Regressions

Dependent variable:	1981–1991 Δln(Population (density))						
	Two-stage least squares (TSLS)						
	CCs and suburbs	Only suburbs	Dist to CC 5.4–11.1 km	Suburban highways			Dist to hwy < 2.4 km
				Yes	New segment	New ramp	
	[1]	[2]	[3]	[4]	[5]	[6]	[7]
1991–2006 ΔDistance to the nearest ramp	0.048 (0.041)	0.005 (0.046)	-0.012 (0.054)	-0.040 (0.045)	0.038 (0.034)	0.028 (0.026)	0.027 (0.037)
Kleibergen-Paap first-stage statistic	29.08	15.60	7.41	18.39	8.05	14.09	25.81
Observations	1300	1177	644	603	202	129	580

Notes: All regressions include MA fixed effects and the same non-transport control variables as in Table 11 column 10 except 1991 socioeconomic controls and ln(1991 population). Instead, ln(1981 population) is included. Socioeconomic controls are not available for 1981. Based on first-stage results in Table 5 columns 4-6, distance to the nearest 1760 main post road instruments for 1991–2006 changes in distance to the nearest highway ramp. All regressions are weighted by 1991 population. Analogous unweighted regressions produce coefficients that are larger in absolute value. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Table 16: Changes in Residential Location and 1991 Highways: Placebo Regressions

Dependent variable:	1981–1991 Δln(Population (density))						
	Two-stage least squares (TSLS)						
	CCs and suburbs	Only suburbs	Dist to CC < 9 km	Suburban highways			Dist to hwy < 2.4 km
				Yes	New segment	New ramp	
	[1]	[2]	[3]	[4]	[5]	[6]	[7]
1991 Distance to the nearest ramp	-0.026 (0.022)	-0.002 (0.021)	0.051 (0.050)	0.030 (0.034)	-0.027 (0.025)	-0.031 (0.028)	-0.021 (0.028)
Kleibergen-Paap first-stage statistic	72.12	52.57	9.43	27.18	18.29	13.91	42.78
Observations	1300	1177	610	603	202	129	580

Notes: All regressions include MA fixed effects and the same non-transport control variables as in Table 11 column 10 except 1991 socioeconomic controls and ln(1991 population). Instead, ln(1981 population) is included. Socioeconomic controls are not available for 1981. Based on first-stage results in Table 5 columns 1-3 and their reduced-form results (available upon request), distance to the nearest 1760 main post road instruments for 1991 distance to the nearest highway ramp. All regressions are weighted by 1991 population. Analogous unweighted regressions produce coefficients that are larger in absolute value. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

5. Conclusions

Over the last twenty-five years Spain has dedicated vast sums of money to fund public investment in new highways. These efforts mean that today Spain has the longest highway network in Europe. Clearly, this scale of investment will have many implications for the country's economy over the next few decades. One of these implications is related to the changes in the urban form of its metropolitan areas.

To examine this, this paper has analyzed the impact of highways on the process of the population suburbanization of Spanish cities. We obtain two main results. First, we find that an additional ray built in a central city between 1991 and 2006 led to a 5 per cent decline in central city population. This evidence, which is in line with findings reported for US and Chinese cities, would seem to confirm that the building of new highways accounts in part for the suburbanization process. Second, in terms of the intrametropolitan location of population, we find that highway improvements also result in population growth at the municipal level, influencing the spatial pattern of the suburbanization process. Specifically, the population of municipalities that enjoyed improved access to the highway system grew 2.5% faster than the average. As the theory suggests, the effect was most marked in suburban municipalities (4.6%), increased with distance to the central city (7.1% in suburbs located 5.4–11.1 km) and concetrated near highways (3.7% in suburbs within 2.4 km). Furthermore, we verify Baum-Snow (2007a)'s prediction that new highways cause population to spread out along the highway segments (4.7%) and ramps (2.7%). In short, our evidence confirms that highway improvements have a significant and not negligible impact on population decentralization and on the location pattern of population in the suburbs.

Our findings are relevant, first, because we contribute European evidence to the general literature, whereas to date what we have known about road infrastructure and city growth has been limited to the US and Chinese experiences. And second, because we provide evidence of the influence of highway investments on suburbanization. In fact, the main contribution of this paper concerns the impact of highway improvements on the population growth patterns of suburban municipalities. Thus, our evidence should help to reduce the potential negative effects of urban sprawl in the future design of new highway networks.

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Appendix A.

Summary Statistics

Table A.1: Summary Statistics

	Mean	Stand. Dev.	Minimum	Maximum
Panel A. Suburbanization and Highway Improvements (Obs.: 123 central cities)				
1991–2011 Δln(Population density)	0.208	0.250	-0.219	1.407
1991–2006 ΔRays of central city highways	1.089	1.101	0.000	4.000
Rays of central city Roman roads	1.106	1.253	0.000	7.000
Rays of central city 1760 main post roads	0.943	1.189	0.000	7.000
Rays of central city 19th c. main roads	2.041	1.776	0.000	8.000
1991–2006 ΔKilometers of metropolitan highways	21.495	21.955	0.000	147.704
Kilometers of metropolitan Roman roads	16.626	18.640	0.000	84.905
Kilometers of metropolitan 1760 main post roads	13.449	18.781	0.000	97.549
Kilometers of metropolitan 19th c. main roads	33.880	31.714	0.000	148.478
1991–2006 ΔKilometers of suburban highways	12.297	14.792	0.000	83.762
Kilometers of suburban Roman roads	9.029	9.664	0.000	33.927
Kilometers of suburban 1760 main post roads	7.159	10.983	0.000	67.528
Kilometers of suburban 19th c. main roads	19.296	21.587	0.000	140.950
ln(Central city land area) (km^2)	4.667	1.242	0.673	7.468
ln(MA land area) (km^2)	6.103	0.648	4.074	7.638
1991–2011 Δln(MA population)	0.263	0.232	-0.200	1.279
ln(1991 MA population)	11.708	0.849	10.278	14.999
1991–2006 Δln(MA simulated income)	0.211	0.014	0.130	0.231
Distance to coast (km)	75.895	98.429	0.093	342.210
Altitude (m)	280.244	302.996	3.000	1131.000
Central city index of terrain ruggedness	40.841	28.235	1.047	148.068
MA index of terrain ruggedness	47.303	31.460	5.923	170.748
Central city elevation range (m)	457.707	315.195	10.000	1491.000
MA elevation range (m)	735.016	463.986	67.000	2816.000
Panel B. The Spatial Pattern of Suburbanization (Obs.: 1300 municipalities = 123 central cities and 1177 suburban municipalities)				
1991–2011 Δln(Population density)	0.470	0.509	-0.538	4.010
1991–2006 ΔDistance to the nearest highway ramp (km)	-11.991	25.113	-158.448	0.000
1991 Distance to the nearest highway ramp (km)	17.268	26.409	0.204	159.588
Distance to the nearest roman road (km)	23.409	30.432	0.016	187.560
Distance to the nearest 1760 main post road (km)	31.222	35.661	0.013	169.557
Rays of central city 19th c. main road (km)	6.968	8.859	0.009	59.697
ln(1991 population)	8.059	1.802	3.045	14.918
ln(Land area) (km^2)	3.148	1.214	-3.507	7.468
Distance to central city (km)	8.347	4.835	0.000	53.227
Distance to coast (km)	77.582	98.275	0.023	352.752
Altitude (m)	322.236	312.008	2.000	1227.000
Index of terrain ruggedness	43.613	35.335	0.000	200.675
Latitude	40.570	1.915	36.133	43.618
Longitude	-1.959	3.001	-8.826	3.077
1991 Unemployment rate	0.140	0.062	0.000	0.449
1991 Employment rate	0.499	0.075	0.203	0.742
1991 Share of manufacturing population	0.265	0.145	0.000	1.069
1991 Share of population over 25 years old	0.605	0.073	0.411	0.931
1991 Share of population with university degree	0.278	0.065	0.082	0.626
1991 Share of foreign-born population	0.010	0.034	0.000	0.588
ln(1981 population)	7.819	2.092	0.000	14.975
ln(1970 population)	7.707	2.015	0.000	14.962
ln(1960 population)	7.573	1.946	0.000	14.631
ln(1950 population)	7.471	1.909	0.000	14.297
ln(1940 population)	7.415	1.895	0.000	13.900
ln(1930 population)	7.360	1.878	0.000	13.821
ln(1920 population)	7.252	1.872	0.000	13.529
ln(1910 population)	7.202	1.855	0.000	13.304
ln(1900 population)	7.108	1.879	0.000	13.199

The Spatial Pattern of Suburbanization: Unweighted Results

Table A.2: Changes in Residential Location and Highway Improvements: Unweighted Results

Dependent variable:	1991–2011 Δln(Population (density))									
	Ordinary least squares (OLS)					Two-stage least squares (TSLS)				
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
1991–2006 ΔDistance to the nearest ramp	-0.008^{a}	-0.009^{a}	-0.010^{a}	-0.008^{a}	-0.008^{a}	-0.054^{a}	-0.046^{b}	-0.055^{a}	-0.051^{a}	-0.054^{a}
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.020)	(0.018)	(0.018)	(0.017)	(0.017)
ln(1991 Population)	N	Y	Y	Y	Y	N	Y	Y	Y	Y
ln(Land area)	N	Y	Y	Y	Y	N	Y	Y	Y	Y
Distance to central city	N	Y	Y	Y	Y	N	Y	Y	Y	Y
Geography	N	N	Y	Y	Y	N	N	Y	Y	Y
1991 Socioeconomic controls	N	N	N	Y	Y	N	N	N	Y	Y
ln(Past populations)	N	N	N	N	Y	N	N	N	N	Y
Adjusted R^2	0.36	0.43	0.45	0.52	0.52					
Kleibergen-Paap first-stage statistic						19.77	21.25	24.36	26.30	24.84

Notes: 1300 observations for each regression (123 are central cities and 1177 are suburban municipalities). All regressions include MA fixed effects and the same non-transport control variables as in Table 11 columns 1-10. Based on first-stage results in Table 5 columns 4-6, distance to the nearest 1760 main road instruments for 1991–2006 changes in distance to the nearest highway ramp. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

The Spatial Pattern of Suburbanization: Historical Links

Table A.3: Changes in Residential Location and Highway Improvements: Historical links

Dependent variable:	1991–2011 Δln(Population (density))
	Two-stage least squares (TSLS)
	[1]
1991–2006 ΔDistance to the nearest ramp	-0.047^{b}
	(0.019)
x Dummy Historical Link	0.002
	(0.003)
Angrist-Pischke first-stage statistic Δ distance	24.28
Angrist-Pischke first-stage statistic Δ distance x Dummy	20.91
Kleibergen-Paap first-stage statistic	12.32

Notes: 603 observations. Regression includes MA fixed effects and the same non-transport control variables as in Table 11 column 10. Based on first-stage results in Table 5 columns 4-6, distance to the nearest 1760 main post road instruments for 1991–2006 changes in distance to the nearest highway ramp. Similarly, the interacted historical variable instruments for the interacted changes in distance. We also include a historically linked municipality dummy variable. Robust standard errors are in parentheses. ^{a}, ^{b}, and ^{c} indicate significant at 1, 5, and 10 percent level, respectively.

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