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Infrastructure and Transport

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ABSTRACT: I investigate the effect of transportation improvements on changes in population location patterns in Barcelona between 1991 and 2006. At a much finer geographical scale, I verify and extend the finding of Baum-Snow (2007a) that transportation cause suburbanization: highway and railroad improvements foster population growth in suburban areas, whereas the transit system also affects the location of population inside the CBD. To estimate the causal relationship between the growth of population (density) and transportation improvements, I rely on an instrumental variables estimation which uses distances to the nearest Roman road, the nearest 19th century main road, and the nearest 19th century railroad network as instruments for the 2001-1991 changes in distance to the nearest highway ramp and the distance to the nearest railroad station.

JEL Codes: R14, R23, R41, R42, R52

Keywords: Urban spatial structure, suburbanization, transportation infrastructure

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1. Introduction

I investigate the effects of highway and railroad improvements on changes in urban spatial structure in the Barcelona Metropolitan Region (BMR) between 1991 and 2006. I find that transportation improvements cause BMR's suburbanization and influence its spatial pattern by attracting population to non-central suburban tracts that improved their access to the highway system between 1991 and 2001 and to central and non-central suburban tracts near railroad stations. Besides causing suburbanization, transportation also affects residential location decisions in the CBD by attracting population near railroad stations. Overall, these results confirm that transportation infrastructure and its improvements are important elements needed to explain, in general, urban spatial structure and, in particular, the suburbanization process and its spatial pattern.

This investigation is of interest for three reasons. First, it furthers our understanding of the role of transportation infrastructure in shaping cities. Baum-Snow (2007a) shows that transportation improvements cause suburbanization. At a more finer geographical scale, my results confirm this finding and indicate that these improvements also influence the spatial pattern of this process. Since suburbanization leads to greater resource consumptions and CO_2 emissions (Kahn, 2000), and to an inefficient supply of public services (Bertaud, 2002), my findings provide a basis for analyzing potential policy interventions that help to redirect the spatial pattern of suburbanization and mitigate its negative consequences.

Second, my results are also useful for planning in two additional ways. Since improvements in transportation infrastructure cause changes in population location patterns, planning policies should also consider the complementary changes in the spatial distribution of the demand for public services. Furthermore, since the effect of transportation improvements depends on the city area where infrastructure is placed, planning policies should be spatially differentiated.

Finally, this research is important because it is centered on an European city and confirms previous evidence from US cities. Despite differences in population size and overall city density, land-use planning, or the use of public transit between US and European cities, these results show that suburbanization is an ongoing phenomenon in a big European city and that it is also related to the transportation infrastructure.

My empirical strategy is based on estimating the relationship between the growth of population (density) in a census tract and its transportation improvements, measured as the changes in census tract distance to the nearest highway ramp and the census tract distance to the nearest railroad station. Departing from this unconditional relationship, I gradually control for the initial level of population density, proximity to the main centers, geography, and history (past populations). I implement this strategy for different city areas: CBD, subcenters and non-central suburban areas.

To carefully establish this causal relationship, I have to deal with an important identification problem: the simultaneous determination of population growth and transportation 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 solve this problem I use instruments as sources of exogenous variation for transportation improvements.

Based on the history of the infrastructure development in Barcelona (and Spain), I derive three instruments from maps of the Roman roads, and the main roads and the railroad network at the end of the 19th century, respectively. Because these old infrastructures were not placed randomly and some of the factors that influenced their location may have also influenced modern transportation improvements, the abovementioned variables of geography and history are needed to control their effect on instruments. To choose among my instruments I implement Murray (2006a,b)'s strategy based on checking first stage and reduced form results for consistency with instruments' rationale.

This research contributes to the existing literature in two ways. First, it extends the conclusions by Baum-Snow (2007a). He investigates the effect of the interstate highway system on suburbanization and finds that highway improvements contributes to central city population decline. Using data on a much finer geographic scale, I also investigate the effect of transportation improvements inside the central city and the suburbs (suburban subcenters and non-central suburban areas). I also distinguish between the effects of the highway system and the railroad network. My results suggest that transportation improvements influence the suburbanization process by attracting population near railroad stations and to non-central suburban areas that improve their access to the highway system.

My work is also related to the large literature on urban spatial structure. Despite the central role of transportation infrastructure in theoretical models of urban spatial structure, much of the empirical literature is concerned with its effect on the spatial distribution of land prices. Only a small number of papers study the relationship between transportation and the spatial distribution of population and employment[1]. With the exception of Baum-Snow (2007a), none of them deal with the simultaneous determination of population density (growth) and transportation infrastructure (improvements). As abovementioned, I resolve this endogeneity problem by exploiting the exogenous variation in three instrumental variables.

The rest of the paper is structured as follows. In the next section, I propose my empirical strategy to estimate the effects of transportation infrastructure improvements on population (density) growth. In Section 3, I describe Barcelona's data focusing the attention on its transportation infrastructure. I present my main results in Section 4. Finally some conclusions are given in Section 5.

2. Urban Spatial Structure and Transportation: Theory and Estimation

The classical monocentric land use theory developed by Alonso (1964), Mills (1967) and Muth (1969) (AMM) considers a non-limited radial-type transportation infrastructure covering the whole city in the same way and therefore allowing the same access to the unique main center or Central Business District (CBD) from any point located at the same distance from this CBD. The way transportation infrastructure is modeled leads to a homogeneous reduction in the density as population move away from the CBD (the CBD gradient), but not from transportation infrastructure. When improvements in transportation infrastructure increase transport speed, population density decreases near the CBD and increases in the suburbs and, as a result, the CBD gradient flattens (Wheaton, 1974)[2].

To motivate my economic strategy, the works by Anas and Moses (1979) and Baum-Snow (2007b) are more useful because they deal with transportation infrastructure in a more realistic way. Anas and Moses (1979) extend

[1] Steen (1986), Baum-Snow (2007a), and Garcia-López (2010) estimate the effect of transportation infrastructure on population density patterns, and McMillen and McDonald (1998) on employment density patterns. Boarnet (1994a,b) and Bollinger and Ihlanfeldt (1997, 2003) consider transportation infrastructure (improvements) as a possible determinant of intrametropolitan population and employment growth.

[2] Non-monocentric/polycentric models allow the possibility of several main centers, the CBD and the subcenters(Fujita and Ogawa, 1982; Anas and Kim, 1996; Lucas and Rossi-Hansberg, 2002). Since they adapt the AMM-type transportation infrastructure, the resulting spatial distribution of population only follows a decreasing density pattern from the CBD (the CBD gradient) and from the subcenters (subcenters' gradients).

the AMM model by considering two competing transportation infrastructures. First, the classical AMM transportation infrastructure based on a dense network of radial streets. Second, a high speed transit system based on sparse radial corridors. Depending on the cost of the competing modes, the authors show that both rents and population densities might decrease with distance to the transit lines (a transportation infrastructure gradient).

More recently, Baum-Snow (2007b) incorporates highways into the transportation infrastructure of a monocentric city. Population commutes to the CBD using these faster sparse radial highways or using a dense network of streets that connects each point in the city to the CBD and to the nearest highway[3]. Concerned with the suburbanization process and the impact of highway improvements previously documented in Baum-Snow (2007a), the author shows that new highways affect urban spatial structure by causing population to spread out along the highways and, as a result, by increasing population densities in areas near highways and decreasing elsewhere.

Based on these works and following other empirical studies, the effect of transportation infrastructure on urban spatial structure can be examined by estimating a type of the so-called density function[4]:

$$lnD_{it} = A_0 + \gamma_{inf} d_{inf,it} + A_1 X_{it} + \epsilon_{it} \tag{1}$$

where lnD_{it} is the natural logarithm of population density for census tract i in year t and $d_{inf,it}$ is the distance from the tract centroid to the transportation infrastructure. γ_{inf} is the transportation infrastructure gradient and measures whether population density increases or decreases with distance to this infrastructure. X denotes a vector of observed census tract characteristics such as location, geography, and history. ϵ is the error term.

To study whether transportation improvements affect changes in urban spatial structure, I estimate a first-difference specification based on Eq. (1):

$$\Delta(lnD_{it}) = B_0 + \beta_{\gamma_{inf}} \Delta(d_{inf,it}) + B_1 \Delta X_{it} + \eta_{it} \tag{2}$$

where $\Delta(lnD_{it}) = lnD_{it} - lnD_{it-1}$ measures population (density) growth. $\Delta(d_{inf,it}) = d_{inf,it} - d_{inf,it-1}$ are the changes in distance to the transportation infrastructure and measure its improvements. $\beta_{\gamma_{inf}}$ is a "growth"

[3]Baum-Snow (2007b) also extends Anas and Moses (1979) by allowing for different "technologies" to access the highways from the streets.

[4]This functional form is the linearized version of a negative exponential function derived from a quasilinear utility (Baum-Snow, 2007a). Monocentric density functions only include the distance to the CBD as explanatory variable (Clark, 1951; McDonald, 1989). Polycentric studies also consider the distance to the nearest subcenter (Anas et al., 1998).

gradient and show whether population (density) increases o decreases near transportation improvements. Since the abovementioned census tract characteristics are time-invariant and, as a result, they drop out of this equation, I include them in level and the initial population density as control variables to account for the possibility that these initial conditions may determine population (density) growth and be correlated with transportation improvements.

If I assumed that the random element of population (density) growth is uncorrelated with transportation improvements, I could estimate Eq. (2) by OLS. However, as Baum-Snow (2007a) points out, transportation improvements are expected to be endogenous to population (density) growth. That is, causation may run from transportation improvements to population (density) growth or the other way round. 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 deal with this identification issue, I model transportation improvements explicitly in Eq. (3), a two-equation model, one to predict transportation improvements, the other to predict the effect of these improvements on population (density) growth:

$$\begin{aligned} \Delta(d_{inf,it}) &= C_0 + C_1\Delta X_{it} + C_2 Z_{it} + \mu_{it} \\ \Delta(lnD_{it}) &= B_0 + \beta_{\gamma_{inf}}\widehat{\Delta(d_{inf,it})} + B_1\Delta X_{it} + \eta_{it} \end{aligned} \tag{3}$$

where $\widehat{\Delta(d_{inf,it})}$ is predicted changes in distance to the transportation infrastructure as estimated in the first stage. Z_{it} are the exogenous instruments that have to predict transportation improvements and being otherwise uncorrelated with population (density) growth. That is, instruments have to satisfy the relevance, $\text{cov}(Z, \Delta(d_{inf,it})|X) \neq 0$, and the exogeneity, $\text{cov}(Z, \eta|X) = 0$, conditions.

3. Data

I center my analysis on the Barcelona Metropolitan Region. It is a convenient case study due to its data availability and two of its characteristics. First, the region is undergoing a process of population suburbanization that is affecting the central city, and benefiting subcenters and, in particular, non-central suburban areas (Garcia-López, 2010). Second, the BMR's transportation infrastructure is based on both a railroad network and a highway system. The former dates back to the 19th century, the latter is from the last quarter of the 20th century. Precisely, the most recent transportation improvements are related to the highway system, which was extended by 191 km and 104 new ramps between 1991 and 2001, and are simultaneous to the suburbanization process.

I use census tract as my unit of observation, implementing my empirical strategy for the whole BMR (3,182 census tracts), as well as for the CBD and the suburbs (1,992 and 1,190 census tracts). Table 1 reports summary statistics for my main variables and Appendix A provides further details about their computation and their associated data.

Table 1: Summary Statistics For Main Variables

	Entire BMR		CBD		Subcenters		Non-Central	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
2006-1991 Δln(Population Density)	0.034	0.471	-0.060	0.477	0.016	0.276	0.353	0.455
1991 ln(Population Density)	5.199	1.753	5.840	0.997	5.626	0.818	2.757	2.118
Distance to CBD (km)	11.653	11.078	5.708	3.352	17.515	11.182	25.342	12.079
Distance to the nearest Subcenter (km)	6.638	4.567	6.934	3.669	1.987	1.365	9.935	5.571
Ruggedness index (m)	28.590	25.836	25.037	22.938	20.854	11.644	47.033	34.245
Distance to coast (km)	6.443	6.504	3.403	1.669	10.681	7.830	12.312	8.438
2001-1991 Changes in Dist to Hwy Ramp (km)	-1.202	2.338	-0.957	1.062	-1.059	2.250	-2.116	4.326
Distance to the nearest Rail Station (km)	0.849	1.359	0.399	0.323	0.915	0.697	2.228	2.474
Distance to the nearest Roman Road (km)	1.394	1.875	0.899	0.700	2.384	3.114	2.076	2.334
Distance to the nearest 19th c. Main Road (km)	1.804	2.129	0.935	0.758	2.959	2.258	3.535	3.175
Distance to the nearest 19th c. Railroad (km)	1.479	1.625	0.917	0.758	1.986	1.201	2.816	2.706
Number of census tracts	3182		1992		568		622	

I collect population data from 1991 Population Census, the earliest census with data at a tract level, and from 2006 Municipal Register, both produced by the Instituto Nacional de Estadística (INE). I compute population densities for each tract by dividing its inhabitants by its total land area. I construct my dependent variable as the 2006-1991 changes in log population densities, $\Delta(lnD_{2006-1991}) = lnD_{2006} - lnD_{1991}$. Since I use tracts "designed" with the same boundaries in 1991 and 2006, their total land do not change and, as a result, my dependent variable can also be interpreted in terms of population growth. The related values in Table 1 show an slightly increase of population (density) in the BMR between 1991 and 2006, but also indicate a process of suburbanization, with population decreasing in the CBD and increasing in the subcenters and, in particular, in non-central suburban areas. To control for initial density conditions, I also use the natural logarithm of 1991 population density.

I control for other initial conditions by including a number of variables describing census tract location, physical geography, and history. Following the large literature on urban spatial structure, I use the census tract distances to the CBD and to the nearest subcenter to characterize its location with respect to main centers. Since physical geography may impact population (density) growth and old and new transportation infrastructure, I use an index of terrain ruggedness and distance to the coast. I also include the natural logarithm of municipal past population every 20 years from 1910 to 1970 to control for history.

My main explanatory variables measure transportation improvements in km and are two, one related to the highway system, the other to the railroad network. Since the most recent transportation improvements are only related to the highway system between 1991 and 2001, I construct the highway variable as the 2001-1991 changes in distance to the nearest highway ramp ($\Delta(d_{hwy,2001-1991}) = d_{hwy,2001} - d_{hwy,1991}$) and the railroad variable as the distance to the nearest railroad station (d_{rail})[5]. To calculate these distances, I use vector digital maps related to the highway system and the railroad network in 2008 created by the Departament de Política Territorial i Obres Públiques (DPTOP). Based on these maps and other information collected from Instituto Geográfico Nacional (IGN) (IGN, 1991, 2008), I created the 1991 and 2001 highway system and the 2006 railroad network maps. These are vector digital maps with polylines (highway and railroad segments) and points (ramps and stations) (Figures 1 and 2). I compute distances in straight line (km) from each tract centroid to the nearest 2001 highway ramp centroid, to the nearest 1991 highway ramp centroid, and to the nearest 2006 railroad station centroid.

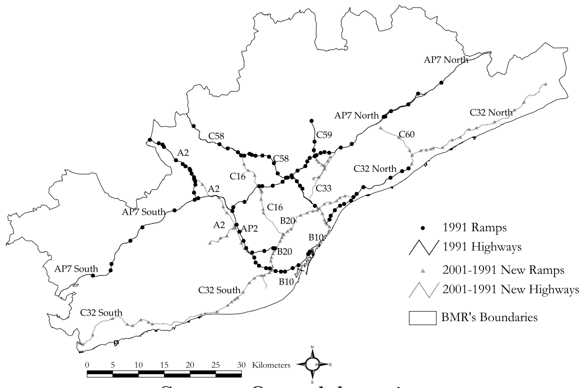
The BMR's highway system is based on 427 km of fast and high-capacity main roads (A2, AP2, AP7, C16, C32, C33, C58, C60, B10 and B20) whose access is limited by 207 ramps located in 68 municipalities (Figure 1). Although its construction began in the late 1960s[6], the boost to build a real highway system began in the 1980s with a national plan called "Plan General de Carreteras" in 1983 and with a state plan called "Pla de Carreteres de Catalunya" in 1985. The former mainly focused on connecting the most important Spanish cities with the capital, Madrid, and, by doing so, relieving the traffic situations of the most congested corridors (Holl, 2011); the latter centered on connecting metropolitan and non-metropolitan Catalan main cities with Barcelona in order to improve their accessibility levels and

[5]Although physically the railroad network did not change, its time schedules did and, as a result, its train frequency was improved.

[6]The first highway was the Maresme highway (the C32 North highway, formerly named the A-19 highway) and was opened in 1969. The northern stretch of the AP-7 highway was opened in 1970 and the southern stretch in 1972. The AP2 highway between Barcelona and Martorell was opened in 1972 (Miralles, 1997).

containing the spread of metropolitan growth.

Figure 1: The BMR's Highway System



Source: Own elaboration.

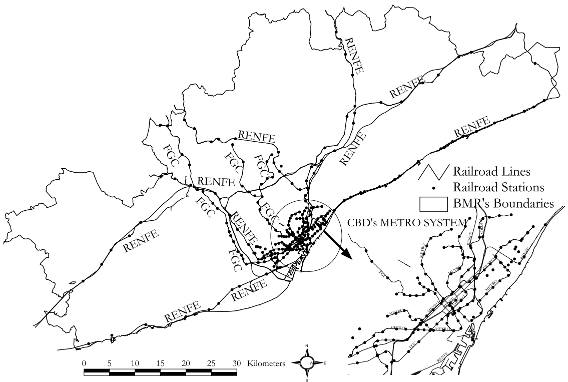
As abovementioned, the most recent improvements are from the 2001-1991 period, when several highways were extended (e.g. the C32 North and A2 highways), new ramps were added (e.g. the AP7 North highway) and new highways were built (e.g. the C32 South, C33 and C60 highways). Furthermore, the first CBD highways were built crossing Barcelona municipality through its mountains (the B20 highway or Ronda de Dalt) and through its seafront (the B10 highway or Ronda Litoral). As a whole, 191 km of new highways and 104 new ramps were built between 1991 and 2001, and the distance to the nearest ramp reduced by 1.2 km for the entire BMR, by 1.0 km in central areas (CBD and subcenters) and by 2.1 km in non-central suburban areas.

The BMR's railroad system is based on an important subway (METRO), and some FGC and RENFE railroad lines (Figure 2). The former covers the whole municipality of Barcelona and partially the CBD and it is owned by a metropolitan public firm (Transports Metropolitans de Barcelona S.A.). The second are owned by a State public firm (Ferrocarrils de la Generalitat de Catalunya S.A.) and provide services to Barcelona, to some CBD's municipalities and to some "counties" nearest to Barcelona. And the latter are part of the National railroad system and communicate different parts of the BMR between them and Barcelona (metropolitan services) and with the rest of the country (long-distance services). The first railroad line was inaugurated in 1848 and connected Barcelona and Mataró, one of its main subcenters[7]. The basic network was completed during the second half of the

[7]In fact, this was also the first Spanish railroad line. Ulterior BMR's railroad lines

19th century and most of the non-subway stations were built during that period. The first subway line was inaugurated in 1924 and most of its current stations were built before the 1992 Olympic Games (Miralles, 1997)[8].

Figure 2: The BMR's Railroad Network



Source: Own elaboration.

It is mainly a passenger-oriented infrastructure with 1,172 km of railroad lines and 282 stations in 76 municipalities. The central city, Barcelona, concentrates 128 railroad stations and there are 185 in the whole CBD (165 are subway stations). On average, a BMR's census tract is less than 1 km from the nearest railroad stations. As expected, central census tracts are closer to these stations (400 m in the CBD and 900 m in the subcenters) than census tracts in non-central suburban areas (2.2 km) (Table 1).

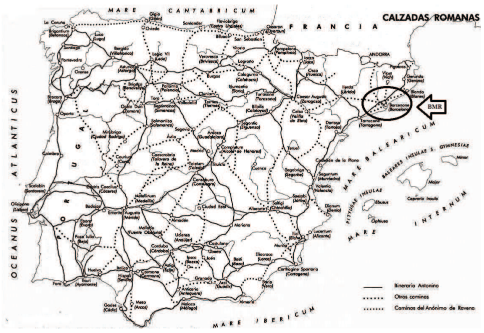
My instruments are based on old transportation infrastructures in Spain: Roman roads (Figure 3), and main roads (Figure 4) and railroad lines (Figure 5) at the end of the 19th century. Duranton and Turner (2011, 2012) also use historic instruments such as the 19th century railroads and the 19th century major expedition routes. The use of Roman roads as instrumental variable is new to the literature. All three instruments are distances in straight line (km) from each tract centroid to the nearest segment of old transportation infrastructure. To compute them, I use vector digital maps based on de Soto (2010) (Roman roads) and Carreras and de Soto (2010) (19th c. main roads and railroad lines), and maps and other information

connected Barcelona with other subcenters such as Granollers (1854), Sabadell (1855), or Martorell (1861).

[8]From 1992 to 2001 only 5 new stations were inaugurated. The new subway lines L9 and L10 are the most recent projects to improve the subway system adding 49 km and 52 new stations. They are under construction since 2006.

collected from Instituto Geográfico Nacional (IGN) (IGN, 1991, 2008).

Figure 3: Roman roads in Spain



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

Figure 4: Spanish 19th Century Main Roads

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

Figure 5: Spanish 19th Century Railroad Network

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

In order to use these instruments, they have to be exogenous and relevant. *A priori*, all three instruments are exogenous because of the length of time since these old infrastructures were built and the fundamental changes in the society and the economy (Duranton and Turner, 2012). In this sense, the BMR's suburbanization process is a phenomenon relatively new that dated back to mid-1980's (Muñiz et al., 2003). It seems obvious that none of these old transportation networks were built to anticipate neither current density patterns nor the current suburbanization process. On the contrary, the main reasons for building these networks were military and administrative reasons, political and communication reasons, or the adaption to the "new" transportation modes. Appendix B provides further details. Because these old infrastructures were not placed randomly and some of the factors that influenced their location may have also influenced modern transportation improvements, instruments exogeneity hinges on controlling for physical geography and historical population.

Conceptually, the relevance of these instruments rest on the fact that new transportation infrastructures are not built in isolation of previous and older infrastructures. In general, new infrastructures are easier and cheaper to build close to old infrastructures (Duranton and Turner, 2012). However, it is also possible that new infrastructures are far from the old networks because of differences in the main reason that motivated their construction (economic vs. political decisions) or due to the competition between transportation modes (road vs. railroads). For the case of Spain, Holl (2011) and Bel (2011) point out the critical role of these historical networks for the placement of the new transportation infrastructure.

4. Results

4.1. OLS Results

I first estimate Eq. (2) by OLS. Although coefficient estimates are not valid due to the endogeneity problem, I use OLS results for descriptive purposes.

Table 2 presents OLS results describing the effects of the 2001-1991 changes in distance to the nearest highway ramp and the distance to the nearest railroad station on the 2006-1991 changes in log population densities. Odd columns show unconditional results, that is, without any control variable. Coefficients on highways indicate that tracts with higher reductions in their distances to the highway system grow more quickly in the entire BMR (column 1) and, in particular, in suburban areas (columns 5 and 7).

Simultaneously, these improvements have a negative impact on growth inside the CBD. Both results are consistent with the finding of Baum-Snow (2007a) that highway improvements cause suburbanization.

Except for the CBD, coefficients on railroads show that tracts located further away from stations grow more quickly. Since the railroad system is older and its stations are located in the most developed and dense tracts of each area, these results also show that when a new transportation infrastructure is built, development occurs first nearby. Then, those nearby tracts get fully developed and subsequent development takes place further away.

Table 2: Changes in Population Location Patterns and Improvements in Highways and Railroads, OLS - Unconditional vs. Conditional Effects

Dependent Variable:	2006-1991 Δln(Population Density)							
Area:	Entire BMR		CBD		Subcenters		Non-Central	
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
ΔDistance to the nearest H. Ramp	-0.0203^{a}	-0.0076^{a}	0.0137^{c}	0.0181^{b}	-0.0195^{a}	-0.0053	-0.0138^{a}	-0.0098^{a}
	(0.003)	(0.003)	(0.008)	(0.008)	(0.007)	(0.005)	(0.004)	(0.004)
Distance to the nearest R. Station	0.0865^{a}	-0.0177^{a}	0.0450	-0.0797^{c}	0.0439^{c}	-0.0166	0.0383^{a}	-0.0246^{a}
	(0.008)	(0.007)	(0.043)	(0.042)	(0.024)	(0.017)	(0.007)	(0.008)
ln(1991 Population Density)		-0.1282^{a}		-0.0983^{a}		-0.2274^{a}		-0.1300^{a}
		(0.006)		(0.012)		(0.016)		(0.010)
Adjusted R^2	0.07	0.21	0.00	0.04	0.04	0.45	0.05	0.30

Notes: All regressions include a constant term. 3182, 1992, 568 and 622 observations for BMR, CBD, Subcenters and Non-Central Areas regressions, respectively. Robust standard errors in parentheses. ^{a}, ^{b}, and ^{c}: Significant at the 1, 5, and 10 percent level, respectively.

Even columns in Table 2 include initial population density as control and, thus, presents conditional results. Since coefficients on highway improvements vary only slightly and become insignificant for subcenters, the above interpretations apply: while highway improvements foster population growth in the entire BMR and, in particular, in non-central suburban areas, they have a negative impact on CBD tracts growth.

As for railroad stations, its coefficients dramatically change and become negative, indicating that, conditional on density, proximity to stations have a positive effect on tract growth, in particular in non-central suburban areas. This conditional effect complements the first finding of a negative unconditional effect: on average, each additional kilometer closer to the nearest station reduces population growth, but conditioning out the fact that nearly everything around the station is dense and developed and that high density tracts grow more slowly, proximity to station still has a positive effect on nearby growth.

Since BMR results are on average, I turn my attention to three extended area results[9]. In Table 3, I gradually include controls for census tract location (columns 1, 4 and 5), physical geography (columns 2, 5 and 8), and history (columns 3, 6 and 9). Adding these controls only changes the significance of CBD coefficients on both transportation variables, which become insignificant. As a result, these extended results confirm the previous ones: railroad proximity and highway improvements have a positive effect on population growth only in non-central areas. Since the Barcelona Metropolitan Region is undergoing a suburbanization process, these results also indicate that transportation improvements cause suburbanization and affect its spatial pattern.

Table 3: Changes in Population Location Patterns and Improvements in Highways and Railroads, OLS - Extended Conditional Effects

Dependent Variable:	2006-1991 Δln(Population Density)								
Area:	CBD			Subcenters			Non-Central Areas		
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
ΔDistance to Ramp	0.0179^b	0.0105	-0.0040	-0.0083	-0.0033	-0.0026	-0.0179^a	-0.0202^a	-0.0196^a
	(0.007)	(0.010)	(0.009)	(0.006)	(0.006)	(0.006)	(0.004)	(0.005)	(0.005)
Distance to Station	-0.0744	-0.0581	-0.0740	-0.0058	-0.0125	-0.0138	-0.0182^b	-0.0171^b	-0.0169^b
	(0.057)	(0.053)	(0.055)	(0.021)	(0.024)	(0.025)	(0.008)	(0.008)	(0.008)
ln(1991 Pop Density)	-0.0989^a	-0.0991^a	-0.0972^a	-0.2392^a	-0.2462^a	-0.2449^a	-0.1383^a	-0.1433^a	-0.1451^a
	(0.012)	(0.012)	(0.012)	(0.021)	(0.022)	(0.022)	(0.011)	(0.014)	(0.015)
Distances to CBD	Y	Y	Y	Y	Y	Y	Y	Y	Y
Geography	N	Y	Y	N	Y	Y	N	Y	Y
ln(Past Populations)	N	N	Y	N	N	Y	N	N	Y
Adjusted R^2	0.03	0.03	0.04	0.45	0.46	0.46	0.31	0.31	0.31

Notes: All regressions include a constant term. 1992, 568 and 622 observations for CBD, Subcenters and Non-Central Areas regressions, respectively. Robust standard errors in parentheses. ^{a}, ^{b}, and ^{c}: Significant at the 1, 5, and 10 percent level, respectively.

4.2. IV Results

First Stage and Reduced Form Results

To econometrically test the relevance of my candidates for instrument, I implement Murray (2006a,b)'s strategy. I estimate reduced form equations predicting transportation improvements (first stage estimates) and population (density) growth (reduced form estimates) as a function of all my candidates. In general, I choose as an instrument the candidate with coefficients significantly different from zero and with signs that support intuition: positive or negative for first stage results, indicating that transportation improvements are close to or far from the instrument, and negative for reduced

[9]BMR results are similar to non-central results and are in Appendix Table C.1.

form results, indicating that proximity to the instrument fosters population growth.

Columns 1-3 of Table 4 presents first stage results for the 2001-1991 changes in distance to the nearest highway ramp, and columns 4-6 for the distance to the nearest railroad station. Columns 7-9 shows reduced form results. Each set of regressions includes the three extended conditional specifications. Panels A, B, and C report results for CBD, subcenters, and non-central suburban areas, respectively.

Table 4: First Stage and Reduced Form Results, OLS

	First Stage Estimates						Reduced Form Estimates		
Dependent Variable:	2001-1991 ΔDist to Ramp			Dist to Station			2006-1991 Δln(Pop Dens)		
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Panel A. CBD									
Dist to Roman Road	-0.4592^a	-0.2922^a	-0.3625^a	0.1496^a	0.1456^a	0.1414^a	-0.0404^a	-0.0300^b	-0.0329^b
	(0.039)	(0.035)	(0.032)	(0.018)	(0.021)	(0.021)	(0.014)	(0.015)	(0.015)
Dist to 19th c. Road	0.1284^a	0.1563^a	0.1645^a	-0.0732^a	-0.0510^a	-0.0644^a	-0.0101	-0.0157	-0.0191
	(0.042)	(0.045)	(0.036)	(0.015)	(0.016)	(0.015)	(0.017)	(0.017)	(0.020)
Dist to 19th c. Rail.	-0.9028^a	-0.6017^a	-0.7060^a	-0.0140	-0.0125	0.0016	-0.0038	0.0120	0.0099
	(0.047)	(0.044)	(0.038)	(0.014)	(0.018)	(0.019)	(0.013)	(0.014)	(0.013)
ln(1991 Pop Dens)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Distances	Y	Y	Y	Y	Y	Y	Y	Y	Y
Geography	N	Y	Y	N	Y	Y	N	Y	Y
ln(Past Pop)	N	N	Y	N	N	Y	N	N	Y
Adjusted R^2	0.35	0.48	0.62	0.38	0.43	0.48	0.03	0.04	0.04
Panel B. Subcenters									
Dist to Roman Road	-0.4238^a	-0.4755^a	-0.4974^a	-0.0289^a	-0.0150^c	-0.0093	0.0027	0.0040	0.0039
	(0.046)	(0.015)	(0.016)	(0.011)	(0.009)	(0.010)	(0.003)	(0.004)	(0.004)
Dist to 19th c. Road	-0.5095^a	-0.1042^a	-0.1810^a	0.1045^a	0.1088^a	0.0885^a	-0.0141^a	-0.0104^c	-0.0102^d
	(0.041)	(0.018)	(0.021)	(0.015)	(0.016)	(0.016)	(0.005)	(0.006)	(0.007)
Dist to 19th c. Rail.	-0.5695^a	-0.2392^a	-0.1183^a	0.1053^a	0.1059^a	0.1050^a	-0.0187^b	-0.0205^b	-0.0293^a
	(0.081)	(0.035)	(0.044)	(0.028)	(0.024)	(0.028)	(0.009)	(0.009)	(0.011)
Adjusted R^2	0.44	0.84	0.86	0.37	0.47	0.48	0.47	0.47	0.47
Panel C. Non-Central Areas									
Dist to Roman Road	-0.4930^a	-0.4470^a	-0.4168^a	0.2266^a	0.1872^a	0.1916^a	-0.0012	0.0007	0.0008
	(0.060)	(0.043)	(0.049)	(0.041)	(0.038)	(0.039)	(0.008)	(0.008)	(0.008)
Dist to 19th c. Road	0.2781^a	0.1392^a	0.0954^b	0.1723^a	0.2269^a	0.2211^a	-0.0236^a	-0.0244^a	-0.0224^a
	(0.041)	(0.040)	(0.041)	(0.034)	(0.033)	(0.033)	(0.005)	(0.006)	(0.006)
Dist to 19th c. Rail.	0.4984^a	0.0789^c	0.0510	0.3091^a	0.3095^a	0.3029^a	0.0021	0.0129^c	0.0134^c
	(0.048)	(0.047)	(0.050)	(0.043)	(0.051)	(0.051)	(0.006)	(0.008)	(0.008)
Adjusted R^2	0.47	0.57	0.61	0.56	0.60	0.61	0.30	0.31	0.31

Notes: All regressions include a constant term. 1992, 568 and 622 observations for regressions in Panel A, Panel B and Panel C, respectively. Robust standard errors in parentheses. ^{a}, ^{b}, ^{c}, and ^{d}: Significant at the 1, 5, 10 and 20 percent level, respectively.

The selection of instruments is easier for subcenters regressions. According to the abovementioned strategy, I choose the distances to the nearest 19th century main road and to the nearest 19th century railroad as instruments. First stage results indicate that highways are improved far from these

19th century infrastructures, whereas modern stations are close to them. Reduced form estimates indicate that proximity to these old networks has a positive effect on population (density) growth.

As for CBD regressions, the selection is not so clear because only one candidate fulfills both criteria: the distance to the nearest Roman road. Since I have two endogenous variables, I choose the distance to the nearest 19th century main road as my second instrument because all its first stage coefficients are significant. For selected instruments, first stage results indicate that highway improvements are far from Roman roads and close to 19th century main roads, whereas railroad stations are near Roman roads and far from 19th century main roads. Reduced form estimates indicate that proximity to Roman roads has a positive effect on population (density) growth.

Similarly, I select the distance to the nearest 19th century main road as instrument for non-central suburban regressions. Despite not satisfying the second criterion, I also select the distance to the nearest Roman road. Their first stage results indicate that highways are improved far from Roman roads and near 19th century main roads, whereas modern stations are close to both old infrastructures. Reduced form estimates show that proximity to the 19th century main roads fosters population growth. I do not choose distance to the 19th century railroad because its reduced form results do not support intuition: its positive coefficients indicate that proximity to this infrastructure has a negative effect on growth.

TSLS Results

Table 5 presents TSLS estimates for Eq. (3). Column 1 include only transportation variables. Column 2 adds initial density as control, column 3 adds location variables, column 4 adds physical geography variables, and columns 5 adds municipal populations every 20 years from 1910 to 1970. Panels A, B, and C report results for CBD, suburban subcenters, and non-central suburban areas, respectively, using their selected instruments.

Table 5 also reports first stage F-statistics for my selected instruments[10]. Since I have two endogenous variables, I present a global F-statistic and two individual F-statistics, one for each endogenous variable. For my unconditional specification in column 1 and my preferred conditional specifications in columns 4 and 5, all individual and most global F-statistics pass the size

[10]They are computed from first stage regressions that only include my selected instruments. Their results are pretty similar to results in Table 4 and are available upon request.

and relative bias tests proposed by Stock and Yogo (2005) in the context of TSLS estimations[11].

Table 5: Changes in Population Location Patterns and Improvements in Highways and Railroads, IV

Dependent Variable:	2006-1991 Δln(Population Density)				
	[1]	[2]	[3]	[4]	[5]
Panel A. CBD					
Instruments: Distances to the nearest Roman Road and to the nearest 19th c. Main road					
2001-1991 ΔDist to Ramp	0.0768	-0.0685	-0.1016	-0.0654	-0.3290
	(0.062)	(0.081)	(0.101)	(0.057)	(0.242)
Distance to Station	0.0064	-0.4192^c	-0.4937^c	-0.2649^b	-0.8067^c
	(0.147)	(0.221)	(0.278)	(0.111)	(0.472)
ln(1991 Population Density)		-0.1388^a	-0.1437^a	-0.1262^a	-0.1394^a
		(0.026)	(0.030)	(0.017)	(0.030)
Distances	N	N	Y	Y	Y
Geography	N	N	N	Y	Y
ln(Past Populations)	N	N	N	N	Y
First Stage Statistic	16.59	8.70	5.08	24.29	2.56
First Stage Statistic Ramp	61.81	38.57	28.07	56.37	8.57
First Stage Statistic Station	37.53	31.49	19.47	50.16	8.40
Panel B. Subcenters					
Instruments: Distances to the nearest 19th c. Main Road and to the nearest 19th c. Railroad					
2001-1991 ΔDist to Ramp	-0.2106^a	-0.0904	0.0041	-0.0297	-0.0343
	(0.056)	(0.073)	(0.021)	(0.029)	(0.028)
Distance to Station	0.2412^a	0.0007	-0.1550^a	-0.1732^b	-0.2503^b
	(0.075)	(0.113)	(0.053)	(0.069)	(0.099)
ln(1991 Population Density)		-0.1778^b	-0.2323^a	-0.2235^a	-0.2171^a
		(0.072)	(0.025)	(0.031)	(0.033)
First Stage Statistic	12.72	1.59	15.62	15.85	9.47
First Stage Statistic Ramp	33.77	5.09	38.18	52.18	35.95
First Stage Statistic Station	115.36	16.59	42.35	38.08	22.55
Panel C. Non-Central Areas					
Instruments: Distances to the nearest Roman Road and to the nearest 19th c. Main Road					
2001-1991 ΔDist to Ramp	-0.0868^b	-0.0503^c	-0.0240^c	-0.0355^c	-0.0392^c
	(0.043)	(0.032)	(0.012)	(0.019)	(0.022)
Distance to Station	-0.0045	-0.0843^a	-0.0547^a	-0.0746^a	-0.0740^a
	(0.017)	(0.023)	(0.018)	(0.021)	(0.023)
ln(1991 Population Density)		-0.1682^a	-0.1629^a	-0.1652^a	-0.1614^a
		(0.018)	(0.015)	(0.017)	(0.017)
First Stage Statistic	4.22	4.71	75.45	35.73	21.39
First Stage Statistic Ramp	9.56	10.82	133.74	106.95	63.36
First Stage Statistic Station	78.91	55.76	72.07	70.15	63.60

Notes: All regressions include a constant term. 1992, 568 and 622 observations for regressions in Panel A, Panel B and Panel C, respectively. Robust standard errors in parentheses. ^{a}, ^{b}, and ^{c}: Significant at the 1, 5, and 10 percent level, respectively. Endogenous variables are instrumented simultaneously.

In general, TSLS results and their OLS counterparts (in Tables 2 and 3) mostly coincide in coefficient interpretation, but differ in magnitude and significance of some variables. If I restrict the attention to unconditional results (column 1), TSLS coefficients on highways confirm the positive effect

[11] Specifications 5 in Panel A and 1 in Panel C do not pass weak instrument tests. LIML estimates provide identical results.

of their improvements on growth and are, on average, 10.8 and 6.3 larger (in absolute values) for subcenters and non-central regressions, respectively. This variable becomes insignificant for CBD regressions. TSLS results also confirm the negative impact of proximity to railroad stations on growth, but only for subcenters.

For conditional results (columns 2-5), TSLS coefficients on stations dramatically increase by an average factor of 27.4 and 14.8 for CBD and subcenters regressions, respectively[12]. Most importantly, now these coefficients are significant for central areas regressions, indicating that proximity to stations have a positive effect on growth in such areas. TSLS coefficients on railroads and highway improvements remain significant and confirm their possitive effect in non-central areas. On average, they are 3.7 and 2.5 larger than their corresponding OLS estimates.

In summary, my TSLS results indicate that transportation affects urban spatial structure. In particular, transportation improvements cause suburbanization and influence the spatial pattern of this process attracting population to non-central suburban tracts that improve their access to the highway system and to central and non-central suburban tracts near railroad stations. Inside the CBD, transportation also affects the spatial distribution of residences attracting population near railroad stations.

Two interesting OLS findings related the effect of transportation infrastructures to the length of time since they were built and the degree of land development. My TSLS results verify these two findings. In particular, unconditional results indicate that population increases in undeveloped tracts close to new transportation infrastructures (highways) and far from old transportation infrastructures (railroads) whose nearby tracts are fully developed. Conditional on land development (density), results also suggest that population still increases near old infrastructures (railroads).

In Table 6 I explore in more detail the second finding by estimating the conditional effect of the 1991 distance to the nearest highway ramp and the distance to the nearest railroad station on the 2006-1991 changes in log population densities. For the non-central area, in columns 1-3 I present OLS regressions, while in columns 4-6 I report TSLS regressions. These regressions are similar to their OLS and TSLS counterparts in Tables 2 (columns 7-9) and 5 (columns 3-5 Panel C), respectively[13]. Results suggest that the sec-

[12]Despite those increments, TSLS-OLS differences are not economically significant. As shown in Table 1, population decreases (-6.0%) and slitghly increases (1.6%) in CBD and subcenters, respectively.

[13]Table 6 also reports first stage F-statistics for my selected instruments. Specification

ond finding still holds for railroads, but not for highways: proximity to 1991 highway ramps has a negative effect on non-central growth. These opposite effects between transportation infrastructures may be due to differences in types of residential development: while tracts around railroad stations show high dwelling densities and can accommodate more growth, residential development in tracts near highway ramps is based on low dwelling densities.

Table 6: Changes in Population Location Patterns and
1991 Highways and Railroads, OLS and IV: Non-Central Suburban Areas

Dependent Variable:	2006-1991 Δln(Population Density)					
	OLS			IV		
	[1]	[2]	[3]	[4]	[5]	[6]
				Instr.: Roman and 19th c. Roads		
1991 Distance to Ramp	0.0122^a	0.0118^b	0.0108^b	0.0321^c	0.0529^c	0.0704^c
	(0.004)	(0.005)	(0.005)	(0.017)	(0.031)	(0.041)
Distance to Station	-0.0289^a	-0.0247^a	-0.0233^a	-0.0860^a	-0.1310^a	-0.1553^b
	(0.008)	(0.009)	(0.009)	(0.022)	(0.045)	(0.069)
ln(1991 Population Density)	-0.1357^a	-0.1421^a	-0.1448^a	-0.1680^a	-0.1784^a	-0.1753^a
	(0.011)	(0.014)	(0.015)	(0.016)	(0.023)	(0.023)
Distances	Y	Y	Y	Y	Y	Y
Geography	N	Y	Y	N	Y	Y
ln(Past Populations)	N	N	Y	N	N	Y
Adjusted R^2	0.30	0.30	0.30			
First Stage Statistic				31.80	10.52	4.09
First Stage Statistic Ramp				72.91	34.54	15.45
First Stage Statistic Station				51.95	24.21	12.73

Notes: All regressions include a constant term. 622 observations for each regression. Robust standard errors in parentheses. ^{a}, ^{b}, and ^{c}: Significant at the 1, 5, and 10 percent level, respectively. Endogenous variables are instrumented simultaneously.

5. Conclusions

This paper investigates the effects of transportation improvements on changes in population location patterns in metropolitan Barcelona between 1991 and 2006. It contributes to the existing literature using data on a much finer geographical scale, census tracts in the CBD, suburban subcenters, and non-central suburban areas, and by considering two types of transportation infrastructure, the highway system through its ramps and the railroad network through its stations.

Because of the endogeneity of infrastructure provision, I rely on IV techniques in order to obtain unbiased estimates. It is also a novelty of the paper

6 does not pass weak instrument tests. Its LIML estimates provide identical results. First stage and reduced form results for selecting instruments are in Appendix Table C.2.

the use of three historic instruments at the intrametropolitan level: the Roman roads, the 19th century main roads and the 19th century railroads. Furthermore, to my knowledge, the use of Roman roads as instrumental variable is new to the literature.

Main results verify and extend the finding of Baum-Snow (2007a) that transportation cause suburbanization: both highway and railroad improvements foster population growth in suburban areas, whereas the transit system also affects the location of population inside the CBD.

Results also indicate that the effect of transportation infrastructures depends on the length of time since they were built, the degree of land development and the type of residential development: population increases in undeveloped tracts close to new transportation infrastructures (2006-1991 highways) and far from old transportation infrastructures (railroads and 1991 highways) whose nearby tracts are fully developed. If residential development of those nearby tracts is based on high dwelling densities, this old infrastructure (railroads) still has a positive effect on nearby growth. If residential development is based on low dwelling densities, population increases far from the old infrastructure (1991 highways).

I leave for future research two topics related to this paper. Since this paper is centered on changes in intrametropolitan location patterns, the first topic is to analyze the effect of transportation improvements on residential land consumption patterns. Since Barcelona is also undergoing a process of employment decentralization that might affect the process of population suburbanization, the second topic is to study simultaneously the effect of transportation improvements on both processes.

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Appendix A. Barcelona's Data

The Barcelona Metropolitan Region is one of the most important European metropolises. It was delimited in 1966 by the Pla Director de l'Àrea Metropolitana, defined by law in 1987 by Lleis d'Ordenació Territorial, and it is currently used as a functional region for Planning purposes by the Pla Territorial General de Catalunya (PTGC)[14]. Made up of 164 municipalities grouped in 7 "comarques" or counties, the BMR covers an area of 324,000 ha in a radius of approximately 55 km. Because of its steep topography, only 67,999 ha were urbanized in 2002[15].

The BMR has been characterized as polycentric by Garcia-López (2010). Defining Barcelona municipality as the main center, the author identifies 7 main subcenters in 2005 (Figure A.1). Using census tract data, main centers are identified applying the non-parametric methodology based on locally weighted regression (LWR) and developed by McMillen (2003). The idea is to estimate a density function that represents a monocentric spatial structure. Using it as a benchmark, the groups of significant deviations from the monocentric configuration (real densities greater than estimated densities) that surpass a cutt-off are the centers.

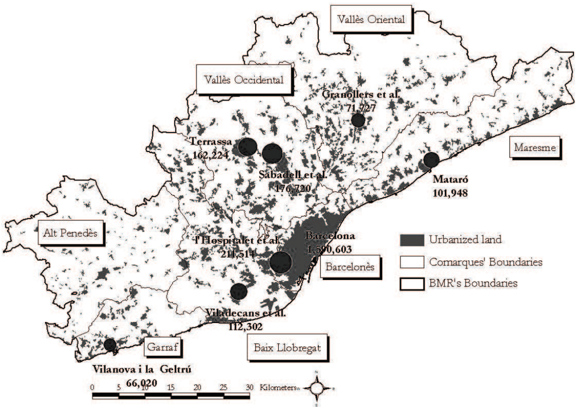
Figure A.2 is upside-down and shows the 2006 estimated three-dimensional density pattern overlapping BMR's transportation infrastructure. Using

[14]The PTGC is the basic planning tool in Catalonia, where other 6 functional regions are considered. For more information, see `http://ca.wikipedia.org/wiki/Pla_territorial_general_de_Catalunya`.

[15]See Muñiz et al. (2008), Garcia-López and Muñiz (2010), Muñiz and Garcia-López (2010) or Garcia-López and Muñiz (2012), among others, for further details.

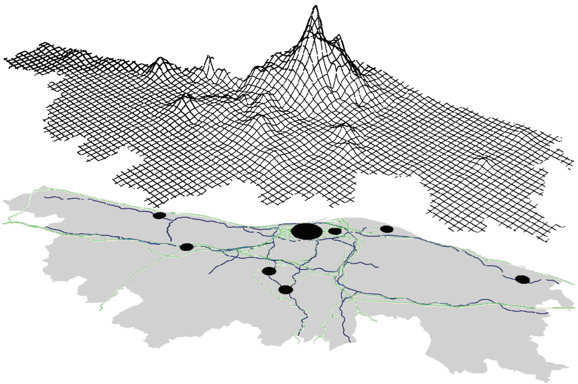
GIS software, the 3D profile is estimated by LWR using an inverted distance weight function and a 1% "neighborhood"[16].

Figure A.1: Polycentricity in Barcelona: CBD and subcenters, 2006



Source: Own elaboration.

Figure A.2: Polycentricity in Barcelona: Density and Infrastructure, 2006



Source: Own elaboration.

Since the number of Barcelona's census tracts changed between 1991 and 2006 from 3,569 to 3,864, I use their related shapefiles to merge some of them and get a sample of 3,182 census tracts with identical boundaries in 1991 and 2006.

To compute location variables, I consider the CBD and 7 subcenters

[16]See McMillen (2001), Redfearn (2009) and McMillen and Redfearn (2010) for details on the LWR procedure.

identified by Garcia-López (2010). I use GIS software to obtain tract centroid coordinates and calculate distances in straight line (km) from each centroid to the CBD's central tract centroid and to the nearest subcenter central tract centroid.

To measure physical geography, I compute 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`). This variable is the average terrain ruggedness index for each census tract. I also compute distance in kilometers from each tract centroid to coast. I do not include tract altitude as explanatory variable because it is highly correlated with the terrain ruggedness index (60%) and distance to coast (80%).

History variables, past populations, are computed at a municipal level because tract data were not available until 1991. These data come from 1910, 1930, 1950 and 1970 Population Censuses produced by the Instituto Nacional de Estadística (INE).

Appendix B. Old Transportation Infrastructures as Instruments

My three instruments are based on old transportation infrastructures in Spain: the Roman roads, the 19th century main roads, and the 19th century railroad lines.

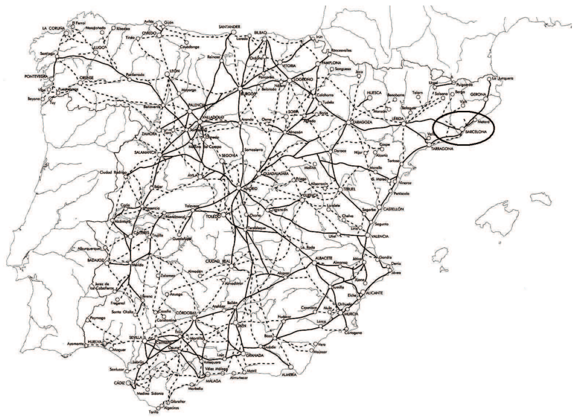
As most European cities that were founded by Romans and/or were part of the Roman Empire, the very beginning of Barcelona's transportation infrastructure are the Roman roads[17]. Although other ancient roads existed, Romans were the first to build a real road system, with paved and crowned roads. At the beginning of the Roman influence, these main roads were built for military purposes: first, the conquest of Hispania (Spain) and, later, its defense. These strategic roads passed through mountains and avoided valleys. During the Pax Romana period some of these military roads were abandoned whereas others were modified to pass through less steeper and faster routes. Furthermore, new roads were built in order to improve the accessibility of Hispania. The resulting road system formed a decentralized mesh network that allowed Barcelona (and Hispania) to increase its

[17]Although Iberians and Greeks settled in the area before the Romans, the foundation of Barcelona as a city was formalized by Caesar Augustus in 14 B.C. with the name of Iulia Augusta Faventia Paterna Barcino or, its shortened name, Barcino. For more details, see `http://en.wikipedia.org/wiki/History_of_Barcelona`.

administrative and commercial relations with the rest of the Empire (Font-i Garolera, 1999; Carreras and de Soto, 2010; Bel, 2011).

My second instrument is based on main roads at the end of the 19th century. This infrastructure was an adaption and an upgrade of the 18th century post routes to the use of automobile. At the very beginning of the 18th century, the Bourbon dynasty came to power in Spain, succeeding the Habsburg dynasty. The new king, Philip V, changed the Spanish political system from a federation of kingdoms to an absolutist state and, as a result, all the political power was centralized in the capital. Adopting the Paris model, Madrid became the real "center" of Spain with the construction of a new transportation infrastructure for the postal service funded by the crown (Figure B.1): a mainly radial network that neglected most of the previous Roman roads. This radial system was designed to improve communications between Madrid and the rest of the new unified king. Since main roads at the end of the 19th century followed the 18th century post routes, I only use the former as instrument[18].

Figure B.1: The Spanish 18th Century Post Routes



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

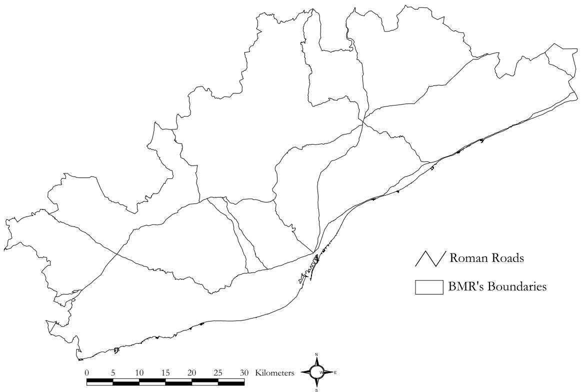
Finally, I consider the 19th century railroad lines because land transportation and its infrastructure also changed dramatically with the appearance of this new transportation mode based on the steam engine, the steam locomotive. As abovementioned in Appendix A, this network was developed during the second half of the 19th century by private companies such as the

[18]The partial correlation between their distances varies from 55% to 79% for CBD and subcenters samples, respectively.

Nothern Company or the Madrid-Zaragoza-Alicante (MZA) Company and without following any general plan. At the very beginning, railroad development was not regulated and private companies were left to extend the network at their will in search of profits. Ulterior developments were regulated by the 1855, 1867 and 1877 laws, prioritizing projects that connected Madrid with the rest of Spain. As a result, the 19th century railroad was designed following the radial system inherited from the 18th century. See Artola (1978) and Font-i Garolera (1999) for more details on the development of railroads in Spain and Catalonia (Barcelona), respectively.

As abovementioned, I use vector digital maps based on de Soto (2010) and Carreras and de Soto (2010) to compute my instruments. These archaeologists analyze the Spanish economy for different historical periods through the study of their transportation infrastructures and their related transportation costs and shipping patterns. Their main innovation is the use of spatial data analysis with GIS and the creation of digital maps. As an example of these maps, Figure B.2 shows Roman roads in the BMR.

Figure B.2: The BMR's Roman Roads



Source: Own elaboration based on de Soto (2010).

Appendix C. Supplemental Results

OLS Results

For the entire BMR, Table C.1 presents OLS results for the three extended conditional specifications. Results confirm the positive effect of both railroad and highway improvements on population (density) growth.

Econometrically, the suburbanization process is verified through positive coefficients on distance to the CBD, which indicate that population increases far away from the CBD. Furthermore, negative coefficients on distance to the nearest subcenter suggests that population also increases close to the suburban subcenters.

Table C.1: Changes in Population Location Patterns and Improvements in Highways and Railroads, OLS - Extended Conditional Effects: BMR

Dependent Variable:	2006-1991 Δln(Population Density)		
Area:	Entire BMR		
	[1]	[2]	[3]
2001-1991 ΔDistance to the nearest Highway Ramp	-0.0054^c	-0.0090^b	-0.0096^a
	(0.003)	(0.004)	(0.004)
Distance to the nearest Railroad Station	-0.0220^a	-0.0174^b	-0.0164^b
	(0.007)	(0.007)	(0.007)
ln(1991 Population Density)	-0.1255^a	-0.1293^a	-0.1271^a
	(0.007)	(0.007)	(0.008)
Distance to CBD	0.0023^a	0.0015^c	0.0004
	(0.001)	(0.001)	(0.001)
Distance to the nearest Subcenter	-0.0046^a	-0.0034^b	-0.0026^c
	(0.001)	(0.002)	(0.002)
Ruggedness		-0.0010^a	-0.0009^b
		(0.000)	(0.000)
Distance to Coast		0.0015	0.0008
		(0.002)	(0.002)
ln(Past Populations)	N	N	Y
Adjusted R^2	0.21	0.21	0.21

Notes: All regressions include a constant term. 3182 observations for each regression. Robust standard errors in parentheses. ^{a}, ^{b}, and ^{c}: Significant at the 1, 5, and 10 percent level, respectively.

First Stage Results

For non-central areas, columns 1-3 of Table C.2 presents first stage results for the 1991 distance to the nearest highway ramp, and columns 4-6 for the distance to the nearest railroad station. Columns 7-9 shows reduced form results. Each set of regressions includes the three extended conditional specifications that gradually add location variables (columns 1, 4 and 7), geography variables (columns 2, 5 and 8), and history variables (columns 3, 6 and 9).

According to Murray (2006a,b)'s strategy, I choose the distance to the nearest 19th century main road as instrument. Although it does not fulfill both criteria, I choose the distance to the nearest Roman road my second instrument because all its first stage coefficients are significant. I do not choose distance to the 19th century railroad because its reduced form results do not support intuition: its positive coefficients indicate that proximity to this infrastructure has a negative effect on growth. For selected instruments, first stage results indicate that 1991 highways and railroads are close to Roman roads and 19th century main roads. Reduced form estimates indicate that proximity to the 19th century main roads roads has a positive effect on non-central suburban growth.

Table C.2: First Stage and Reduced Form Results, OLS
Non-Central Areas and 1991 Distance to the nearest Highway

	First Stage Estimates						Reduced Form Estimates		
Dependent Variable:	1991 Dist to Ramp			Dist to Station			2006-1991 Δln(Pop Dens)		
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Dist to Roman Road	0.5931[a]	0.5059[a]	0.4609[a]	0.2266[a]	0.1872[a]	0.1916[a]	-0.0012	0.0007	0.0008
	(0.057)	(0.047)	(0.053)	(0.041)	(0.038)	(0.039)	(0.008)	(0.008)	(0.008)
Dist to 19th c. Road	-0.0085	0.1616[a]	0.2157[a]	0.1723[a]	0.2269[a]	0.2211[a]	-0.0236[a]	-0.0244[a]	-0.0224[a]
	(0.051)	(0.049)	(0.049)	(0.034)	(0.033)	(0.033)	(0.005)	(0.006)	(0.006)
Dist to 19th c. Rail.	-0.2017[a]	0.0732	0.1060[d]	0.3091[a]	0.3095[a]	0.3029[a]	0.0021	0.0129[c]	0.0134[c]
	(0.062)	(0.076)	(0.072)	(0.043)	(0.051)	(0.051)	(0.006)	(0.008)	(0.008)
ln(1991 Pop Dens)	Y	Y	Y	Y	Y	Y	Y	Y	Y
Distances	Y	Y	Y	Y	Y	Y	Y	Y	Y
Geography	N	Y	Y	N	Y	Y	N	Y	Y
ln(Past Pop)	N	N	Y	N	N	Y	N	N	Y
Adjusted R^2	0.52	0.59	0.64	0.56	0.60	0.61	0.30	0.31	0.31

Notes: All regressions include a constant term. 622 observations for each regression. Robust standard errors in parentheses. Selected instruments are highlighted in grey. [a], [b], [c], and [d]: Significant at the 1, 5, 10 and 20 percent level, respectively.

2010

2010/1, De Borger, B., Pauwels, W.: "A Nash bargaining solution to models of tax and investment competition: tolls and investment in serial transport corridors"
2010/2, Chirinko, R.; Wilson, D.: "Can Lower Tax Rates Be Bought? Business Rent-Seeking And Tax Competition Among U.S. States"
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2011

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