Institut d'Economia de Barcelona

IEB Working Paper 2018/02

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EVIDENCE FROM EUROPEAN CITIES

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Cities

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ALL ROADS LEAD TO ROME... AND TO SPRAWL? EVIDENCE FROM EUROPEAN CITIES [*]

Miquel-Àngel Garcia-López

ABSTRACT: I investigate the effect of highways on residential sprawl in European cities between 1990 and 2012. I find that a 10% increase in the stock of highways (km) causes a 0.4% growth in the residential land area, a 1.7% growth in the number of residential lots, and a 0.7% growth in the percentage of undeveloped land surrounding residential land over 20 years. At the regional level, only the effect on residential area is smaller in Northwestern cities than in Mediterranean and Eastern LUZs. I also explore the impact on population growth a la Duranton and Turner (2012) and find significant positive effects. Jointly, land and population results show a negative effect of highways on the intensity of use of land. As a whole, these results confirm that highways expand cities with more fragmented residential developments surrounded by undeveloped land and reducing the overall city density.

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[*] Financial support from Ministerio de Economía y Competitividad (research project ECO614-52999-R), Generalitat de Catalunya (research projects 2014SGR1326), and 'Xarxa de Referència d'R+D+I en Economia Aplicada' is gratefully acknowledged.

1. Introduction

Traditionally, European cities have been settlements with higher density and more continuous land developments than their American counterparts, and sprawl has been considered a US phenomenon. However, European cities were more compact and less sprawled in the mid 1950s than they are today. Computations based on data from Corine Land Cover project show that residential land in Europe increased from 139,000 to 157,000 square kilometers (13%) between 1990 and 2012[1]. These new land developments were more fragmented and simultaneously increased the number of residential land lots from 121,000 to 143,000 (18%). Although the percentage of undeveloped land surrounding residential land did not increase in Europe as a whole (36%), it indeed increased in Eastern Europe from 40 to 42% and in some Mediterranean and Northwestern cities. As a whole, these recent trends in land developments are rising some concerns about the future of compactness in Europe (European Environment Agency, 2006, 2010, Couch, Leontidou, and Petschel-Held, 2007, Arribas-Bel, Nijkamp, and Scholten, 2011).

At the same time, although the first highway dates back to the early twentieth century and, by the mid-1980s, some Northwestern countries had built national networks of remarkable length and achieved high levels of infrastructural density, highway construction is still ongoing in Europe: the European network increased from 44,000 to 68,000 km (46%) between 1990 and 2010. In fact, highway construction is a priority for the European Union: the new transportation policy was approved in 2014 with a budget of €24 billion up to 2020 and it aims to encompass 90,000 km of highways and high-quality roads by 2020.

Those who claim the emergence of sprawl in Europe also point out its connection with highways: new low-density and discontinuous land developments are observed along highway corridors (European Environment Agency, 2006, Couch *et al.*, 2007). The question is whether this is a causal relationship. Do highways expand cities with new land developments? Do they encourage scattered or compact developments? Do they foster developments with more undeveloped surroundings?

To answer these three questions, in this paper I investigate the effect of highways on sprawl in European cities between 1990 and 2012. I find that a 10% increase in the stock of highways (km) causes a 0.4% growth in the residential land area, a 1.7% growth in the number of residential lots, and a 0.7% growth in the percentage of undeveloped land surrounding residential land over 20 years. At the regional level, only the effect on residential area is smaller in Northwestern cities than in Mediterranean and Eastern LUZs. I also explore the impact on population growth *a la* Duranton and Turner (2012) and find significant positive effects. Jointly, land and population effects show a negative effect of highways on the intensity of use of land. These results confirm that highways expand cities with more fragmented land developments surrounded by undeveloped land and reducing the overall city density.

This investigation is of interest for three reasons. First, although this is not the first attempt to study the determinants of sprawl, the literature on this topic is still scarce. Brueckner and

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[1] This increase is similar to the 17% increase in overall developed (urban) land in the US between 1990 and 2007 (Nickerson, Ebel, Brochers, and Carriazo, 2011).

Fansler (1983), Deng, Huang, Roxell, and Uchida (2008), McGrath (2005) focus on the spatial sizes of cities in terms of developed land area. Burchfield, Overman, Puga, and Turner (2006) and Angel, Parent, and Civco (2012) analyze the type of land developments, scattered or compact, with an indicator that measure the percentage of undeveloped land surrounding developed land. Finally, Oueslati, Alvanides, and Garrod (2015) study the size of the developed land area and its fragmentation in different land lots. Since the 'size of developed land area', the 'degree of fragmentation' and the 'degree of undeveloped surroundings' are all dimensions that jointly characterize sprawl, in this research I analyze all of them: the expansion of cities with new land developments in a scattered (compact) way and by increasing (decreasing) their undeveloped surroundings. Furthermore, I take advantage of my dataset to study the effects of transportation on population growth (*a la* Duranton and Turner (2012)) and, by comparing land and population effects, I assess the effect on city density conditions.

Second, it furthers our understanding on the effects of transportation. Recent research shows that highways shape cities. They foster urban growth (Duranton and Turner, 2012), cause population suburbanization (Baum-Snow, 2007, Garcia-López, Holl, and Viladecans-Marsal, 2015*a*, Garcia-López, Pasidis, and Viladecans-Marsal, 2015*b*) and employment decentralization (Baum-Snow, Brandt, Henderson, Turner, and Zhang, Forthcoming), spread suburban population out along their ramps (Garcia-López, 2012, Garcia-López *et al.*, 2015*a*), and modify local zoning policies (Garcia-López, Solé-Ollé, and Viladecans-Marsal, 2015*c*). However, little is known about their role in sprawling cities in terms of land developments.

This paper is among the first to provide empirical evidence on this topic. Brueckner and Fansler (1983), McGrath (2005) and Angel *et al.* (2012) use 'indirect' indicators to proxy transportation: the percentage of households owning automobiles and the consumer price index for private transportation. Burchfield *et al.* (2006) study the effect of the density of major suburban roads, neglecting the effect of central roads on population and employment suburbanization and, as a result, on sprawl. On the other hand, Deng *et al.* (2008) and Oueslati *et al.* (2015) use the density of highways at the regional and county levels, respectively. These measurements exceeds LUZ and urban core boundaries and, as a result, include additional information that might bias their results. In this paper I use the length of the highway network at the metropolitan level as my main explanatory variables. With it, I pay attention not only to commuting costs, but also to the size of the highway network.

Furthermore, the above mentioned related literature assume that their transportation variables are exogenous to land development. In this paper I address endogeneity concerns relying on Instrumental Variables (IV) techniques with historical instruments built on ancient (rail)roads such as the 3rd century Roman roads, the 15th century trade routes, and the 19th century post roads (1810) and railroads (1870).

Finally, this research is important because it provides relevant evidence that was needed for Europe. European cities are interesting not only for the emergence of sprawl and the huge investments on highways, but also because of differences in household location patterns, for example, by income: richer central cities and poorer suburbs than their American counterparts (Brueckner, Thisse, and Zenou, 1999). While most papers center their analyses on US cities, only Oueslati *et al.* (2015) exclusively focus on Europe and, in particular, on 282 European cities. However, they use dependent variables computed at the city level whereas most of their explanatory variables and, in particular, the transportation one are computed at the regional level. In this paper I focus on a more representative set of 579 European cities from 29 countries, I use more recent land data (2012) and I compute all variables at the city level.

The remainder of the paper is structured as follows. In the next section, I describe the sprawl phenomenon in Europe and its cities and the highway network and other old (rail)roads. In Section 3, I review the theoretical and empirical literature. The empirical strategy is discussed in Section 4. In Sections 5, 6 and 7 I answer the three questions about the relationship between highways and sprawl. In Section 8, I analyze the effects on population growth and, by comparison, on residential density conditions. Finally I present conclusions in Section 9.

2. Sprawl and highways in Europe

I use the Large Urban Zone (LUZ) defined by Eurostat in the Urban Audit project as the unit of observation. As the Metropolitan Statistical Area (MSA) in the US and the Functional Urban Area (FUA) for the OECD, the LUZs are funtional urban regions defined using commuting criteria[2].

My dataset includes 579 LUZs located in 29 European countries. Based on political, cultural and geographical reasons, I group the cities in three cateogries. First, the *Mediterranean* group includes 171 LUZs located in Greece, Spain, Cyprus, Southern France ('le Midi'), Italy, Malta and Portugal.

The *Eastern* group includes 156 LUZs located in Bulgaria, Czech Republic, East Germany (old German Democratic Republic), Estonia, Croatia, Hungary, Latvia, Poland, Romania, and Slovakia.

Finally, the 252 *Northwestern* LUZs are located in Austria, Belgium, Switzerland, West Germany (old Federal Replublic of Germany), Denmark, Finland, Northern France, Ireland, Iceland, Luxembourg, Latvia, The Netherlands, Norway, Sweden, and United Kingdom.

2.1 *Sprawl in Europe*

To measure sprawl in terms of residential land developments, I use land data from the Corine Land Cover (CLC) project. Coordinated by the European Environment Agency, the project integrates CLC databases from 27 to 39 European countries in 1990 and 2012, respectively. The CLC is produced by the majority of countries by visual interpretation of high resolution satellite imagery, using a minimun mapping unit of 25 ha for areal phenomena (5 ha for changes in land cover layers) and a minimum width of 100 m for linear phenomena[3].

The CLC database and related GIS maps are available for years 1990, 2000, 2006 and 2012 (the latest update used in this research was released in November 2015) and classify land in 44 classes. There are 11 classes labeled as 'Artificial surface' and I jointly use them to compute 'All developed land' variables in additional descriptives in Table A.3 Panel A and in additional results

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[2] See `http://ec.europa.eu/eurostat/statistics-explained/index.php/European_cities_-_spatial_dimension` for more details.

[3] See `http://land.copernicus.eu/pan-european/corine-land-cover/view` for further information.

in Table D.1. Similarly, class 121 is labeled as 'Industrial and commercial units' and I use it for 'Industrial and commercial land' computations in Table A.3 Panel B and Table D.2. However, my main focus is on residential sprawl and, as a result, I only consider 'Artificial' classes more related with houses: Classes 111 and 112 are labeled as 'Urban fabric' and I use them to compute 'Residential land' variables[4].

I characterize residential sprawl with the three above mentioned dimensions. First, I use the CLC vector maps to measure the 'size of residential land developments' (and its evolution) with the square kilometers of residential land area for 1990 and 2012.

Second, the 'degree of fragmentation' is measured with the number of residential land lots. In this case, residential land lots are identified as discontinuous polygons in the CLC vector maps.

Finally, to measure the 'degree of undeveloped surroundings' I compute the *sprawl* index proposed by Burchfield *et al.* (2006): the percentage of undeveloped land surrounding residential land. To do so, I use the CLC raster maps (100 m resolution) for 1990 and 2012. For each residential cell I compute the percentage of undeveloped land in the surrounding square kilometer. The index for each LUZ is computed averaging across all residential cells in each LUZ.

Table 1 shows computations of these three indicators for Europe, the whole sample of 579 European cities, and each of the three regional subsamples of LUZs. As a whole, residential land increased from 139,000 to 157,000 square kilometers in Europe between 1990 and 2012 (13%). At the city level, residential area also grew in European LUZs, being the Eastern cities the ones that experienced the highest growth both in absolute (3,082 km^2) and relative (25%) terms.

Table 1: Residential land area, fragmentation and surroundings in Europe and its cities

	Area (km^2)			Fragmentation (*Lots*)			Surroundings (% *Und.*)	
	1990	2012	1990–2012	1990	2012	1990–2012	1990	2012
Europe (29)	139,334	156,691	17,357 (13%)	121,270	142,794	21,524 (18%)	36.9	36.5
All 579 LUZs	63,622	71,162	7,540 (12%)	43,000	50,106	7,106 (17%)	37.4	37.1
171 Medit	12,398	14,243	1,845 (15%)	7,822	9.077	1,255 (16%)	37.3	36.3
156 Eastern	12,371	15,453	3,082 (25%)	10,836	14,194	3,358 (31%)	39.6	42.0
252 NWest	38,853	41,466	2,613 (7%)	24,342	26,835	2,493 (10%)	35.0	33.3

Notes: 'Area' refers to square kilometers of developed land area, 'Fragmentation' refers to the number of residential land lots, and 'Surroundings' refers to the % of undeveloped land surrounding residential land. Total areas are: 4,851,351 km^2 for Europe (29 countries), 976,178 km^2 for the 579 LUZs, 217,785 km^2 for the 171 Mediterranean cities, 241.078 km^2 for the 156 Eastern cities, and 517,315 km^2 for the 256 Northwestern cities.

These new residential developments were more fragmented and the number of residential lots increased from 121,000 to 143,000 (18%) in all Europe, and from 43,000 to 50,000 (17%) in all LUZs. Similarly to area results, the 1990-2012 growth in the degree of residential fragmentation was more important in Eastern cities (3,358 lots, 31%) (Table 1).

Regarding the surroundings, Table 1 results show that the average percentage of undeveloped land surrounding residential land only increased in Eastern cities (from 40 to 42%), while this

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[4] I do not pay attention to the other eight 'Artificial' classes because they are very heterogeneous (e.g., 'Mineral extraction sites', 'Dump sites', and 'Construction sites') and include land directly related to transportation infrastructure such as 'Road and rail networks and associated land', 'Port areas', and 'Airports' classes.

index decreased in Mediterranean cities (from 37 to 36%) and in Northwestern cities (from 35 to 33%).

While area and fragmentation indicators in Table 1 were computed as total indicators (i.e., sum of all LUZ values), Table 2 reports the main summary statistics: mean and standard deviation for each LUZ sample. In 2012, an average European city had 123 square kilometers of residential land and was made up of 87 residential land lots. By regions, Northwestern cities were bigger and more fragmented than Eastern LUZs and, in particular, Mediterranean LUZs. Similar to Table 1 results, the average residential area and the average number of residential lots increased between 1990 and 2012, and the rates were higher in Eastern cities (37% and 61%, respectively) and smaller in Northwestern LUZs (9% and 10%, respectively). The high standard deviations for the area and fragmentation indicators show that their year values and, in particular, their growth rates were quite different not only between LUZ samples, but also within them.

Table 2: Residential land area, fragmentation and surroudings in LUZs: Summary statistics

	All 579		171 Medit		156 Eastern		252 NWest	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1990–2012 Residential land area growth (%)	19.1	32.2	18.3	25.8	36.5	50.8	8.9	7.5
2012 Residential land area (km^2)	122.9	175.8	83.3	115.5	99.1	122.7	164.5	222.8
1990 Residential land area (km^2)	109.9	166.2	72.5	100.3	79.3	99.3	154.2	217.2
1990–2012 Fragmentation growth (%)	32.4	83.0	39.1	110.8	61.2	100.6	10.1	15.49
2012 Fragmentation (*Number of lots*)	86.5	105.1	53.1	55.9	91.0	106.2	106.5	123.3
1990 Fragmentation (*Number of lots*)	74.3	94.6	45.7	51.1	69.5	88.3	96.6	113.9
1990–2012 Undeveloped surroundings growth (%)	-0.6	15.8	-1.6	20.0	7.7	16.7	-5.1	8.2
2012 Undeveloped surroundings (%)	36.5	10.7	36.3	8.6	42.0	9.8	33.3	11.2
1990 Undeveloped surroundings (%)	36.9	10.3	37.3	8.5	39.6	10.2	35.0	11.2

As for the surroundings indexes that were already computed in their sample means in Table 1, their growth rates reported in Table 2 confirm the decrease of undeveloped land in the average European city and in the average Northwestern and Mediterranean LUZs, but also the average increase of this index in Eastern cities. These important differences in the surroundings values between LUZ samples is also observed within LUZ samples, as shown by their high standard deviations. In fact, all LUZ samples also include cities that experienced an increased in the percentage of undeveloped surroundings: A third of the 579 European cities (182), that is, 40 Mediterranean, 91 Eastern, and 51 Northwestern LUZs.

In Table 3 I report individual computations for the 60 larger LUZs, the ones with population over million inhabitants in 2012. According to their residential area, the 5 largest cities in 2012 were London (UK), Paris (FR), Berlin (DE), Essen (Ruhrgebiet, DE) and Warszawa (PL), and the 5 smallest ones were Sevilla (ES), Valencia (ES), Rotterdam (NL), Bucuresti (RO), and Torino (IT). Most cities increased their residential area and the top LUZs with highest growth were Warszawa (PL), Kraków (PL), Athina (EL), Madrid (ES) and Hamburg (DE). In fact, there were 5 cities that reduced their size: Barcelona (ES), Birmingham (West Midlands, UK), Helsinki (FI), Manchester (UK), and Sofia (BF).

Table 3: Residential land area, fragmentation and surroundings in 60 LUZs with population over one million, 1990–2012

	Area			Fragmentation		Surroundings			Area			Fragmentation		Surroundings	
LUZ (Country)	Total	1990	2012	1990	2012	1990	2012	LUZ (Country)	Total	1990	2012	1990	2012	1990	2012
Amsterdam (NL)	2,914	346	388	101	107	19.9	15.5	London (UK)	8,024	1,867	1,887	325	367	14.4	13.4
Antwerpen (BE)	1,191	308	314	66	67	27.9	26.1	Lyon (FR)	3,670	443	474	290	308	36.3	33.5
Athina (EL)	3,030	386	543	85	102	16.5	15.6	Madrid (ES)	8,025	545	654	234	309	27.5	24.6
Barcelona (ES)	1,794	384	358	169	171	29.2	26.3	Manchester (UK)	1,817	560	532	42	53	14.7	13.5
Berlin (DE)	17,484	1,329	1,336	972	997	31.3	30.1	Mannheim (DE)	2,045	223	243	168	180	36.1	34.9
Bordeaux (FR)	5,543	381	444	202	229	32.3	31.1	Marseille (FR)	4,235	360	421	167	202	30.2	29.2
Braunschweig (DE)	4,128	297	333	322	348	43.0	40.3	Milano (IT)	2,638	521	562	257	258	28.1	26.6
Bremen (DE)	5,895	375	419	288	313	39.7	36.5	München (DE)	5,499	485	512	313	365	30.7	30.5
Bruxelles (BE)	3,266	843	848	248	253	41.4	40.2	Napoli (IT)	1,552	362	392	112	98	35.7	32.5
Bucuresti (RO)	1,078	203	226	60	58	18.1	16.1	Newcastle (UK)	5,437	227	248	76	92	19.3	18.9
Budapest (HU)	6,077	660	721	215	216	25.0	23.2	Nürnberg (DE)	2,934	278	287	199	246	36.4	37.5
Dresden (DE)	5,835	463	507	416	502	41.7	44.3	Oslo (NO)	7,428	345	351	152	154	24.4	24.4
Dublin (IE)	6,991	327	395	117	144	20.0	20.2	Ostrava (CZ)	3,878	340	342	340	344	47.9	47.4
Düsseldorf (DE)	1,202	277	285	107	151	27.0	24.7	Paris (FR)	12,098	1,742	1,793	982	981	25.6	24.7
Frankfurt (DE)	4,303	471	517	356	389	36.3	34.5	Porto (PT)	952	209	242	87	105	36.5	31.5
Gdansk (PL)	2,630	140	245	80	191	29.4	38.3	Praha (CZ)	6,980	548	604	722	761	45.9	44.5
Glasgow (UK)	3,373	383	413	76	95	16.6	16.8	Roma (IT)	5,744	506	551	280	284	32.0	30.6
Grad Zagreb (HR)	3,903	242	249	130	136	37.5	37.1	Rotterdam (NL)	1,518	188	209	65	67	16.2	12.9
Hamburg (DE)	7,343	744	851	458	578	31.8	30.9	Ruhrgebiet (DE)	4,440	1,011	1,060	301	335	23.0	20.5
Hannover (DE)	2,973	321	345	230	251	36.5	35.0	Sevilla (ES)	3,076	125	142	68	70	30.4	24.7
Helsinki (FI)	3,822	471	442	232	200	26.6	25.1	Sofia (BG)	5,717	332	327	243	255	34.6	34.5
Katowice (PL)	3,945	483	544	281	335	34.3	36.1	Stockholm (SE)	7,093	582	592	269	279	19.1	19.3
Kraków (PL)	3,757	172	421	161	315	45.1	49.6	Stuttgart (DE)	3,654	482	499	360	402	39.2	37.0
Köln (DE)	1,626	335	360	131	161	25.8	25.9	Torino (IT)	1,781	218	227	115	110	28.3	28.3
København (DK)	2,789	470	483	155	151	17.0	15.9	Toulouse (FR)	5,246	306	389	192	232	36.2	32.9
Leeds (UK)	1,494	231	252	64	89	21.7	23.5	Valencia (ES)	1,443	130	165	104	118	37.2	31.9
Leipzig (DE)	3,979	298	332	250	374	37.5	40.4	Warszawa (PL)	8,615	561	917	368	725	35.5	39.7
Lille (FR)	1,443	265	289	148	144	30.0	28.0	West Midlands (UK)	2,075	613	581	62	83	9.5	9.8
Lisboa (PT)	3,901	387	488	206	246	32.5	29.6	Wien (AT)	9,205	822	890	616	740	39.1	40.3
Liverpool (UK)	725	287	288	27	26	10.7	10.2	Zürich (CH)	1,090	253	254	117	116	30.2	30.1

Notes: 'Area' refers to square kilometers of developed land area, 'Fragmentation' refers to the number of developed land lots, and 'Surroundings' refers to the % of undeveloped land surrounding residential land.

In 2012, the more compact cities were Liverpool (UK), Manchester (UK), Bucuresti (RO), Rotterdam (NL), and Antwerpen (BE), and the more fragmented were Warszawa (PL), Wien (AT), Praha (CZ), Paris (FR), and Berlin (DE). Between 1990 and 2012, while there were cities that became more compact decreasing the number of residential lots, such as Helsinki (FI), Napoli (IT), Torino (IT), Lille (FR) and København (DK), most LUZs became more fragmented, such as Hamburg (DE), Wien (AT), Leipzig (DE), Kraków (PL) and Warsawa (PL).

Finally, the heterogeneity between and within LUZ samples can also be observed in the surroundings indicator computed *a la* Burchfield *et al.* (2006). In 2012, the lower rates of undeveloped surroundings were in Birmingham (West Midlands, UK), Liverpool (UK), Rotterdam (NL), London (UK) and Manchester (UK), and the most sprawled cities with highest percentages were Leipzig (DE), Dresden (DE), Praha (CZ), Ostrava (CZ) and Kraków. Between 1990 and 2012, a quarter of the 60 LUZs (14) increased their undeveloped surroundings, such as Gdansk (PL), Krakóv (PL), Warszawa (PL), Leipzig (DE) and Dresden (DE), while this index was smaller in the other 46 cities, such as Sevilla (ES), Valencia (ES), Porto (PT), Amsterdam (NL) and Rotterdam (NL).

As a whole, results in Tables 1, Table 2, and 3 show that European cities are undergoing a process of sprawl that increases their size with new and more fragmented residential land developments and, in some cases, with a higher percentage of undeveloped surroundings. Additional summary statistics in Appendix Table A.1 confirm the above mentioned spatial trends.

2.2 *Highways in Europe*

2.2.1 *Modern highways*

The study of highways in Europe is important for, at least, three reasons. First, highways are a short and long term priority for the European Union. The goal of the Trans-European Transport Network (TEN-T) programme and, in particular, of the Trans-European Road Network (TERN) project is to improve the internal road infrastructure of the EU (see Council Decision 93/629/EEC). The TERN includes highways and high-quality roads, whether existing, new or to be adapted, which play an important role in long-distance traffic, bypass urban centers, provide interconnection with other modes of transport, or link landlocked and peripheral regions to central regions of the Union (see Article 9 of Decision 661/2010/EU).

Second, as Duranton and Turner (2012) highlight for the case of US, highways are large segments of the economy and large amounts of money are devoted to road transportation. According to the ERF 2010 European Road Statistics, 53% of the EU structural funds were allocated to roads between 2007 and 2013. Furthermore, the above mentioned new EU transportation policy was approved in 2014 with a budget of €24 billion up to 2020[5]. Given the magnitude of these investments it is important that the impact of the EU policy on city's outcomes be carefully evaluated.

Finally, highway construction in Europe was important during the 20th century and it is still ongoing in the 21st century. The first European highways date back to the early twentieth

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[5] See `http://ec.europa.eu/transport/themes/infrastructure/index_en.htm` for further information.

century and were built in Italy (83 km in 1925). Up to 1940, two other countries built highways, Germany (with its *Reichsautobahn* program) and the Netherlands. By 1960, there were around 259 km of highways concentrated in the above mentioned countries, but also few kilometers were built in Belgium, Croatia and Poland. Between 1960 and 1980 highways unevenly spread in Europe with almost 28,000 new kilometers of highways. In particular, some Northwestern countries built national networks of remarkable length and achieved high levels of infrastructural density. Between 1980 and 1990, the European Union partially funded highway construction in Mediterranean countries, in particular in Spain, Greece and Portugal, and the network increased with 16,000 km. Similarly, with the latest enlargements of the European Union, the EU Regional policy targeted the new members from Eastern Europe and funded the expansion of the European highway network up to 68,000 km in 2010. The above mentioned TERN project aims to encompass 90,000 km of highways and high-quality roads by 2020.

Table 4: Highways and old (rail)roads in Europe and its cities

Km of	Highways						
	1990	2010	1990–2010	200 Roman	15th Trade	1810 Post	1870 Rail
Europe-29	43,502	67,779	24,227 (46%)	103,090	19,615	128,000	81,151
All 579 LUZs	22,834	32,270	9,436 (41%)	7,721	2,051	10,784	13,616
171 Medit	5,586	10,432	4,846 (87%)	3,984	152	2,492	2,005
156 Eastern	1,655	3,533	1,878 (114%)	411	526	1,888	1,671
252 NWest	15,593	18,305	2,712 (17%)	3,326	1,373	6,404	9,940

Table 5: Highways and old (rail)roads in LUZs: Summary statistics

	All 579		171 Medit		156 Eastern		252 NWest	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
2010 Km of highways	55.7	74.8	61.0	78.1	22.7	41.5	72.6	82.0
1990 Km of highways	39.4	62.8	32.7	47.2	10.6	25.8	61.9	78.2
Km of Roman roads	13.3	52.0	23.3	90.2	2.6	7.3	13.2	23.4
Km of Trade routes	3.5	10.0	0.9	5.7	3.3	8.9	5.5	12.2
Km of 1810 Post roads	18.6	28.7	14.6	18.3	12.1	11.5	25.4	38.8
Km of 1870 Railroads	23.5	48.0	11.7	16.7	10.7	19.0	39.5	66.7
Km of max(Roman roads, 1870 Railroads)	29.8	67.5	27.1	90.1	12.5	19.1	42.4	66.5
Km of max(Roman, Trade, 1810 Post, 1870 Rail)	34.7	67.3	31.3	90.1	18.1	18.8	47.4	66.2

To measure highways I use the dataset developed by Garcia-López *et al.* (2015*b*) using Eurostat data at the country level and the RRG GIS Database at the LUZ level. Tables 4 and 5 show total and summary statistics (mean and standard deviation) of the length of the highway network for each LUZ sample. These computations confirm that, at the city level, the highway network is not evenly distributed between LUZ samples. Both in 1990 and 2010, Northwestern cities had the largest total (15,000 and 18,000 km) and average length (62 and 73 km), whereas the Eastern ones had smaller networks (1,600 and 3,500 km, and 33 and 61 km). Between 1990 and 2010, LUZ highways increased from 23,000 to 32,000 km, and half of the new kilometers were built in Mediterranean cities (4,800 km), which almost double their average size (from 33 to 61 km). At a smaller scale, Eastern LUZs also double their highway network (from 11 to 23 km). Similar to land variables, the high standard deviations also show big differences between LUZs in the same sample in terms of individual network sizes and growth rates.

Table 6 shows the evolution of different transportation networks in the 60 most populated European cities. For the case of highways, the bigger networks in 2012 were in Madrid (ES), Essen (Ruhrgebiet, DE), Paris (FR), London (UK) and Berlin (DE), and the smaller ones were in Warszawa (PL), Newcastle (UK), Gdansk (PL), Bucuresti (RO) and Ostrava (CZ). Between 1990 and 2010, 23 cities, mainly Northwestern ones, do not changed their highway length such as London (UK), Berlin (DE), Bruxelles (BE), Lille (FR), Rotterdam (NL) or Oslo (NO), among others. The remaining 556 LUZs increased their highway network, in particular in Madrid (ES), Dublin (IE), Barcelona (ES), Porto (PT) and Lisboa (PT).

As a whole, LUZ sample computations in Tables 4 and 5 and individual computations in Table 6 show that highways (and their construction) are unevenly distribution in Europe and between its cities.

2.2.2 *Ancient 'highways'*

Tables 4, 5 and 6 also report length computations for transportation networks in Europe that were important in the past: the Roman roads, the 15th century Trade routes, the 1810 Postal roads, and the 1870 Railroads. As I elaborate in detail in the next section, the lengths of some of these old (rail)roads predict modern highways. Furthermore, the lengths of some combinations of them still affect modern patterns of residential land.

I first consider the Roman road network using the GIS map created by McCormick, Huang, Zambotti, and Lavash (2013). The Romans were the first to built an extensive and sophisticated network of paved and crowned roads. These roads radiated from Rome and connected the different parts of the Empire, from Britain to Syria (O'Flaherty, 1996). As a whole, there were more than 100,000 km of main and secondary roads in Europe. At the city level, 7,700 km of Roman roads were built in 285 LUZs, that is, 4,000 km in 123 Mediterranean cities, 3,300 in 136 Northwestern cities, and only 400 km in 26 Eastern cities (Table 4).

This uneven spatial distribution of Roman roads between and within LUZ samples can also be observed in the mean and standard deviation computations in Table 5 and 6: with an average length of 23 km, the largest Roman networks were in Mediterranean cities (e.g., Rome (IT), Barcelona (ES), Athina (EL), Marseille (FR) and Lisboa (PT)), but also in some Northwestern cities (e.g., London (UK), Paris (FR), Stuttgart (DE), Manchester (UK) and München (DE)), and only in three largest Eastern cities (Zagreb (HR), Budapest (HU) and Sofia (BF)).

Based on Ciolek (2005)'s digital map, I compute the length of the main trade routes in the Holy Roman Empire in the 15th century. As its name indicates, the map includes the main routes between Central and Eastern cities (e.g., Berlin (DE), Wien (AT), Warszawa (PL), Budapest (HU) or Zelenogradsk (RU)), but also with some other main European cities (e.g., Paris (FR), Basel (CH), Bruxelles (BE), Genova (IT) or Milano (IT)). As a whole, there were around 20,000 km of routes in Europe, 2,000 km in 134 of 579 LUZs (79 Northwestern, 43 Eastern and 12 Mediterranean cities). Computations in Tables 4, 5 and 6 show the smaller spatial scope of this network.

Table 6: Highways and old (rail)roads in 60 LUZs with population over one million

Km of	Highways						Km of	Highways					
LUZ (Country)	1990	2010	Roman	Trade	1810 Post	1870 Rail	LUZ (Country)	1990	2010	Roman	Trade	1810 Post	1870 Rail
Amsterdam (NL)	228	275	0	0	0	24	London (UK)	460	460	220	0	438	784
Antwerpen (BE)	126	167	1	12	6	25	Lyon (FR)	235	235	52	0	44	33
Athina (EL)	91	177	64	0	25	0	Madrid (ES)	105	679	23	0	141	45
Barcelona (ES)	205	338	72	0	68	116	Manchester (UK)	146	146	71	0	124	343
Berlin (DE)	395	395	0	10	135	186	Mannheim (DE)	132	132	25	10	50	97
Bordeaux (FR)	159	179	36	0	23	20	Marseille (FR)	286	286	57	0	32	22
Braunschweig (DE)	184	184	0	47	53	59	Milano (IT)	193	205	119	60	138	103
Bremen (DE)	117	134	0	28	82	54	München (DE)	281	281	52	6	88	53
Bruxelles (BE)	267	267	34	0	38	152	Napoli (IT)	105	110	87	0	33	53
Bucuresti (RO)	10	28	0	0	26	1	Newcastle (UK)	2	4	29	0	78	94
Budapest (HU)	129	246	25	20	35	45	Nürnberg (DE)	172	172	0	60	84	64
Dresden (DE)	140	179	0	13	30	88	Oslo (NO)	139	139	0	0	49	25
Dublin (IE)	39	216	0	0	169	100	Ostrava (CZ)	0	54	0	0	46	59
Düsseldorf (DE)	223	249	8	3	10	114	Paris (FR)	530	535	131	16	200	260
Frankfurt (DE)	293	293	30	53	77	129	Porto (PT)	70	198	18	0	47	7
Gdansk (PL)	0	18	0	2	36	6	Praha (CZ)	130	149	0	17	52	53
Glasgow (UK)	88	162	15	0	98	237	Roma (IT)	225	271	1162	0	48	29
Grad Zagreb (HR)	95	192	19	0	18	16	Rotterdam (NL)	97	97	0	0	0	23
Hamburg (DE)	259	345	0	20	110	59	Ruhrgebiet (DE)	563	563	20	12	10	343
Hannover (DE)	171	171	0	30	25	57	Sevilla (ES)	41	151	23	0	45	8
Helsinki (FI)	147	180	0	0	0	15	Sofia (BG)	84	121	43	0	18	0
Katowice (PL)	83	122	0	21	20	138	Stockholm (SE)	250	278	0	0	15	13
Kraków (PL)	43	62	0	27	12	14	Stuttgart (DE)	89	89	86	2	33	82
Köln (DE)	149	149	14	59	25	99	Torino (IT)	135	151	61	0	16	80
København (DK)	141	141	0	0	35	15	Toulouse (FR)	113	204	28	0	20	48
Leeds (UK)	27	89	44	0	43	157	Valencia (ES)	19	75	12	0	15	9
Leipzig (DE)	94	124	0	36	32	116	Warszawa (PL)	0	0	0	15	18	49
Lille (FR)	123	123	13	0	24	30	West Midlands (UK)	180	180	45	0	144	267
Lisboa (PT)	162	288	40	0	56	16	Wien (AT)	214	277	41	19	77	99
Liverpool (UK)	59	59	8	0	94	142	Zürich (CH)	145	145	21	2	44	77

Following communication and, in particular, military reasons, post roads and post stations were built in Europe and contributed to the rise of absolute monarchies during the 17th and 18th centuries. While first post roads were relatively primitive, they were improved in the last quarter of the 18th century and allowed the use of wheeled coaches and wagons for carrying letters, goods and people. According to Crew, Kleindofer, and Campbell (2008), post stations were located every 10 to 15 miles. For the whole of Europe, there were around 8,000 post stations in 1,799 (Elias, 1982). As a result, I estimated the total length of European post roads in 128,000 km (=8,000 stations × 10 mi/station × 1.6 km/mi) (Table 4).

At the city level, I use a digital vector map that I created from the *Map exhibiting the great post roads, physical and political divisions of Europe* by A. Arrowsmith in 1810 and downloaded from the David Rumsey Historical Map Collection `http://www.davidrumsey.com`. Almost 11,000 km of 1810 post roads were built in 487 of 579 LUZs, mostly in Northwestern cities whose average length were the biggest (e.g., London (UK), Paris (FR), Dublin (IE) or Birmingham (UK)), but also in some Mediterranean and Eastern cities (e.g., Madrid (ES) or Praha (CZ)). According to the high standard deviations, the size of the 1810 post road network is quite heterogeneous within LUZ sample (Tables 5 and 6).

Finally, I consider the 1870 railroad network because, as Duranton and Turner (2012) point out, old railroads may be easily converted to automobile roads reducing construction costs such as levelling and grading. In fact, while the network kept expanding and linking up much of Europe between 1870 and 1900, many lines were closed down and some converted between 1900 and 1960 and, in particular, during the highway expansion between 1960 and 2010 (Garcia-López *et al.*, 2015*b*).

To compute the European and LUZ lengths, I create a digital vector map based on the online maps by Historical GIS for European Integration Studies (`http://www.europa.udl.cat/hgise`). As a whole, 81,000 km of railroads were built in Europe by 1870, and 13,000 km of them in 441 LUZs. Railroad construction clearly benefitted Northwestern cities with the biggest total and average network (almost 10,000 km and 40 km, respectively), and also the highest standard deviations (Tables 4 and 5). By region, the largest 1870 railroad networks were in Barcelona (ES) (116 km) and Milano (IT) (103 km) for Mediterranean cities, Katowice (PL) (137 km) and Leipzing (DE) (116 km) for Eastern cities, and London (UK) (780 km) and Manchester (UK) (343 km) for Northwestern cities (Table 6).

In summary, computations reported in Tables 4 and 5 confirm that highways and old (rail)roads are important in Europe and its cities, but also show their non-homogenous spatial distribution. Additional summary statistics in Appendix Table A.1 confirm the above mentioned spatial trends.

3. A brief literature review on urban spatial structure, residential land and sprawl

3.1 Theory

Transportation plays a crucial role in the spatial distribution of residences and firms within cities. The classical monocentric city model developed by Alonso (1964), Mills (1967) and Muth

(1969) shows that transportation (accessibility) is the main factor that determines urban land use (Duranton and Puga, 2015). Transportation is characterized as a non-limited, radial-type infrastructure covering the whole city in the same way and therefore allowing the same access to the unique main center or CBD from any point located at the same distance from this CBD. This homogeneous and continuous spatial distribution of transportation infrastructure leads to (1) a continuous (and non-fragmented) development of land for urban uses and (2) an homogeneous reduction in land use intensity (i.e., population density) as population moves away from the CBD.

The monocentric city model also predicts that transportation improvements foster both the physical expansion of the city with new and continuous residential land developments and the increase of city population. Since the former effect is larger than the latter, transportation improvements also foster the (relative) suburbanization of population and reduce the overall city density (Duranton and Puga, 2015).

Anas and Moses (1979) and, in particular, Baum-Snow (2007) extend the monocentric model by considering two competing transportation infrastructures. First, the classical transportation infrastructure based on a dense network of radial streets. Second, a high speed transit system (Anas and Moses, 1979) or a highway network (Baum-Snow, 2007) both based on sparse radial corridors. Depending on the cost of alternative transportation modes, the authors find that population spread out along the sparse corridors, increasing land rents and densities near them and decreasing elsewhere. As Anas and Moses (1979) show through several graphical examples, the total residential land area of the city, its size and its shape depend on the size of the transportation networks.

In the above mentioned works, residential land area is continuous (and non-fragmented) because the authors assume that highways and railroads can be accessed from any point of the network. On the contrary, if we assume that these infrastructures can only be accessed through their access points (highway ramps and railroad stations), population and residential land developments will locate around them (and not along the whole infrastructure). As a result, the number of residential land lots and the percentage of undeveloped surroundings also depend on the size of the transportation networks.

In summary, the theoretical literature on urban land use inspired by the monocentric model shows that transportation influences (1) the size of the city in terms of residential land, (2) the degree of fragmentation in terms of residential land lots, and (3) the degree of undeveloped surroundings.

3.2 *Empirics*

Despite several works document the phenomenon of sprawl in terms of land development in the US (Brueckner and Fansler, 1983, Burchfield *et al.*, 2006, McGrath, 2005, Paulsen, 2012), China (Deng *et al.*, 2008), Europe (Oueslati *et al.*, 2015) and even around the world (Angel *et al.*, 2012), the literature on the determinants of sprawl and, in particular, on the effects of transportation is still scarce.

According to the above mentioned three dimensions of sprawl, most papers study the impact of transportation (costs) on the spatial size of cities in terms of developed land area. For a sample of 40 US urbanized areas in 1970, Brueckner and Fansler (1983) do not find any significant effect related to two alternative proxies for commuting costs: the percentage of households owning automobiles and the percentage of commuters using public transit. On the contrary, McGrath (2005) uses panel data techniques in a sample of 33 large US cities between 1950 and 1990 and finds a significant negative effect of the consumer price index for private transportation. Centered on Chinese counties, Deng *et al.* (2008) find significant positive effects of the density of highways on buil-up area of urban cores between 1988, 1995 and 2000. Similarly, Oueslati *et al.* (2015) find significant positive effect of the regional density of highways in 282 European cities between 1990, 2000 and 2006.

Only Oueslati *et al.* (2015) study the impact of transportation in the degree of land fragmentation measured as the ratio between the number of urban land lots and total developed area. Contrary to their total developed land findings, there is no significant effect of the regional highway density.

Finally, Burchfield *et al.* (2006) and Angel *et al.* (2012) study the impact of transportation on the average percentage of undeveloped land surrounding developed land. Using the density of suburban roads as its transportation variable, Burchfield *et al.* (2006) do not find any significant effect in 275 US metropolitan areas between 1976 and 1992. On the contrary, Angel *et al.* (2012) find that a greater automobile ownership encourages compact developments and, as a result, reduces the percentage of undeveloped surroundings in 120 cities in the world. They suggest that this result arises when private transport complements public transit (railroads, buses) and development concentrates around their access points (railroad stations, bus stops).

The above works do not show a clear evidence of the effect of transportation on the phenomenon of sprawl. A possible explanation may be the transportation variables they use. Brueckner and Fansler (1983), McGrath (2005) and Angel *et al.* (2012) use 'indirect' proxies for commuting costs (private transportation ownership and price index). On the other hand, Burchfield *et al.* (2006), Deng *et al.* (2008) and Oueslati *et al.* (2015) use 'more direct' proxies (density of highways) that allow to measure the effect of the network size (while including commuting costs). However, by focusing on suburban roads, Burchfield *et al.* (2006) neglect the effect of central roads on population and employment suburbanization and, as a result, on sprawl. Deng *et al.* (2008) and Oueslati *et al.* (2015) use the density of highways computed at the county and regional levels, respectively. Since both measurements exceed the spatial boundaries used in the dependent variables (LUZs and county urban cores, respectively), results might be biased.

Another possible reason for these inconclusive results may be endogeneity (Duranton and Puga, 2015). While more cars or highways can lead to more (and fragmented) land development, cities that sprawl for other reasons can also cause an increase of car ownership and highways availability. Unfortunately, most of the above mentioned empirical papers assumes that their transportation variables are exogenous to land development. While this is true in the case of Burchfield *et al.* (2006) because of the construction of their dependent variable, endogeneity is not addressed in the other five papers and, as result, their estimated coefficients (and their stastistical significance) may be biased. As I elaborate in the following section, I address endogeneity concerns in my transportation explanatory variables relying on IV techniques.

4. The empirical strategy

4.1 *Empirical model*

To study the role of highways on residential sprawl in 579 LUZs, I empirically answer three questions: Do highways expand cities? Do they encourage scattered developments? Do they foster developments with more undeveloped surroundings?

To do so, I separately estimate the following growth equation with three residential land indicators as dependent variable: the 1990–2012 growth in (1) the km^2 of residential land area, (2) the number of residential land lots, and (3) the percentage of undeveloped land surrounding residential land.

$$\begin{aligned}
&\text{1990–2012 } \Delta\ln(\text{Residential land variable}) = \\
&\quad \alpha_0 + \alpha_1 \times \text{1990 ln(Km of highways)} \\
&\quad\quad + \alpha_2 \times \text{1990 ln(Km}^2\text{ of residential land area)} \\
&\quad\quad + \alpha_3 \times \text{1990 ln(Number of residential land lots)} \\
&\quad\quad + \alpha_4 \times \text{1990 ln(\% of undeveloped land surrounding residential land)} \\
&\quad\quad + \sum_i (\alpha_{5,i} \times \text{Geography}_i) + \sum_i (\alpha_{6,i} \times \text{History}_i) + \sum_i (\alpha_{7,i} \times \text{1990 Socioeconomy}_i)
\end{aligned} \tag{1}$$

My main explanatory variable is the 1990 length of the highway network (in km) and it measures the size of the network.

I simultaneously include the initial values of the three dependent variables: the 1990 km^2 of residential area, the 1990 number of residential lots, and the 1990 percentage of undeveloped surroundings.

I control for LUZ physical geography by including variables such as total land area (km^2), altitude (m), elevation range (m), and terrain ruggedness index *a la* Riley, DeGloria, and Elliot (1999).

I also add control variables for history. First, I control for population history with the decennial population[6] levels from 1960 to 1990. Second, since railroads are also important in European cities, I include rail history variables such as the km of railroads between 1960 and 1990. Third, I include dummy variables for LUZs (1) that were Roman settlements, (2) with monasteries between the 12th and 16th centuries, (3) with Bishoprics between years 600 and 1450, (4) with universities between the 12th and 15th centuries, (5) that used to be major towns between the 10th and the 15th centuries and (6) in 1850. Dummies (1) to (5) come from the Digital Atlas of Roman and Medieval Civilization (`http://darmc.harvard.edu`). Dummy (6) is based on Bairoch (1988).

Finally, I control for socioeconomic characteristics such as (1) income, proxied by the 1990 GDP, (2) unemployment rate, proxied by ((active population - employment)/active population), and (3) industrial composition, proxied by the share of employment in manufacturing. Since there are

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[6] Besides historical reasons, I also include the 1990 population to consider the effect of population on residential developments. In other specifications, I use the 1990–2010 population growth which I instrument with temperature and precipitation variables. Main results do not change and are available upon request.

no data available at the LUZ level, all three variables are computed using data from the NUTS3 where the LUZ is located.

Summary statistics for all explanatory variables are in Appendix Tables A.1 and A.2.

4.2 *Method*

Under the assumption that the random element of land development is uncorrelated with transportation, I can estimate Eq. (1) by ordinary least squares (OLS). However, as I pointed out in the two previous sections, highway length is expected to be endogenous to land development because of reverse causation (e.g., land developments fostering the construction of new highways), measurement error (e.g., the stock of highways mismeasured because some may have just opened ore are about to be opened) and omitted variables (e.g., geography, amenities or economic structure leading to more highways at the beginning of the period). To address endogeneity concerns I rely on IV estimations (two stage least squares, TSLS) which use historical instruments built on two combinations of the previously commented ancient (rail)roads in Europe: (1) the maximum length between the 3rd century Roman roads and the 1870 railroads, and (2) the maximum length between the 3rd century Roman roads, the 15th century trade routes, the 1810 post roads and the 1870 railroads.

Instruments need to be relevant. First, common sense suggests that they are because modern highways are not built in isolation of previous historical road networks. On the contrary, new infrastructures are easier and cheaper to build close to old infrastructures (Duranton and Turner, 2012).

Second, I econometrically test the relevance of each individual historical (rail)road and of their two combinations in Appendix B. I run first-stage regressions in which I separately regress the stock of the highway network (km) on the length of each ancient (rail)road (km). Valid instruments should have positive and significant effects on modern highways and high first-stage statistic values. I also run reduced-form regressions in which I separately regress the growth of each residential land variable (area, fragmentation and surroundings) on the length of each historical network. As Murray (2006) points out, valid instruments should also have positive and significant effects on the dependent variable of interest.

Results in Table B.1 show that, although some individual historical instruments predict the stock of highways (first-stage), only the two combinations of (old)railroads are valid instruments: they both predict the stock of highways (first-stage) and the dependent variables (reduced-form), and show first-stage statistics that are above the Stock and Yogo (2005)'s rule of thumb (F>10) and near or above the Stock and Yogo (2005) critical values for the size test in the context of TSLS estimation. Among these valid instruments, I use the one with the highest first-stage statistic. The selected instrument for residential area regressions is the maximum length between Roman roads and 1870 railroads whereas for fragmentation and surroundings regressions is the maximum length between Roman roads, trade routes, 1810 post roads and 1870 railroads. It is important to notice that these results are in line with the above mentioned non-homogeneous distribution of ancient (rail)roads: since none of the individual historical networks separately have a full European (sample) coverage, only the two combinations are valid instruments.

Instruments need to be exogenous. Historical transportation networks may be exogenous because of the length of time since they were built and the significant changes undergone by society and economy in the intervening years (Duranton and Turner, 2012). In my case, none of the ancient networks were built to anticipate the current land developments in European cities hundreds of years later. Roman roads were built to achieve military, administrative, and commercial goals between the different parts of the Roman Empire (Garcia-López *et al.*, 2015*a*). As above mentioned and their name indicate, the 15th century trade routes were built for commercial purposes (Garcia-López *et al.*, 2015*b*). The 18th and 19th centuries post roads were designed as a central government tool for nation building (military and communication purposes) (Garcia-López, 2012). Finally, similar to the US, most of the 1870 railroad network was built for profit by private companies at the beginning of the second industrial revolution, when cities' economy and industrial specialization were quite different than today (Duranton and Turner, 2012, Garcia-López, 2012).

Since the suitability of geography could have influenced the construction of both ancient (rail)roads and modern highways, it is important to control for physical geography to fulfill with the exogeneity condition. As above mentioned, I include geography variables such as total land area, altitude, elevation range and terrain ruggedness index for each LUZ.

Ancient (rail)roads have surely shaped the historical development of European cities in other ways (e.g., LUZs with more historical networks tend to be larger than other cities). As a result, my instruments predict my dependent variables (residential area, fragmentation and undeveloped surroundings growth) directly as well indirectly by predicting modern highways. According to Duranton and Turner (2011, 2012), the exclusion restriction requires the orthogonality of the dependent variable and the instrument conditional on control variables. In other words, the exogeneity of my instruments also hinges on having an appropriate set of historical controls. In my case, I consider the above mentioned decennial population levels from 1960 to 1990 (population history), the stock of railroads between 1960 and 1990 (rail history), and six dummy variables capturing the historical importance of each LUZ (city history).

In summary, I estimate Eq. (1) with three dependent variables related to three dimensions of sprawl: the growth of residential area, of fragmentation and of undeveloped surroundings between 1990 and 2012. Since my main explanatory variable (the 1990 stock of highways) is endogenous, I rely on IV estimations using the maximum length between Roman roads and 1870 railroads (area regressions) and the maximum length between Roman roads, 15th century trade routes, 1810 post roads and 1870 railroads (fragmentation and surroundings regressions) as my instruments. According to their first-stage and reduced-form results, and the above comments, I believe that these instruments are relevant and, conditional on controls, exogenous.

5. Do highways expand cities with new land developments?

To study the impact of highways on residential sprawl, I first investigate whether they foster new land developments increasing the residential land area (size) of the city as theory suggests. To do so, I use Eq. (1) to estimate the effect of the 1990 length (km) of highways on the 1990–2012 growth in residential land area.

Table 7 presents results for different specifications of Eq. (1). Column 1 includes the 1990 highway stock, the 1990 residential area and country fixed-effects, column 2 adds the 1990 fragmentation and surroundings variables, column 3 adds controls for geography, column 4 adds population, railroad and city history variables, and column 5 adds socioeconomic variables. Since descriptive results in Section 2 shows that there is some degree of regional heterogeneity both in the sprawl phenomenon and the highway network, I also explore whether highway effects are heterogeneous among European regions. To do so, columns 6-8 in Table 7 add a regional dummy and its interaction with the highway variable[7].

Table 7: The effect of highways on residential land area in European cities

Dependent variable:	1990–2012 Δln(Km^2 of residential land area)							
Region:						Med	East	NW
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A: OLS results								
1990 ln(Km of highways)	0.010	0.010	0.012	0.005	0.005	0.003	0.006	0.005
	(0.007)	(0.006)	(0.007)	(0.006)	(0.006)	(0.004)	(0.007)	(0.009)
1990 ln(Km of highways) × Region dummy						0.004	-0.005	0.000
						(0.013)	(0.007)	(0.009)
1990 ln(Km^2 of residential land area)	-0.039^{a}	-0.113^{b}	-0.123^{b}	-0.269^{a}	-0.270^{a}	-0.278^{a}	-0.272^{a}	-0.270^{a}
	(0.012)	(0.055)	(0.053)	(0.066)	(0.066)	(0.062)	(0.066)	(0.066)
Adjusted R^2	0.59	0.60	0.64	0.69	0.69	0.69	0.70	0.69
Panel B: TSLS results								
1990 ln(Km of highways)	0.056^{b}	0.048^{b}	0.051^{b}	0.041^{c}	0.041^{b}	0.039^{c}	0.032^{c}	0.047^{b}
	(0.027)	(0.024)	(0.020)	(0.021)	(0.020)	(0.021)	(0.019)	(0.022)
1990 ln(Km of highways) × Region dummy						0.010	0.013	-0.023^{c}
						(0.019)	(0.021)	(0.013)
1990 ln(Km^2 of residential land area)	-0.086^{a}	-0.144^{a}	-0.153^{a}	-0.275^{a}	-0.277^{a}	-0.283^{a}	-0.278^{a}	-0.274^{a}
	(0.029)	(0.056)	(0.049)	(0.055)	(0.055)	(0.050)	(0.056)	(0.053)
First-stage F-statistic	40.41	31.32	32.57	30.69	33.57	18.01	17.63	14.67
Instrument	ln(Km of max(Roman roads, 1870 Railroads))							
						ln(Km) × Region dummy		
1990 ln(Number of residential lots)	N	Y	Y	Y	Y	Y	Y	Y
1990 ln(% Undeveloped land surroundings)	N	Y	Y	Y	Y	Y	Y	Y
Geography	N	N	Y	Y	Y	Y	Y	Y
Population history	N	N	N	Y	Y	Y	Y	Y
Railroad history	N	N	N	Y	Y	Y	Y	Y
City history	N	N	N	Y	Y	Y	Y	Y
Socioeconomy	N	N	N	N	Y	Y	Y	Y
Region dummy	N	N	N	N	N	Y	Y	Y
Country FE	Y	Y	Y	Y	Y	Y	Y	Y

Notes: 579 observations in each regression. Instrument selection based on First-stage and Reduced-form results for Column 5 in Table B.1. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Panel A shows OLS results. Panel B shows TSLS results when instrumenting highway length

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[7] Alternatively, I consider that heterogeneity affects the whole set of control variables by separately estimating each LUZ subsample. Although with low first-stage statistics, results are similar and they are available upon request.

with the maximum length between Roman roads and 1870 railroads (columns 1-8) and when also instrumenting the interacted highway length with an interaction of the original instrument (columns 6-8). Table 7 also reports first-stage statistics and all of them are above the Stock and Yogo (2005) critical values.

While OLS estimates are very close to zero and non-significant, their TSLS counterparts are quite stable and clearly show that highways have a significant effect on residential development. In particular, results in my preferred specification in column 5 indicate that a 10% increase in the stock of highways (km) expands cities with a 0.4% growth in their residential land areas over 20 years. The TSLS estimated coefficients for the interacted highway variables are positive but not significant for Mediterranean and Eastern cities, and negative and significant for Northwestern cities. These results indicate that highway effects on residential land developments are similar to the average in Northwestern and Eastern LUZs (0.4%), but smaller in Northwestern LUZs (0.2%).

To get a perspective on TSLS results, I focus on the estimated coefficient for highway length (0.04) to interpret it in terms of the 'recent past' and 'near future' evolution of residential area in the 579 LUZs. Regarding the 'recent past', the 22,834 km of highways in 1990 (Table 4) increased residential area between 1990 and 2012 in 913 km^2 (=22,834×0.04). Since residential land increased as a whole in 7,540 km^2 (Table 1), a 12% of them can be attributed to highways. As for the 'near future' changes, since there were 71,162 km^2 of residential land in 2012 (Table 1) and the kilometers of highways increased an average 41% between 1990 and 2010 (Table 4), the expected increase of residential land when holding everything else constant is around 1,167 km^2 (=71,162×41%×0.04) for the next 20 years. As a whole, these computations clearly confirm that, although they are not the only driving force, highways are important for explaining the phenomenon of residential sprawl in Europe.

In Appendices C, D, E and F, I check the robustness of the above results. First, I use an alternative variable for highways: the number of highway ramps in 1990. OLS and TSLS results in Table C.1 are similar to the above mentioned: OLS estimates are zero and non-significant, and their TSLS counterparts are positive and significant. In particular, TSLS results for my preferred specification in column 5 show that a 10% increase in the stock of highways (ramps) expands cities with a 0.8% growth in their residential land areas over 20 years. At the regional level, the effect is smaller in Northwestern cities (5%). With less ramps than kilometers, the ramp coefficient is higher than its length counterpart.

Second, I consider two other types of land developments to compute my dependent and explanatory land variables. Columns 1 and 2 in Table D.1 report results for all developed land, that is when I use all classes of 'Artificial surfaces' from Corine Land Cover project. Since 70% of all developed land (Table D.1) is residential, it is not surprising that their estimated coefficients are virtually identical to those of residential in Table 7. To study the effect of highways on firms' location and, in particular, on the sprawl of their land, I compute land variables with the industrial and commercial units land class. In terms of area, this type of land increased from 10,711 to 14,130 km^2 (32%) between 1990 and 2012. Results in Table D.2 columns 1 and 2 show that highways also expand cities in terms of industrial and commercial land. In fact, the effect seems to be higher than their residential counterparts: a 10% increase in the stock of highways causes a 1.2% growth in industrial and commercial land area.

Third, the above results are based on Eq. (1), an equation which only considers the effect of initial conditions on growth. This assumption is not new and empirical literature has extensively used it and, in particular, when studying growth in cities (e.g., Glaeser, Kallal, Scheinkman, and Shleifer, 1992, Henderson, Kuncoro, and Turner, 1995, Duranton and Turner, 2012). As a robustness check, I investigate the existence of a simultaneous effect related to the 1990–2010 highway improvements. While I can not add this second highway variable because I do not have another valid instrument, I can jointly consider the effect of highway improvements and the effect of the initial stock of highways by estimating the effect of the final stock of highways. Columns 1 and 2 in Table E.1 (Appendix E) show OLS results (Panel A) and their TSLS counterparts (Panel B) when the highway variable is computed for 2000 and 2010. Once again OLS estimates are close to zero and non-significant, and TSLS estimated coefficients, although smaller, are positive and significant, and not statistically different from their 1990 counterparts in Table 7 Column 5. Perhaps because highway effects need time, it seems that highways expand cities only through a dynamic-inertial effect of their initial stock and not through a simultaneous effect of their improvements.

Fourth, as discussed in Section 4, I do not have another valid instrument for railroads and, as a result, I only can control for their effects by including decennial values of railroads variables between 1960 and 1990. In Appendix F I investigate whether this strategy performs well by estimating Eq. (1) using as main explanatory variables the kilometers of highways and railroads (without any additional history control for transportation). Results in Table F.1 Panel A confirm that the joint stock of highways and railroads (km) expand cities fostering new residential land developments. However, since these estimates are not statiscally different from their counterparts in Table 7, it seems that the transportation effect is only related to the stock of highways and not to railroads.

In summary, TSLS results in this section confirm that highways expand cities in terms of residential land. They are in line with Garcia-López *et al.* (2015*a*)'s and Garcia-López *et al.* (2015*b*)'s findings for population. The former find that highways and their ramps foster population growth in Spain's suburban municipalities between 1960 and 2006 and also influence the spatial pattern of suburbanization by spreading population out along the new highways. The latter show that highways caused suburbanization population in the 579 European LUZs between 1960 and 2010.

Finally, the difference between our preferred TSLS coefficient in column 5 (0.041) and its OLS counterpart (0.005) suggests that construction of highways in Europe is endogenous. Why? It may be due to classical measurement error, but, since similar OLS-TSLS differences are found when using more modern highway variables (2000 and 2010 kilometers in Table E.1) and, in particular, when using a different measure of highways (ramps in Table C.1) or a combination of transportation networks (highways and railroads in Table F.1), I rule out this possibility.

It may also be due to a negative correlation between the initial stock of highways and the error term because of missing variables or reverse causation. Despite controlling for geography, population history, rail history, city history, socioeconomy and country-region fixed-effects, the possibility remains that the TSLS-OLS differences could be explained by a missing variable such as the local land use regulations, which could be associated with higher residential area growth and with fewer initial highways.

Alternatively, it may be that conditional on controls, less sprawled cities on average experience positive shocks to their stock of highways. Although not reported for reasons of space, first-stage results confirm this through a significant estimated coefficient of -0.337 for the log of the initial number of residential land lots.

6. Do highways encourage scattered or compact developments?

After establishing that highways foster new residential land developments, I now turn my attention to study their impact on the degree of residential fragmentation. To do so, I estimate Eq. (1) using the 1990–2012 growth in the number of residential land lots as dependent variable.

Table 8: The effect of highways on residential fragmentation in European cities

Dependent variable:	1990–2012 Δln(Number of residential land lots)							
Region:						Med	East	NW
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A: OLS results								
1990 ln(Km of highways)	0.015	0.005	0.011	0.008	0.006	0.009	0.007	0.003
	(0.009)	(0.006)	(0.007)	(0.006)	(0.006)	(0.007)	(0.005)	(0.008)
1990 ln(Km of highways)× Region dummy						-0.006	-0.003	0.007
						(0.008)	(0.010)	(0.007)
1990 ln(Number of residential land lots)	-0.108^b	-0.230	-0.370^b	-0.361^b	-0.379^b	-0.385^b	-0.377^b	-0.381^b
	(0.047)	(0.141)	(0.173)	(0.157)	(0.158)	(0.161)	(0.159)	(0.157)
Adjusted R^2	0.53	0.54	0.62	0.63	0.64	0.64	0.64	0.64
Panel B: TSLS results								
1990 ln(Km of highways)	0.119	0.141	0.114^b	0.176^b	0.173^c	0.170^c	0.164^c	0.177^c
	(0.075)	(0.090)	(0.057)	(0.087)	(0.096)	(0.091)	(0.089)	(0.106)
1990 ln(Km of highways)× Region dummy						0.004	0.026	-0.026
						(0.043)	(0.044)	(0.044)
1990 ln(Number of residential land lots)	-0.196^b	-0.254	-0.404^b	-0.332^b	-0.339^b	-0.349^b	-0.339^b	-0.340^b
	(0.090)	(0.173)	(0.197)	(0.159)	(0.146)	(0.147)	(0.147)	(0.144)
First-stage F-statistic	26.36	13.93	16.33	12.98	12.12	6.74	6.60	5.35
Instrument	ln(Km of max(Roman, Trade, 1810 Post, 1870 Rail))							
						ln(Km) × Region dummy		
1990 ln(Km^2 of residential land area)	N	Y	Y	Y	Y	Y	Y	Y
1990 ln(% Undeveloped land surroundings)	N	Y	Y	Y	Y	Y	Y	Y
Geography	N	N	Y	Y	Y	Y	Y	Y
Population history	N	N	N	Y	Y	Y	Y	Y
Railroad history	N	N	N	Y	Y	Y	Y	Y
City history	N	N	N	Y	Y	Y	Y	Y
Socioeconomy	N	N	N	N	Y	Y	Y	Y
Region dummy	N	N	N	N	N	Y	Y	Y
Country FE	Y	Y	Y	Y	Y	Y	Y	Y

Notes: 579 observations in each regression. Instrument selection based on First-stage and Reduced-form results for Column 5 in Table B.1. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Table 8 reports OLS results in Panel A and, as previously, highways have no significant effect on fragmentation. On the contrary, after instrumenting with the maximum length between Roman roads, trade routes, 1810 post roads and 1870 railroads, gradual TSLS results in Panel B confirm that highways foster residential fragmentation. In particular, my preferred specification in column 5 shows that a 10% increase in the stock of highways (km) causes a 1.7% growth in the number of residential lots over 20 years. In other words, this effect implies that (1) the 1990 highway length increased the number of residential lots in 4,110 (=22,834×0.18) between 1990 and 2012 (a 58% of the total increase), and (2) *ceteris paribus* the 41% growth in the highway network will increase residential lots in 3,698 (=50,106 lots in 2012 × 41% highway growth × 0.18) in the next 20 years. TSLS results in columns 6-8 indicate that this effect is homogeneous among regions. Table 8 also reports first-stage statistics values that are above the Stock and Yogo (2005) critical vales or near the Stock and Yogo (2005)'s rule of thumb (F>10).

As previously explained in more detail, the difference between OLS and TSLS estimates can be explained by a missing variable such as the local land use regulation. Alternatively, it may also be due to the construction of highways on more compact cities, as shown by the significant estimated coefficient of -0.293 for the log of the initial number of residential land lots in the associated first-stage regression.

I run some additional regressions as robustness checks in Appendices D, E and F. First, column 4 in Tables D.1 and D.2 confirm significant effects of highways on fragmentation both in terms of all developed land and industrial and commercial land, respectively. Although not strictly comparable because the sum of all developed lots is not the sum of individual artificial lots, these effects are slightly smaller than their residential counterparts.

Second, the estimated coefficients for 2000 and 2010 highway variables in Table E.1 Panel B columns 3 and 4 are not statistically different from their 1990 counterparts in Table 8 Panel B column 5. As a result, highways only encourage fragmentation through a dynamic-inertial effect of their initial stock.

Finally, I validate my empirical strategy to identify highway effects by estimating the joint effect of highways and railroads (Table F.1 Panel B). Although TSLS results are smaller, they are not stastistically different from their counterparts in Table 8. As a result, while these results confirm the effect of highways, it is not clear the effect of railroads on the number of residential lots.

To sum up, in line with Garcia-López *et al.* (2015*a*)'s findings that population suburbanization in Spain followed the construction of highway ramps between 1960 and 2006, in this section I find that highways expand cities with new and discontinuous (fragmented) residential lots.

7. Do highways foster developments with more undeveloped surroundings?

Now that we know that highways encourage scattered residential developments, I investigate whether highways influence the degree of undeveloped surroundings: Do highways promote residential lots that are much more isolated from other artificial lands? To answer this question, I estimate Eq. (1) using the 1990–2012 growth in the percentage of undeveloped land surrounding residential land.

Table 9 follows the same structure than the previous ones. OLS results in Panel A show no significant effect for the stock of highways (km). Instrumenting with the maximum length between Roman roads, trade routes, 1810 post roads and 1870 railroads (columns 1-5) and with its interaction with regional dummies (columns 6-8), TSLS results in Panel B indicate a significant and homogeneous effect of highways on undeveloped surroundings: a 10% increase in the stock of highways causes a 0.7% growth in the percentage of undeveloped land surrounding residential land over 20 years. First-stage statistics values are above the Stock and Yogo (2005) critical vales or near the Stock and Yogo (2005)'s rule of thumb (F>10). Once again, the OLS-TSLS differences can be explained by a missing variable (local land use regulations) and/or by a positive shock on highway construciton on more compact cities.

Table 9: The effect of highways on undeveloped surroundings in European cities

Dependent variable:	1990–2012 Δln(% of undeveloped land surrounding residential land)							
Region:						Med	East	NW
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A: OLS results								
1990 ln(Km of highways)	-0.007^{c}	-0.002	-0.000	0.002	0.001	0.002	0.002	-0.000
	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.003)	(0.002)	(0.003)
1990 ln(Km of highways)× Region dummy						-0.000	-0.006	0.004
						(0.004)	(0.008)	(0.005)
1990 ln(% Und. land surrounding residential)	-0.110	-0.110	-0.103	-0.180^{b}	-0.176^{b}	-0.177^{b}	-0.173^{b}	-0.176^{b}
	(0.071)	(0.070)	(0.074)	(0.077)	(0.070)	(0.071)	(0.069)	(0.072)
Adjusted R^2	0.38	0.39	0.43	0.47	0.48	0.48	0.48	0.48
Panel B: TSLS results								
1990 ln(Km of highways)	-0.001	0.044^{c}	0.037^{b}	0.069^{b}	0.067^{c}	0.065^{b}	0.069^{c}	0.067^{c}
	(0.004)	(0.026)	(0.015)	(0.032)	(0.037)	(0.033)	(0.037)	(0.039)
1990 ln(Km of highways)× Region dummy						0.003	-0.002	-0.003
						(0.015)	(0.014)	(0.016)
1990 ln(% Und. land surrounding residential)	-0.101	-0.070	-0.067	-0.207^{a}	-0.204^{a}	-0.207^{a}	-0.202^{a}	-0.208^{a}
	(0.067)	(0.071)	(0.070)	(0.066)	(0.063)	(0.065)	(0.062)	(0.067)
First-stage F-statistic	52.34	13.93	16.33	12.98	12.12	6.74	6.60	5.35
Instrument	ln(Km of max(Roman, Trade, 1810 Post, 1870 Rail))					ln(Km) × Region dummy		
1990 ln(Km^2 of residential land area)	N	Y	Y	Y	Y	Y	Y	Y
1990 ln(Number of residential land lots)	N	Y	Y	Y	Y	Y	Y	Y
Geography	N	N	Y	Y	Y	Y	Y	Y
Population history	N	N	N	Y	Y	Y	Y	Y
Railroad history	N	N	N	Y	Y	Y	Y	Y
City history	N	N	N	Y	Y	Y	Y	Y
Socioeconomy	N	N	N	N	Y	Y	Y	Y
Region dummy	N	N	N	N	N	Y	Y	Y
Country FE	Y	Y	Y	Y	Y	Y	Y	Y

Notes: 579 observations in each regression. Instrument selection based on First-stage and Reduced-form results for Column 5 in Table B.1. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

In contrast with descriptive evidence for residential land, Table A.3 Panel A shows the existence of sprawl in all developed land affecting the degree of undeveloped surroundings: the percentage of undeveloped land surrounding developed land increased from 40.2 to 40.4% between 1990 and 2012. For the case of industrial and commercial land, descriptive results in Table A.3 Panel B show a reduction on the degree of undeveloped surroundings in all samples. Despite these facts, results in Tables D.1 and D.2 columns 5 and 6 show that highways have a non-significant effect on undeveloped surroundings for these types of land.

Robustness checks for the 2000 and 2010 highway networks are in Table E.1 columns 5 and 6. Since their TSLS estimated coefficients are not statistically different from their 1990 counterparts in Table 9 column 4, these results also indicate that highways only increase the degree of undeveloped surroundings through the initial stock.

Finally, TSLS results in Table F.1 Panel C show significant but smaller joint effects of highways and railroads on the growth in the percentage of undeveloped land surrounding residential land. Once again, since these TSLS results are not statistically different from their counterparts in Table 9, I verify the effect of highways on the degree of undeveloped surroundings, but not the effect of railroads.

As a whole, these findings show that highways promote more isolated residential developments and, as a result, increase the percentage of undeveloped surroundings. While this result also applies for all developed land, I do not find a significant effect on industrial and commercial land.

8. What are the effects on population growth and on density conditions?

This analysis so far shows that highways foster new and fragmented residential land developments surrounded by undeveloped land. For the case of the US, Duranton and Turner (2012) show that highways cause urban growth in terms of employment and population. The questions that arise are two. Do highways also foster urban growth in Europe, in particular in terms of population? If so, what happens with the intensity of use of residential land, i.e. with city density conditions?

These two additional questions are important because, besides the 13% growth in residential land (Table 1), European population also grew a 6%, from 484 to 513 million inhabitants (Table 10), and, as a result, the overall residential density decreased between 1990 and 2010. Despite population growth clearly took place in cities (an 82% of the European growth), there were also important differences by regions: while Northwestern and Mediterranean LUZs were the most populated and increased their population in 15 and 9 million inhabitants (10% and 12%) respectively, Eastern cities lost 1.3% of their population (Table 10). Almost a quarter of the sample lost population between 1990 and 2010: 81 Eastern cities, but also 26 Mediterranean and 24 Northwestern LUZs. London (UK) increased its population in almost 2 million inhabitants, Madrid (ES) and Paris (FR) in more than 1 million, Barcelona (ES) in half a million and Dublin (IE) in 400 thousand. On the other hand, Essen (Ruhrgebiet, DE) and Katowice (PL) lost more than 200 thousand inhabitants, Dresden (DE) more than 100 thousand, Lódz (PL) and Genova (IT) more than 90 thousand.

Table 10: Population in Europe and its cities

	1990	2010	1990–2010
Europe (29)	483,863,136	512,500,480	28,637,344 (5.9%)
All 579 LUZs	276,342,656	299,751,072	23,408,416 (8.5%)
171 Mediterranean	74,422,088	83,488,224	9,066,136 (12.2%)
156 Eastern	54,419,692	53,733,420	-686,272 (-1.3%)
252 Northwestern	147,500,864	162,529,440	15,028,576 (10.2%)

To jointly answer both questions I rely on an empirical strategy based on Duranton and Turner (2012)'s preferred specification. That is, in Eq. (2) I regress 1990–2010 population growth on the 1990 stock of highways (km), the 1990 population, geography and history variables, and country fixed-effects:

$$
\begin{aligned}
\text{1990–2010 } \Delta\ln(\text{Population}) = \beta_0 &+ \beta_1 \times \text{1990 } \ln(\text{Km of highways}) \\
&+ \beta_2 \times \text{1990 } \ln(\text{Population}) \\
&+ \sum_i (\beta_{3,i} \times \text{Geography}_i) + \sum_i (\beta_{4,i} \times \text{History}_i)
\end{aligned} \tag{2}
$$

Table 11 reports OLS estimates (columns 1-4) close to zero and non-significant. On the contrary, TSLS estimates are in columns 5-8 and confirm that highways have a significant effect on population dynamics: a 10% increase in the stock of highways causes a 0.3% increase in population over the 20 year period. At the regional level, this effect is smaller in Mediterranean cities, but higher in Eastern LUZs. For all these TSLS, their first-stage statistics values are above/near the Stock and Yogo (2005) critical vales or near the Stock and Yogo (2005)'s rule of thumb (F>10).

Table 11: The effect of transportation on population growth in European cities

Dependent variable:	1990–2010 Δln(Population)							
Method:	OLS				TSLS			
Region:	[1]	Med [2]	East [3]	NW [4]	[5]	Med [6]	East [7]	NW [8]
1990 ln(Km of highways)	0.003	0.004	0.002	0.003	0.025^b	0.034^b	0.013	0.023^b
	(0.003)	(0.004)	(0.002)	(0.003)	(0.012)	(0.015)	(0.010)	(0.011)
1990 ln(Hwy) × Region dummy		-0.004	0.005	0.001		-0.019^c	0.028^a	-0.001
		(0.005)	(0.006)	(0.004)		(0.010)	(0.010)	(0.007)
1990 ln(Population)	0.434^b	0.427^b	0.372^a	0.424^a	0.424^a	0.407^a	0.367^a	0.415^a
	(0.161)	(0.159)	(0.129)	(0.152)	(0.148)	(0.145)	(0.120)	(0.141)
Adjusted R^2	0.64	0.65	0.69	0.65				
First-stage F-statistic					11.62	6.52	6.63	5.22
Instrument					ln(Km of max(Roman, Trade, 1810 Post, 1870 Rail)) ln(Km) × Region dummy			

Notes: 579 observations in each regression. All regressions include the above mentioned controls for geography and history, and country fixed-effects. Regressions in Columns 2, 3 and 4, and 6, 7 and 8 include a regional dummy for Mediterranean, Eastern and Northwestern cities, respectively. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

These results are in line with Garcia-López *et al.* (2015*a*)'s findings on the 'growth effect': each radial highway built caused a 5.6% growth in suburban population in Spain. Although the magnitude of their estimated is not strictly comparable with mine because of differences between highways variables used (rays vs. km) and the time length considered (1960–2006 vs. 1990-2010), both results point in the same direction: a positive effect of highways on population growth.

My specification in column 5 for highway length is exactly the same than Duranton and Turner (2012)'s preferred specification in their Table 3 column 8. A comparison of results shows that (1) highways have a higher effect in US than in European cities (0.13 vs. 0.02), and (2) agglomeration effects related with the initial size of population are positive but higher in Europe than in the US (0.42 vs. 0.24).

The above results can also be used to assess the effect of highways on residential density conditions. For the case of highway length, I compare the estimated coefficient for population in column 5 (0.03) with its counterpart for residential land in Table 7 Panel B column 5 (0.04). As theory suggests, effects on residential land are higher than on population (Duranton and Puga, 2015). As a result, highways have a negative effect on the intensity of use of residential land.

As a whole, results in previous sections and in this section confirm that highways expand cities with more fragmented residential land developments surrounded by undeveloped land and reducing the overall city density.

9. Conclusions

Although the first highways were built in the beginning of the 20th century and today the European highway network is highly developed and comprises more than 70,000 km, highway construction is still ongoing in Europe and a priority for the European Union, which aims to encompass 90,000 km of highways and high-quality roads by 2020 with a budget of €24 billion.

Simultaneously, sprawl has emerged in Europe and its cities. Between 1990 and 2012, residential land increased a 13%, a rate similar to the 17% increase in the US between 1990 and 2007 (Nickerson *et al.*, 2011). The new residential land were more fragmented and the number of residential lots increased an 18%. For some samples and cities, the percentage of undeveloped land surrounding residential land increased.

In this paper, I investigate the effect of highways on residential sprawl in Europe between 1990 and 2012. My results confirm the causal effect and, in particular, show that a 10% increase in the stock of highways (km) causes a 0.4% growth in the residential land area, a 1.7% growth in the number of residential lots, and a 0.7% growth in the percentage of undeveloped land surrounding residential land over this 20 year period.

I also investigate the effect of highways on population growth and I find positive effects (0.3%). When I compare these population effects with the above mentioned land effects, I assess a joint negative effect of highways on residential density (which decreases with an increase in the stock of highways).

At the regional level, I find some heterogeneous effects: an smaller effect on residential area in Northwestern cities, and smaller and higher effects on population in Mediterranean and Eastern LUZs respectively.

The contributions of the paper are relevant. First, because the literature on the determinants of sprawl is still scarce and considers only one or two dimensions of sprawl. In this paper, I study the effects on three dimensions of sprawl and population (size of residential land, fragmentation, surroundings and intensity of land use). Second, because this paper is the first to center the analysis on the effect of transportation and, in particular, of highways. To do so, I address endogeneity concerns using IV techniques with instruments built on ancient (rail)roads. Finally, because this paper provides evidence that was needed for Europe and its cities.

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Appendix A. Some descriptive statistics

Table A.1: Summary statistics for my main variables

	All 579 LUZs				171 Medit LUZs				156 Eastern LUZs				252 NWestern LUZs			
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Land area																
1990–2012 Residential area growth (%)	19.1	32.2	-52.5	250.2	18.3	25.8	-52.5	173.1	36.5	50.8	-23.1	250.2	8.9	7.5	-9.6	31.23
1990–2012 Residential area change (km^2)	13.0	26.4	-32.0	355.5	10.8	20.6	-26.2	157.4	19.8	42.0	-22.2	355.5	10.4	13.8	-32.0	107.2
2012 Residential area (km^2)	122.9	175.8	5.6	1,887	83.3	115.5	5.6	654.1	99.1	122.7	9.8	917.0	164.5	222.8	14.5	1,887
1990 Residential area (km^2)	109.9	166.2	5.6	1,867	72.5	100.3	7.2	544.8	79.3	99.3	5.6	660.3	154.2	217.2	14.3	1,867
Fragmentation																
1990–2012 Residential fragmentation growth (%)	32.4	83.0	-50.0	850.0	39.1	110.8	-50.0	850.0	61.2	100.6	-25.0	733.3	10.1	15.49	-25.0	95.0
1990–2012 Residential fragmentation change (*Lots*)	12.3	26.9	-37	357	7.3	13.4	-14	85	21.5	43.0	-37	357	9.9	18.1	-32	124
2012 Residential fragmentation (*Lots*)	86.5	105.1	2	997	53.1	55.9	2	309	91.0	106.2	2	761	106.5	123.3	3	997
1990 Residential fragmentation (*Lots*)	74.3	94.6	1	982	45.7	51.1	2	290	69.5	88.3	1	722	96.6	113.9	4	982
Surroundings																
1990–2012 Undeveloped surroundings growth (%)	-0.6	15.8	-59.9	127.5	-1.6	20.0	-37.4	127.5	7.7	16.7	-25.8	73.5	-5.1	8.2	-59.9	17.5
1990–2012 Undeveloped surroundings change (%)	-0.4	4.6	-17.9	29.6	-1.0	5.6	-17.9	29.6	2.4	5.1	-11.7	19.9	-1.7	2.3	-9.6	7.1
2012 Undeveloped surroundings (%)	36.5	10.7	6.0	62.6	36.3	8.6	15.6	57.1	42.0	9.8	13.5	62.6	33.3	11.2	6.01	58.0
1990 Undeveloped surroundings (%)	36.9	10.3	9.5	61.6	37.3	8.5	16.5	57.8	39.6	10.2	11.2	61.6	35.0	11.2	9.5	60.0
Population																
1990–2010 Population growth (%)	7.8	12.2	-29.0	75.7	13.1	13.2	-11.8	75.7	-2.1	8.5	-29.0	15.5	10.4	9.7	-24.5	54.9
1990–2010 Population change (*'000*)	40	129	-246	1,964	53	122	-96	1,300	-4	40	-238	239	60	160	-246	1,964
2010 Population (*'000*)	518	971	68	12,100	488	849	69	6,324	344	480	68	3,015	645	1,226	71	12,100
1990 Population (*'000*)	477	869	54	10,580	435	752	60	5,024	349	475	60	2,868	585	1,093	54	10,580
Highways and railroads																
2010 Km of highways	55.7	74.8	0	678.6	61.0	78.1	0	678.6	22.7	41.5	0	246.1	72.6	82.0	0	562.9
1990 Km of highways	39.4	62.8	0	562.9	32.7	47.2	0	286.5	10.6	25.8	0	130.1	61.9	78.2	0	562.9
2010 Km of railroads	90.2	128.6	0	1,381	60.8	75.1	0	552.8	62.6	84.6	0	625.6	127.3	165.6	0	1,381
1990 Km of railroads	54.9	70.8	0	595.5	41.8	52.8	0	446.5	29.4	47.5	0	269.3	79.7	84.4	0	595.5
Old (rail)roads and instruments																
Km of Roman roads	13.3	52.0	0	1,162	23.3	90.2	0	1,162	2.6	7.3	0	43.4	13.2	23.4	0	220.3
Km of Trade routes	3.5	10.0	0	63.0	0.9	5.7	0	59.9	3.3	8.9	0	63.0	5.5	12.2	0	60.20
Km of 1810 Post roads	18.6	28.7	0	437.9	14.6	18.3	0	140.7	12.1	11.5	0	58.0	25.4	38.8	0	437.9
Km of 1870 Railroads	23.5	48.0	0	783.6	11.7	16.7	0	115.9	10.7	19.0	0	137.9	39.5	66.70	0	783.6
Km of max(Roman roads, 1870 Railroads)	29.8	67.5	0	1,162	27.1	90.1	0	1,162	12.5	19.1	0	137.9	42.4	66.5	0	783.6
Km of max(Roman, Trade, 1810 Post, 1870 Rail)	34.7	67.3	0	1,162	31.3	90.1	0	1,162	18.1	18.8	0	137.9	47.4	66.2	0	783.6

Table A.2: Summary statistics for geography, history and socieconomy variables

	All 579 LUZs				171 Medit LUZs				156 Eastern LUZs				252 NWestern LUZs			
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Geography																
Total area (Km^2)	1,686	1,814	57.4	17,484	1,274	1,223	70.4	8,025	1,545	1,419	110.5	8,615	2,053	2,248	57.4	17,484
Terrain ruggedness index	82.5	239.1	0	3,756	80.3	68.0	0	302.6	41.2	39.2	3.9	192.6	109.6	354.7	0	3,756
Altitude (m)	62.4	41.6	0.9	169.7	74.2	42.0	2.1	155.6	65.6	36.8	2.8	148.1	52.3	41.9	0.9	169.7
Elevation range (m)	78.3	44.8	2	186	112.4	47.4	3	186	62.9	32.0	8	177	64.6	36.6	2	179
Population history																
1980 Population (*'000*)	460	843	49	9,985	418	731	56	4,701	334	465	49	2,943	568	1,057	45	9,985
1970 Population (*'000*)	432	827	37	10,720	368	640	37	3,793	298	431	39	2,812	557	1,075	42	10,720
1960 Population (*'000*)	385	766	24	10,620	305	498	24	3,049	262	390	33	2,527	514	1,028	34	10,620
Highway history																
1980 Km of highways	29.4	50	0	428.7	23.8	36.9	0	248.0	5.9	17.0	0	94.8	47.6	62.9	0	428.7
1970 Km of highways	16.0	33.9	0	358.7	11.9	25.2	0	164.0	3.3	12.9	0	94.8	26.7	43.4	0	358.7
1960 Km of highways	4.5	19.6	0	310.7	1.4	7.7	0	80.7	2.5	10.5	0	85.9	7.8	27.4	0	310.7
Railroad history																
1980 Km of railroads	54.7	70.1	0	580.6	41.7	52.8	0	446.5	29.4	47.5	0	269.3	79.2	83.2	0	580.6
1970 Km of railroads	54.6	70.0	0	580.6	41.6	52.9	0	446.5	29.2	46.7	0	269.3	79.2	83.2	0	580.6
1960 Km of railroads	54.6	70.0	0	580.6	41.6	52.9	0	446.5	29.1	46.5	0	269.3	79.2	83.2	0	580.6
City history																
Dummy for Roman settlements	0.39	0.49	0	1	0.68	0.47	0	1	0.19	0.39	0	1	0.31	0.47	0	1
Dummy for Medieval monasteries	0.56	0.50	0	1	0.67	0.47	0	1	0.39	0.49	0	1	0.60	0.49	0	1
Dummy for Bishoprics (600-1450)	0.31	0.46	0	1	0.58	0.50	0	1	0.10	0.30	0	1	0.25	0.43	0	1
Dummy for Universities (12-15 c.)	0.14	0.34	0	1	0.21	0.41	0	1	0.06	0.25	0	1	0.13	0.33	0	1
Dummy for Major towns (814-1450)	0.51	0.50	0	1	0.65	0.48	0	1	0.36	0.48	0	1	0.51	0.50	0	1
Dummy for Major towns in 1850 (Bairoch)	0.81	0.40	0	1	0.87	0.34	0	1	0.64	0.48	0	1	0.87	0.342	0	1
Socioeconomy																
1990 GDP (*€bn 2005 prices*)	11.4	15.1	0.51	129.4	14.9	17.6	1.37	115.4	3.03	2.92	0.51	20.51	14.2	15.8	2.00	129.4
1990 Unemployment rate proxy (%)	13.1	10.3	0.14	51.8	11.9	8.19	0.37	38.9	17.4	12.7	0.14	51.8	10.9	8.96	0.18	41.53
1990 Employment in manufacturing (%)	23.4	9.20	2.80	54.3	21.1	9.18	2.80	46.5	29.3	9.28	5.57	47.2	21.2	7.36	5.63	54.3

Table A.3: Developed land area, fragmentation and surroundings in Europe and its cities

	Area (km^2)			Fragmentation (*Lots*)			Surroundings (% *Und.*)	
	1990	2012	1990–2012	1990	2012	1990–2012	1990	2012
Panel A: All developed land								
Europe-29	185,971	213,307	27,337 (15%)	138,868	162,819	23,951 (17%)	40.2	40.4
All 579 LUZs	88,300	101,043	12,743 (14%)	48,471	56,040	7,569 (16%)	36.3	36.1
171 Medit	17,565	21,136	3,571 (20%)	9,435	10,677	1,242 (13%)	37.7	36.9
156 Eastern	17,814	21,479	3,665 (21%)	12,146	15,598	3,452 (28%)	38.1	40.5
252 NWest	52,921	58,428	5,507 (10%)	26,894	29,765	2,875 (11%)	34.1	32.8
Panel B: Industrial and commercial units land								
Europe-29	19,850	25,868	6,018 (30%)	26,822	33,901	7,079 (26%)	34.4	34.3
All 579 LUZs	10,711	14,130	3,419 (32%)	12,224	16,245	4,021 (33%)	33.0	31.1
171 Medit	2,747	3,723	976 (36%)	3,021	3,898	877 (29%)	39.7	35.7
156 Eastern	2,465	2,906	441 (18%)	3,064	3,587	523 (17%)	34.9	33.2
252 NWest	5,499	7,501	2,002 (36%)	6,139	8,760	2,621 (43%)	27.2	26.6

Notes: ’Area’ refers to square kilometers of developed land area, ’Fragmentation’ refers to the number of developed land lots, and ’Surroundings’ refers to the % of undeveloped land surrounding developed land. Total areas are: 4,851,351 km^2 for Europe (29 countries), 976,178 km^2 for the 579 LUZs, 217,785 km^2 for the 171 Mediterranean cities, 241.078 km^2 for the 156 Eastern cities, and 517,315 km^2 for the 256 Northwestern cities.

Appendix B. First-stage and reduced-form results

Table B.1: Modern highway length, historical (rail)roads and residential land in European cities

Regression: Land indicator:	FS All [1]	RF Area [2]	RF Fragm [3]	RF Surr [4]	FS All [5]	RF Area [6]	RF Fragm [7]	RF Surr [8]	FS All [9]	RF Area [10]	RF Fragm [11]	RF Surr [12]
Panel A:	**Roman roads**				**Trade routes**				**1810 Post roads**			
ln(Km of ...)	0.162^{a}	0.002	0.012^{b}	0.004	0.007	-0.002	0.015	0.007^{b}	0.138^{b}	0.002	0.022	0.009
	(0.058)	(0.004)	(0.006)	(0.003)	(0.121)	(0.004)	(0.011)	(0.003)	(0.067)	(0.007)	(0.017)	(0.006)
Adjusted R^2	0.39	0.27	0.30	0.20	0.38	0.27	0.30	0.20	0.38	0.27	0.30	0.21
FS F-statistic	7.88				0.00				4.27			
Panel B:	**1870 Railroads**				**max(Roman, 1870 Rail)**				**max(Roman, Trade, Post, Rail)**			
ln(Km of ...)	0.193^{a}	-0.001	-0.005	-0.002	0.234^{a}	0.010^{b}	0.005	0.001	0.202^{a}	0.013^{b}	0.035^{c}	0.014^{b}
	(0.040)	(0.005)	(0.019)	(0.006)	(0.040)	(0.004)	(0.014)	(0.004)	(0.058)	(0.006)	(0.018)	(0.006)
Adjusted R^2	0.39	0.27	0.30	0.20	0.39	0.27	0.30	0.20	0.39	0.28	0.31	0.21
FS F-statistic	22.87				33.57				12.12			

Notes: First-stage (FS) and Reduced-form (RF) results for regressions in Tables 7, 8 and 9 Panel A Column 5. FS and RF dependent variables are the 1990 log of kilometers of highways and 1990–2012 Δln(Residential variable), respectively. 'Area' refers to square kilometers of residential land area, 'Fragm' refers to the number of residential land lots, and 'Surr' refers to the % of undeveloped land surrounding residential land. 579 observations in each regression. All regressions include control variables for the 1990 log of residential land area, the 1990 log of the number of residential lots, the 1990 log of % of undeveloped land surrounding residential land, geography, history, socioeconomy and country fixed-effects. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Appendix C. The effect of highway ramps

Table C.1: The effect of highway ramps on residential land area in European cities

Dependent variable:	1990–2012 $\Delta\ln(\text{Km}^2$ of residential land area)							
Region:						Med	East	NW
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A: OLS results								
1990 ln(Number of highway ramps)	0.026^b	0.026^b	0.027^b	0.011	0.011	0.010	0.010	0.011
	(0.011)	(0.010)	(0.010)	(0.007)	(0.008)	(0.007)	(0.008)	(0.012)
1990 ln(Number of ramps) × Region dummy						0.001	-0.001	0.000
						(0.013)	(0.012)	(0.011)
1990 ln(Km^2 of residential land area)	-0.051^a	-0.123^b	-0.132^b	-0.267^a	-0.268^a	-0.275^a	-0.270^a	-0.268^a
	(0.014)	(0.056)	(0.054)	(0.064)	(0.064)	(0.060)	(0.064)	(0.064)
Adjusted R^2	0.59	0.60	0.64	0.69	0.69	0.69	0.69	0.69
Panel B: TSLS results								
1990 ln(Number of highway ramps)	0.090^b	0.077^b	0.082^a	0.079^b	0.077^b	0.075^b	0.059^c	0.096^b
	(0.038)	(0.033)	(0.027)	(0.036)	(0.034)	(0.033)	(0.032)	(0.042)
1990 ln(Number of ramps) × Region dummy						0.018	0.033	-0.045^b
						(0.028)	(0.027)	(0.021)
1990 ln(Km^2 of residential land area)	-0.106^a	-0.159^a	-0.169^a	-0.267^a	-0.268^a	-0.272^a	-0.270^a	-0.264^a
	(0.035)	(0.060)	(0.054)	(0.053)	(0.053)	(0.048)	(0.055)	(0.050)
First-stage F-statistic	55.84	43.53	42.22	24.77	23.73	11.89	15.62	12.89
Instrument	ln(Km of max(Roman roads, 1870 Railroads))							
						ln(Km) × Region dummy		
1990 ln(Number of residential lots)	N	Y	Y	Y	Y	Y	Y	Y
1990 ln(% Undeveloped land surroundings)	N	Y	Y	Y	Y	Y	Y	Y
Geography	N	N	Y	Y	Y	Y	Y	Y
Population history	N	N	N	Y	Y	Y	Y	Y
Railroad history	N	N	N	Y	Y	Y	Y	Y
City history	N	N	N	Y	Y	Y	Y	Y
Socioeconomy	N	N	N	N	Y	Y	Y	Y
Region dummy	N	N	N	N	N	Y	Y	Y
Country FE	Y	Y	Y	Y	Y	Y	Y	Y

Notes: 579 observations in each regression. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Appendix D. Results for 'All developed' and 'Industrial and commercial units' land

Table D.1: The effect of highways on land area, fragmentation and undeveloped surroundings in European cities: All developed land

Dependent variable:	1990–2012 Δln(All developed indicator)					
Land indicator:	Km^2 of land area		Number of lots		% Und. surroundings	
Method:	OLS [1]	TSLS [2]	OLS [3]	TSLS [4]	OLS [5]	TSLS [6]
1990 ln(Km of highways)	0.006	0.044^c	0.005	0.073^c	-0.001	0.044
	(0.006)	(0.023)	(0.006)	(0.040)	(0.002)	(0.030)
1990 ln(All developed indicator)	-0.284^a	-0.298^a	-0.209^a	-0.190^a	-0.260^a	-0.291^a
	(0.062)	(0.059)	(0.069)	(0.069)	(0.059)	(0.065)
Adjusted R^2	0.72		0.63		0.52	
First-stage F-statistic		37.22		7.73		12.19
Instrument: ln(Km of ...)	max(Roman, Rail)		Roman roads		max(Roman, Trade, Post, Rail)	

Notes: 579 observations in each TSLS regression. All regressions include control variables for the 1990 log of residential land area, the 1990 log of the number of residential lots, the 1990 log of % of undeveloped land surrounding residential land, geography, history, socioeconomy and country fixed-effects. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Table D.2: The effect of highways on land area, fragmentation and undeveloped surroundings in European cities: Industrial and commercial land

Dependent variable:	1990–2012 Δln(Industrial and commercial indicator)					
Land indicator:	Km^2 of land area		Number of lots		% Und. surroundings	
Method:	OLS [1]	TSLS [2]	OLS [3]	TSLS [4]	OLS [5]	TSLS [6]
1990 ln(Highway indicator)	0.009^c	0.111^c	0.003	0.122^c	-0.008	0.011
	(0.005)	(0.062)	(0.007)	(0.066)	(0.005)	(0.023)
1990 ln(Ind & com indicator)	-0.368^a	-0.395^a	-0.369^a	-0.339^a	-0.441^a	-0.447^a
	(0.058)	(0.077)	(0.062)	(0.054)	(0.056)	(0.052)
Adjusted R^2	0.67		0.69		0.50	
First-stage F-statistic		32.19		32.19		32.19
Instrument	ln(Km of max(Roman roads, Trade routes, 1810 Post roads, 1870 Railroads))					

Notes: 579 observations in each TSLS regression. All regressions include control variables for the 1990 log of residential land area, the 1990 log of the number of residential lots, the 1990 log of % of undeveloped land surrounding residential land, geography, history, socioeconomy and country fixed-effects. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Appendix E. Joint effect of 1990 highways and 1990-2000/10 improvements

Table E.1: The joint effect of 1990 highways and its 1990-2000/10 improvements on land area, fragmentation and undeveloped surroundings in European cities

Dependent variable:	1990–2012 Δln(Residential indicator)					
Land indicator:	Km^2 of land area		Number of lots		% Und. surroundings	
	[1]	[2]	[3]	[4]	[5]	[6]
Panel A: OLS results						
2000 ln(Km of highways)	0.005 (0.007)		0.006 (0.008)		0.002 (0.003)	
2010 ln(Km of highways)		0.004 (0.006)		0.006 (0.008)		0.002 (0.004)
Adjusted R^2	0.69	0.69	0.64	0.64	0.48	0.48
Panel B: TSLS results						
2000 ln(Km of highways)	0.035^b (0.018)		0.156^c (0.097)		0.060^c (0.037)	
2010 ln(Km of highways)		0.031^b (0.013)		0.110^b (0.050)		0.043^b (0.017)
First-stage F-statistic	34.16	47.72	9.15	25.34	9.15	25.34
Instrument: ln(Km of ...)	max(Roman, Rail)		max(Roman roads, Trade, 1810 Post, 1870 Rail)			

Notes: 579 observations in each TSLS regression. All regressions include control variables for the 1990 log of residential land area, the 1990 log of the number of residential lots, the 1990 log of % of undeveloped land surrounding residential land, geography, history, socioeconomy and country fixed-effects. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Appendix F. Joint effect of 1990 highways and railroads

Table F.1: The joint effect of highways and railroads on residential land area, fragmentation and undeveloped surroundings in European cities

Dependent variable:	1990–2012 Δln(Residential indicator)							
Method:	OLS				TSLS			
Region:	[1]	Med [2]	East [3]	NW [4]	[5]	Med [6]	East [7]	NW [8]
Panel A: Effects on 1990–2012 Δln(Km^2 of residential land area)								
1990 ln(Km of highways and railroads)	0.002	-0.002	0.011	0.002	0.053^{a}	0.048^{a}	0.047^{c}	0.059^{a}
	(0.007)	(0.004)	(0.011)	(0.009)	(0.018)	(0.015)	(0.026)	(0.020)
1990 ln(Km) × Region dummy		0.019	-0.016	0.002		0.024	0.003	-0.020
		(0.019)	(0.011)	(0.010)		(0.034)	(0.023)	(0.014)
1990 ln(Km^2 residential area)	-0.265^{a}	-0.271^{a}	-0.264^{a}	-0.265^{a}	-0.253^{a}	-0.259^{a}	-0.257^{a}	-0.253^{a}
	(0.063)	(0.056)	(0.061)	(0.063)	(0.056)	(0.048)	(0.053)	(0.055)
Adjusted R^2	0.69	0.69	0.70	0.69				
First-stage F-statistic					30.90	16.88	19.22	14.26
Panel B: Effects on 1990–2012 Δln(Number of residential land lots)								
1990 ln(Km of highways and railroads)	0.001	-0.001	0.015	-0.005	0.123^{b}	0.112^{b}	0.143^{b}	0.120^{b}
	(0.007)	(0.006)	(0.012)	(0.008)	(0.051)	(0.048)	(0.056)	(0.052)
1990 ln(Km) × Region dummy		0.007	-0.026^{c}	0.025^{b}		0.044	-0.047	0.004
		(0.015)	(0.013)	(0.011)		(0.031)	(0.029)	(0.021)
1990 ln(Number residential lots)	-0.383^{b}	-0.385^{b}	-0.383^{b}	-0.389^{b}	-0.404^{a}	-0.401^{b}	-0.406^{a}	-0.406^{a}
	(0.159)	(0.163)	(0.161)	(0.158)	(0.152)	(0.156)	(0.154)	(0.150)
Adjusted R^2	0.63	0.64	0.64	0.64				
First-stage F-statistic					30.90	16.88	19.22	14.26
Panel C: Effects on 1990–2012 Δln(% of undeveloped land surrounding residential land)								
1990 ln(Km of highways and railroads)	0.003	0.002	0.009^{a}	0.000	0.050^{a}	0.045^{a}	0.064^{a}	0.046^{a}
	(0.002)	(0.003)	(0.003)	(0.003)	(0.015)	(0.013)	(0.017)	(0.017)
1990 ln(Km) × Region dummy		0.002	-0.011^{b}	0.011^{c}		0.018	-0.030^{b}	0.011
		(0.004)	(0.005)	(0.006)		(0.014)	(0.014)	(0.013)
1990 ln(% undev. surroundings)	-0.166^{b}	-0.167^{b}	-0.162^{b}	-0.162^{b}	-0.163^{a}	-0.169^{a}	-0.158^{a}	-0.159^{a}
	(0.068)	(0.069)	(0.068)	(0.070)	(0.060)	(0.062)	(0.061)	(0.061)
Adjusted R^2	0.47	0.47	0.47	0.47				
First-stage F-statistic					30.90	16.88	19.22	14.26
Instrument					ln(Km of max(Roman, Trade,1810 Post,1870 Rail)) ln(Km)×Region dummy			

Notes: 579 observations in each regression. All regressions include the above mentioned controls for geography, history, and socioeconomy, and country fixed-effects. Regressions in Columns 2, 3, and 4, and 6, 7 and 8 include a regional dummy for Mediterranean, Eastern and Northwestern cities, respectively. Robust standard errors clustered by country are in parentheses. ^{a}, ^{b}, and ^{c} indicates significant at 1, 5, and 10 percent level, respectively. respectively.

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