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Express Delivery to the Suburbs.
The Effects of Transportation in Europe's Heterogeneous Cities.

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Abstract

This paper provides evidence for the causal effect of the highway and railway infrastructure on the suburbanization of population in European cities. We adopt different measures of transportation infrastructure and estimate their joint effects on suburbanization using a two-step panel approach. Our main results suggest that an additional highway ray displaced approximately 4% of the central city population in European cities over a 10-year period, whereas we find no significant effect for the railways on average. However, railways did cause suburbanization those located in Central-North Europe. When employing the full time span covered by our data and accounting for the diversity of European cities, we find a smaller effect of highways on suburbanization during more recent decades and for ”cities with history”. Factors such as historical urban amenities, traffic congestion, urban policies etc. appear to provide reasonable explanations for these differences. The findings of this paper are novel and provide valuable insights for European regional and transport policies.

JEL-codes: R400, R200, O400.

Keywords: suburbanization, transportation, Europe.

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1. Introduction

Much of our knowledge about urban decentralization and urban sprawl derives from a tiny number of papers (Duranton and Puga, 2015). While many detailed studies of small areas have been reported, few examine broad cross-sections of cities, and even fewer turn their attention to analyse cities across various countries. One of the main problems impeding such analyses at the European level is the lack of harmonized urban data. In this paper, we are able to overcome this problem by manually creating most of the variables used in our analysis from maps. Using historical transportation in Europe as an instrument, we estimate the joint causal effects of highway and railway infrastructure on the suburbanization of 579 cities in 29 European countries in the period 1961-2011. To the best of our knowledge, these effects have never been studied before and certainly not at this scale. Yet, the impact of transport infrastructure improvements on urban spatial structure is a major concern for Europe.

The highway network in Europe expanded rapidly during the second half of the 20th and has continued to do so at the beginning of the 21st century, with much of this development being financed by EU Regional and Cohesion Funds. At the same time, EU policies have sought to mitigate the problems that the literature has identified as the potential repercussions of suburbanization and urban sprawl i.e. CO_2 emissions, energy inefficiency (Glaeser and Kahn, 2010) and social segregation (Glaeser and Kahn, 2004)[1]. Thus, the confirmation of our hypothesis that highways caused suburbanization in European cities would reveal a contradiction with these EU policies. However, the expansion of the highway network should not be considered in isolation, given the important role played also by the continent's railways since the 19th century. Indeed, the share of railroads has recently increased, reflecting EU objectives for a *Single European Railway Area* (European Commission, 2010).

Europe presents a series of unique characteristics that make it a particularly interesting case to study. The average population density of the 25 states of the European Union (EU) in 2005 was about 117.5 inhabitants per km^2 compared to just 31.6 in the US. Moreover, in most European countries, strong polycentric urban systems can be found (Couch et al., 2008) and in many big cities (including London, Paris, Copenhagen, Milan, Antwerp, and Manchester) highways do not cut across the city cores (Cox et al., 2008). Differences in the urban amenities embedded in the central cities have been used to explain differences in the dominant urban spatial structures in Europe and the US (Brueckner et al., 1999). These differences in the nature of European and US cities, together with joint membership of the EU and the heterogeneous historical background of European cities, highlight the importance of an integrated study for the whole of Europe.

Previous studies for the US (Baum-Snow, 2007a) and Spain (Garcia-López et al., 2015) estimated the causal effect of highway 'rays' on suburbanization at 9-12% and 8-9%, respectively, while the same effect was estimated at 4% for China (Baum-Snow et al., 2015). The latter study also found that ring roads displaced an additional 20% of central city population, while they

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[1] *The Europe 2020* strategy focuses on reducing CO_2 emissions and increasing in energy efficiency; fighting social exclusion; and promoting education and R&D. Although the last two areas might seem to be irrelevant to this discussion, they reflect typical criticism levelled at the allocation of EU funding, often believed to favour "hard infrastructure" (e.g. highways) as opposed to "soft infrastructure" (e.g. human capital) investments.

found no effects of railways on suburbanization. Finally, these authors sought to estimate the joint effect of highways and railways on suburbanization, but given their instrument's strength, the estimation is relegated to the Appendix. In this paper, we estimate the *joint causal* effect of highways and railways on suburbanization for the whole of our panel dataset and for different subsamples. Our preferred specification suggests that an additional highway 'ray' displaced, on average, approximately 4% of central city population in European cities during the period 1961-2011, while we find no significant effect of the railways.

In order to tackle the problem of endogeneity, we extend the standard instrumental variables (IV) in a long-difference specification by employing panel data methods, using city fixed effects and regional time trends in addition to the IV two-step approach. We take advantage of the rich history of Europe, which is reflected in the number of different types of transport infrastructure employed since the Romans built their roads more than 2,000 years ago[2]. Specifically, we find that the main postal routes in 1810 and the railways in 1870 may explain the topology of the modern transport network[3], while being exogenous to modern suburbanization.

The findings of this paper confirm the causal relation between the highway infrastructure and suburbanization reported in the literature. However, we find that the marginal effect of highways on the suburbanization of European cities is relatively subdued compared to the previous empirical findings for developed countries. A potential explanation for this could be the aforementioned "idiosyncrasy" of European cities. Another novel finding in our analysis is that the effect of highways on suburbanization varies significantly with the period of time under consideration. Specifically, the estimated effect of highways on suburbanization was more marked during the period 1961-1981 than it was during the more recent decades. Moreover, apart from the radial variables, we also include the nodes of the two networks (ramps and stations) to account for accessibility to the transport infrastructure network. We find evidence that the effects of highways on suburbanization cannot be solely attributed to the radial nature of the networks.

A number of other interesting findings derive from the heterogeneity of European cities. By exploiting this heterogeneity, we test whether the effects of transport infrastructure on suburbanization vary when cities with different spatial structures, histories or geographies are considered. Although we find no statistically significant differences between most of these city subgroups, we observe some interesting heterogeneous patterns. Specifically, we observe a pattern indicating that highways caused less suburbanization in the cities with "more history". Brueckner et al. (1999) report evidence of the importance of historical urban amenities in European central cities, which further supports this finding. In addition, while on average the effect of railways on suburbanization is not significant, we do find significant effects for big cities and for Central-Northern and Eastern (Ex-Soviet) European cities. Traffic congestion and urban policies are factors that may account for these differences. Finally, we attempt to estimate the impact of the EU and, in

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[2] The historical transport variables that have actually been tested in this study as potentially valid instruments are the Roman roads, the main trade routes in the Holy Roman Empire and neighbouring countries in 1500, the main and secondary postal routes in 1810 and the railways in 1870. Most of these variables have not previously been used as instruments.

[3] The title of this paper is inspired by the fact that the modern highway system that facilitates the "express delivery" of goods and people to and from the suburbs has followed the routes of the main postal network that ensured the rapid delivery of mail in 1810.

particular, the different EU integration phases and the effect of European regional policies on suburbanization. However, we do not find a significant effect of the latter on suburbanization.

The rest of this paper is organized in four sections and two Appendices. Section 2 describes the process of database construction and presents some stylized facts about suburbanization and the evolution of the transport network in Europe. In Section 3, we discuss our identification strategy and we present our first- and second-stage results. Section 4 comprises six subsections, in which we present heterogeneous estimates of the effect of transport infrastructure on suburbanization when we divide our sample of cities according to the time period considered, their urban form, city history, geographical area and the natural geography. Finally, in Section 5, we highlight the most important findings of this work and seek to translate our results into policy recommendations. Appendix A includes the maps that are discussed in the main text and Appendix B presents additional heterogeneous results.

2. Suburbanization and transportation infrastructure in Europe

All the data (except for the population data) that have been used in this paper are derived from maps using GIS software. Although this task involved a considerable amount of map processing (including geo-referencing, map vectorizations, manual network editing, etc.), this data collection strategy allowed us to focus on the city level for the whole of Europe and for a long period of time.

The urban population dataset employed in this paper was constructed using census population figures collected every 10 years at the municipal level for the period 1961-2011 in 34 European countries, as provided by the DG REGIO of the European Commission. In our analysis, we use 29 countries for which complete data were available and that Eurostat includes in its Urban Audit. The countries included in our dataset are the member-states of EU28 member states (with the exception of Slovenia and Lithuania, for which data were not available) and three non-EU countries, Switzerland, Norway and Iceland. To the best of our knowledge, this is the first time that this new integrated census population dataset has been used in an empirical study.

The units of our analysis are the *Core Cities* (*CCs*)[4] and the *Large Urban Zones* (*LUZs*) as defined by Eurostat in the 2008 Urban Audit[5]. Eurostat defines LUZs not only in terms of their administrative and statistical unit borders but also in relation to commuting criteria, defining a functional urban area based on a perfectly harmonised methodology across Europe[6]. This definition comprises all the settlements that interact economically with the core (Arribas-Bel et al., 2011). Thus, Eurostat's LUZs were chosen as the most appropriate spatial unit for the analysis of

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[4] In this paper our use of the term *central cities* is synonymous with that of core cities.

[5] For London and Paris, which are by far the biggest cities in our sample, we use Eurostat's *Kernel* definition since in these cases their CC area is extremely small with respect to that of their LUZ area (0.04% and 0.8% respectively) and it does not reflect the actual extent of their CBD.

[6] Eurostat's LUZs approximate the *Functional Urban Area* (*FUA*) as defined by the OECD. The OECD and the European Commission developed a new harmonized definition of a city and its commuting zone in 2011. This new OECD-EC definition identified more than 800 cities with an urban centre of at least 50,000 inhabitants in the EU, Switzerland, Croatia, Iceland and Norway.

suburbanization in Europe. The Urban Audit uses the concept of the CC as a legal, administrative entity and defines it in relation to its political/administrative boundaries.

In spite of being one of the most solid and comprehensive statistical datasets available at the city level in Europe, the Urban Audit suffers from many missing values (even in the city population series), which means many of its variables are unsuitable for use. For this reason, we only adopt the delineation of the LUZ and the CC areas, and use census data at the municipal level to construct our LUZ and CC population dataset. This was a challenging task as it meant retrieving information for the numerous municipal mergers and changes in municipal codes from the national statistical offices. Our final dataset comprises 579 LUZs, each consisting of a CC and a suburban area, for the period 1961-2011.

The transport infrastructure measures that we use in this paper were calculated using GIS maps of the road system and the railroad network in Europe that form part of the *RRG* GIS Database[7]. The highway and railway definitions used in this dataset follow their corresponding country definitions. In order to construct our panel highway and railway network for each decade in the period 1961-2011, we used the 2011 RRG operational networks as our starting point[8]. From the resulting digital maps, we calculated the number of highway and railway 'rays', in line with Baum-Snow (2007a) definition, as "limited access highways connecting the central city to a significant part of the suburbs"[9]. Finally, the RRG GIS Database also provides information for highway ramps and train stations.

We also calculated an alternative measure of the number of radial highways and railways by modifying the algorithm used for counting rays presented in Baum-Snow et al. (2015). In our version, we use the CC "smoothed" *area*[10] as opposed to the CBD *point*. Then we use a buffer ring of 5-km radius, clipped in order to match the borders of the LUZs (should the ring extend beyond its borders). We then count the number of highways intersecting the 5-km buffer ring[11] and with the CC smoothed border. We exclude the intersection points that coincide in both the ring and the smoothed CC. Thus, the number of algorithm rays for any given city is the minimum number of highway intersection points considering both the smoothed CC border and the 5-km buffer ring. Although this method provides an alternative rays measure, the manual count of rays is more accurate.

To compute our historical instruments, we worked with two digital vector maps. For the 1810 postal routes and for the 1870 railroads, we created our own GIS maps by geo-referencing and vectorizing the scanned map from the David Rumsey Historical Map Collection[12] and the map from the Historical GIS for European Integration Studies[13], respectively. To calculate the number

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[7] Büro für Raumforschung, Raumplanung und Geoinformation (RRG) GIS Database.

[8] We exclude the high-speed rail lines as they were built for long-distance travel. High-speed trains make very few stops and, hence, they do not usually facilitate intra-metropolitan commuting.

[9] Baum-Snow (2007a) uses the CBD *points* as opposed to Core City *areas*.

[10] First, we buffered out and in the CC border using a 5-km radius in order to eliminate any irregularities in the shape of the CC area that might result in a spurious count of the intersecting highways.

[11] Baum-Snow et al. (2015) also use a 5-km and a 10-km radius circles around each CBD point.

[12] See `http://www.davidrumseny.com`.

[13] HGISE, see `http://www.europa.udl.cat/hgise`.

of these historical transport infrastructure rays, we adopted the same definition as that used above for the highways and railways.

We also include a number of historical variables in our analysis. The main historical variables used are dummy variables for the Roman cities, Medieval cities, major cities in 1000 and 1450[14] and the population in 1850 (Bairoch et al., 1988)[15]. In addition, we created dummy variables for the cities with universities between the 12th and the 15th centuries, cities with Roman settlements and cities with bishoprics (in 600, 1000 and 1450) from the maps in the Digital Atlas of Roman and Medieval Civilization. We also created dummy variables for cities with medieval monasteries and for cities with a historical city centre or another landmark recognized by UNESCO.

In addition, we used a number of geographical control variables, namely mean elevation, altitude range and the Riley et al. (1999) index of terrain ruggedness for each CC and each LUZ[16]. Another important geographical variable is the distance separating each LUZ centroid from the closest coastline. Finally, we use raster GIS temperature data for 0.86 km² cells from `http://www.worldclim.org/tiles.php?Zone=16` and data on navigable rivers from `https://www.evl.uic.edu/pape/data/WDB/`.

2.1 *Patterns of suburbanization in Europe*

In this section, we present some descriptive statistics of the population in the central cities and in the suburbs of the LUZ areas included in our sample to illustrate patterns of suburbanization in Europe. We define the degree of *relative urbanization/suburbanization*[17] as the difference between population growth in the CC and population growth in the suburbs. When this difference is positive, a city experiences urbanization; when it is negative, the city experiences suburbanization. As can be observed in the last row of the last column of Table 1, on average, European cities experienced suburbanization in the period 1961-2011. Moreover, the degree of suburbanization did not vary substantially over time but remained relatively stable throughout the whole period of study. However, in the decade 1961-1971, the growth in city population was by far the highest in the whole period.

Table 1: Average population growth and (sub)urbanization

	1961-1971	**1971-1981**	**1981-1991**	**1991-2001**	**2001-2011**	**1961-2011**
Population Growth (LUZ)	12.29%	6.69%	3.66%	3.07%	5.29%	**34.77%**
(*i*) CC Population Growth	10.83%	4.23%	1.72%	0.13%	4.22%	**22.62%**
(*ii*) Suburban Population Growth	14.08%	7.49%	7.95%	6.25%	6.38%	**49.61%**
Relative (Sub)urbanization [(*i*) - (*ii*)]	**-3.26%**	**-3.26%**	**-6.22%**	**-6.11%**	**-2.16%**	**-26.99%**

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[14] We created these variables from the maps contained in the Digital Atlas of Roman and Medieval Civilization.

[15] The European cities included in this dataset are those that had 5,000 or more inhabitants at any point between the 8th and the 18th centuries. For 1850, we have information regarding the exact population of these cities.

[16] The original GIS raster maps were downloaded from the Digital Elevation Model over Europe; see `http://www.eea.europa.eu/data-and-maps/data/eu-dem`.

[17] Urbanization/suburbanization hereafter.

Notwithstanding this, Table 1 indicates that suburbanization was, on aggregate, the dominant process in Europe, with 299 of the 579 urban centres (roughly 50%) in our analysis experiencing suburbanization during the period 1961-2011. This seemingly contradictory evidence is partly explained in Table 2. The last column of this table shows that the overall suburbanization pattern (as highlighted in Table 1) was driven mainly by the population displacement in Europe's biggest cities (4th quartile). In contrast, small and medium-small cities (1st and 2nd quartile) experienced intense urbanization during the first few decades but underwent processes of suburbanization in the last two decades of our sample. On the other hand, medium-big (3rd quartile) cities experienced moderate suburbanization on average, while the most intense suburbanization was recorded in the big cities (4th quartile).

Table 2: Quartile city size (sub)urbanization by decade

City size quartiles (1961 LUZ residents)	**1961-1971**	**1971-1981**	**1981-1991**	**1991-2001**	**2001-2011**	**1961-2011**
1st (23,892 - 111,673)	27.84%	18.30%	7.88%	-5.00%	-5.47%	**62.14%**
2nd (111,674 - 178,017)	15.99%	6.89%	2.77%	-5.36%	-5.15%	**17.69%**
3rd (178,018 - 343,067)	7.01%	4.51%	-3.49%	-6.33%	-3.71%	**-3.35%**
4th (343,067 - 10,618,868)	-10.36%	-11.58%	-6.69%	-6.45%	-1.19%	**-44.36%**

Another useful descriptive measure of the pattern of suburbanization in Europe can be obtained from Map A.1. The cities in Eastern Europe and in the Mediterranean countries experienced significant urbanization in those years that the cities in Western Europe suburbanized. This heterogeneous pattern of urbanization/suburbanization presented by cities of different sizes and from different geographical locations motivated the heterogeneous estimations that we present in Section 4.2.

2.2 *European transport infrastructure: Origins and evolution*

The origins of Europe's modern transport infrastructure can be traced to the Roman era, before which the continent's roads were of a distinctly local nature being used to facilitate short distance journeys. The Romans were the first to build an extensive and sophisticated network of paved and crowned roads, designed to meet military and commercial goals. Overall, they built more than 85,000 km of main roads, which radiated out from Rome, linking up the different territories in its Empire, from Britain to Syria (O'Flaherty, 1996). Other important ancient roads of note included the "amber routes", which connected the northern European sea-shores with the Adriatic Sea during the Bronze Age, and in the 15th century the main trade routes in the Holy Roman Empire and neighbouring countries that linked up various centres of commerce in Central and Northern Europe with Instanbul.

Although there have been roads in Europe since ancient times, they only became popular a few centuries ago. At the beginning of the 17th century, the continent's governments realized that an improved road system could foster economic prosperity and better governance and that roads could facilitate the creation of a reliable postal system. Post road systems were thus developed throughout Europe during the 17th and 18th centuries. While postal routes were relatively primitive until the middle of the 18th century, in the last quarter of that century, the improvement in road construction, including the introduction of hard surfaces and the development of much improved carriages, permitted the use of wheeled coaches and wagons, which in turn led to the development of coach services between towns. These coaches were provided primarily by the public mail service which was designed to carry letters, packages, and people. Indeed, until the 19th century, most passenger coach travel was monopolized by the postal carriers. These improvements resulted in a significant increase in road traffic, ushering in the so-called "mail coach era", which lasted until the middle of the 19th century when railroads became the primary mode of transportation (Elias, 1981, 1982).

The postal route network can be regarded as the precursor of Europe's modern intercity road network. Due to its earlier popularity and Europe's rugged landscape, modern highways have tended to follow its path. However, almost no 19th-century postal routes have been preserved to the present day. Map A.2 and Table 3 depict the evolution of the highway network in Europe between 1961 and 2011[18]. In 1961, there were very few any highways concentrated in a handful of countries[19]. However, during the sixties, Europe's highway network grew enormously. By 2011, the highway network had expanded across the whole European continent. The fact that in 1961 the highway network in Europe had hardly developed allows us to use this year as the starting point for its subsequent evolution.

Table 3: The evolution of the highway and railway network in Europe.

Year	Highway length (km)	Railway length (km)
1960	259	297,942
1970	15,036	269,659
1980	28,213	260,464
1990	43,502	235,263
2000	57,763	217,324
2010	67,779	225,333

Notes: The highway length statistics refer to the EU28 countries (except for Greece), as well as Norway, Switzerland, Turkey and the Former Yugoslav Republic of Macedonia. The railway length statistics refer to the EU15 countries (except for Luxembourg) as well as Hungary, Norway, Poland, Romania, Switzerland and the Former Yugoslavia countries.

Source: Highways: Eurostat
Railways: Atlas on European Communications and Transport Infrastructures and RRG dataset (2010)

The prominent role played by highway infrastructure in Europe is clear from Map A.2. However, we should not neglect the other main transport infrastructure, namely the railroads. The development of Europe's rail network can be divided in four stages: initial expansion (1840-1860), general expansion (1860-1910), stabilisation (1910-1960) and contraction (1960-2010) (Martí-Henneberg, 2013). Until 1860, Europe's railway network in Europe was very sparse and only in the UK had the network acquired any degree of density. However, by 1870, the railroads had expanded across the whole continent and the importance of Europe's railway network was well established.

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[18] The highway and railway datasets included in our empirical analysis were only constructed for the metropolitan areas in our sample. To show the evolution of the whole transport network, we use data at the country level.

[19] Primarily in Germany, the Netherlands, some in Northern Italy and very few in Belgium, Croatia and Poland.

As can be seen in Map A.3 and Table 3, by 1870 the railroads linked up much of Europe. However, during the following century, the railway network expanded to virtually every corner of the continent and its density increased enormously. In the period 1870-1900, numerous lines were opened up, while in the periods 1910-1960 and 1960-2010, while many new lines continued to be created, many lines were also closed down. Most of these railway closures occurred in Western Europe, where the 1870 railway network had been denser and they were typically attributable to underlying political factors[20]. The large number of lines closures, together with the inauguration of many new lines, suggests that the rail network changed radically between 1870 and the decades from 1960 to 2010. These circumstances support the use of this initial expansion of the railroad network in 1870 as an exogenous instrument for the modern railroad network.

3. Impact of transportation on the urban structure of European cities

3.1 Identification

The classical monocentric land use theory developed by Alonso (1964), Mills (1967) and Muth (1969) predicts that the declining transport costs push some people away from the city core, thus lowering population densities in city centres. Wheaton (1974) shows that higher metropolitan populations lead to an expansion of the metropolitan boundary and rising densities throughout the city without any modification to the rent and density gradients of the open city system. The combined impact of population growth and the effects of transportation causes a flattening of rent and density gradients, while rents and population density increase in the suburbs. Based on this extension of the basic monocentric model and on the model of radial commuting highways proposed by Baum-Snow (2007b), we estimate the effect of highway rays, highway ramps, railway rays and railway stations on central city population. We measure the effect of transportation infrastructure on suburbanization indirectly by using the LUZ population as a control variable.

Concerns about endogeneity in this estimation have already been discussed in the associated literature (Baum-Snow, 2007a, Duranton and Turner, 2012, Garcia-López et al., 2015). Here, a main issue is the simultaneous causality bias between the transport infrastructure variables and population change in the CC. As argued in the literature, it is not only highways than can impact central city populations, but a city's prospects for growth or decline can also affect the policies regarding the allocation of new lines of transport infrastructure in that cities. Another endogeneity issue might arise owing to the fact that unobservable factors can cause omitted variable bias in an OLS specification. Here, it is clear that a city's past and recent economic can affect both the CC's population change and the allocation of transport infrastructure.

In European cities, the bias introduced by both these concerns could be either positive or negative. On the one hand, more transport infrastructure investments have typically been allocated to the more thriving urban areas, in terms of population or income. On the other hand, EU Regional and Cohesion Policies (and even some national policies) have targeted the

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[20] For example, the Federal Republic of Germany rationalized its railway network after the large-scale expansion during the Third Reich (Mitchell, 2006), while the Democratic Republic of Germany decided to maintain its public sector infrastructure.

lagging regions and cities in order to promote their growth potential and convergence with the rest of the EU.

To obtain an estimate of the causal effect of transport infrastructure improvements on CC population growth, we employ two-stage least square (TSLS) regressions using the exogenous variation provided by the historical transport infrastructure measures, which we use as instrumental variables. However, using panel data IV requires an instrument that varies over time. To this end, we use local ”shift-share” (Bartik, 1991) or ”smoothed” instruments, similar to the ”smoothed rays in the plan” instrument in Baum-Snow (2007a).

Smoothed postal route rays are calculated by multiplying the number of postal route rays in 1810 by the fraction of the highway mileage in each LUZ completed at each point in time. The postal route rays' instrument can be thought of as the segments of the 1810 postal route rays that would have been completed in every decade had the postal route network followed the same rate of evolution of the modern highway network (length) in each urban area[21]. It should be borne in mind that the fraction of the constructed network is a weight that takes values in the interval [0,1]. Therefore, the number of smoothed postal route rays will never be higher than the actual number of postal route rays and it will always be zero for cities with no postal route rays in 1810. The same process is followed when calculating the smoothed radial railways in 1870. By the same token, we have applied this methodology for the postal route and 1870 rail *length* variables, which we use as instruments for the highway ramps and the railway stations, respectively.

While the related literature (Baum-Snow, 2007a, Baum-Snow et al., 2015, Garcia-López et al., 2015) has focused mainly on long-difference specifications to estimate the suburbanization effect, we use panel specifications that allow us to control for unobservable city characteristics and for regional time trends. By using regional decade trends, we control for changes in the CC population that are decade-specific for the cities of the same NUTS1 region[22]. These interaction dummy variables, together with the LUZ fixed effects and the exogenous variation provided by our instruments, constitute the identification strategy and the main methodological contribution made by this paper.

An important innovation made by this paper is the fact that we do not only estimate individual effects, but we also estimate the joint effects of different transport infrastructure types and measures on the suburbanization of European cities.

$$ln(Pop_{it}^{CC}) = \beta_0 + \sum \beta_1 \widehat{Transport\ var}_{it} + \beta_2 ln(Pop_{it}^{LUZ}) + \vartheta^{LUZ} + \vartheta^{t} * \vartheta^{NUTS1} + \nu_{it} \tag{1}$$

Equation (1) is the second-stage specification in which we regress the highway and railway variables, $\widehat{Transport\ var}_{it}$, on the logarithm of the population that lives in the CC of city i in year t, $ln(Pop_{it}^{CC})$, controlling for the LUZ logarithm of population, $ln(POP_{it}^{LUZ})$. The reason why we use the summation symbol before $\widehat{Transport\ var}_{it}$ is because, in addition to individual effects, we

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[21] We have also used the fraction of mileage in each NUTS1 region and our main results continued to hold.

[22] On average, there are 6.2 cities in the same NUTS1 region.

also estimate the joint effects of two different transport infrastructure measures[23]. Finally, ϑ^{LUZ}, ϑ^{t} and ϑ^{NUTS1} stand for LUZ, decade and NUTS1 regional dummies, respectively. Standard errors are clustered by LUZ. However, clustering standard errors by NUTS1 regions in order to control for intraregional city interaction effects does not affect the standard errors of our estimates.

$$\widehat{Transport\ var_{it}} = \alpha_0 + \sum \alpha_1 Historical\ var_{it} + \alpha_2 ln(Pop_{it}^{LUZ}) + \eta^{LUZ} + \eta^{t} * \eta^{NUTS1} + \epsilon_{it} \qquad (2)$$

Equation (2) presents a general form of the first-stage specification where $\widehat{Transport\ var_{it}}$ includes highway rays, highway ramps, railway rays or railway stations. $\sum \alpha_1 Historical\ var_{it}$ are the historical transport variables that are used as instruments in each specification. As discussed, we are able to estimate the joint effects of two different transport infrastructure measures. As a result, instrumenting two independent variables means that the first-stage equation of each of these variables includes both instruments[24].

3.2 *First-stage results: History paved the way*

In Section 2.2, we documented the history and evolution of Europe's modern transport infrastructure. Accordingly, it seems that Europe's highway network has followed the routes taken by its historical postal network in 1810, while the modern railway network has expanded adhering to the first extension of the continent's railways in 1870. In addition, it is our contention that it is unlikely that these two historical transportation systems directly affected the population of European central cities during the second half of the 20th and the beginning of the 21st centuries, providing intuitive evidence that the postal routes of 1810 and the railways of 1870 satisfy the assumption of instrument exogeneity and that of instrument relevance. In this Section, we present the first-stage panel and long-difference estimates[25], which empirically show that the postal routes in 1810 and the railways in 1870 are relevant instruments for the modern highway and railway networks, respectively.

Panel A in Table 4 includes the first-stage results of our panel estimates. All these panel specifications include the logarithm of the LUZ population, LUZ fixed effects, as well as NUTS1 decade trends[26]. Columns [1] and [2] show the first-stage results for the highway ray and ramp variables, respectively. As can be seen, the smoothed postal route rays that we use as an instrument for the number of highway rays in each decade is highly statistically significant and positive. The same holds for the logarithm of the suburban postal route length as an explanatory variable of the logarithm of highway ramps. The railway results presented in Columns [3] and [4] are no different. We calculated the logarithms of all the length and node measures and added one unit to each observation in order to avoid dropping any observation with zero values.

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[23] The reason why we only use two transport infrastructure measures at a time is because when using more than two instruments the partial correlation between the different measures increases substantially and the first-stage F-statistic tests become less reliable.

[24] We always use the same number of instrumented variables and instruments (equations are identified exactly).

[25] However, we dropped the 2nd-stage estimates of the long-difference specification because we consider the panel estimation to be substantially more robust than the former.

[26] This is the interaction of the 97 NUTS1 regional dummies with the six decade (year) dummies.

Table 4: Modern and historical transport infrastructure: First stage results

Panel A					**Panel B**				
Panel 1st stage					Long-difference 1st stage				
	Decade variables					2011 variables			
Dependent variable:	Highw. rays	ln(sub. ramps)	Railw. rays	ln(sub. stations)	Dependent variable:	Highw. rays	ln(sub. ramps)	Railw. rays	ln(sub. stations)
	OLS [1]	OLS [2]	OLS [3]	OLS [4]		OLS [5]	OLS [6]	OLS [7]	OLS [8]
1810 post route rays	0.429^{a}				1810 post route rays	0.103^{b}			
	(0.027)					(0.041)			
ln(1810 post route km)		0.258^{a}			ln(1810 post route km)		0.061^{a}		
		(0.016)					(0.022)		
1870 railroad rays			0.404^{a}		1870 railroad rays			0.542^{a}	
			(0.070)					(0.110)	
ln(1870 railroad km)				0.419^{a}	ln(1870 railroad km)				0.078^{a}
				(0.033)					(0.021)
ln(LUZ population)	✓	✓	✓	✓	ln(1961 LUZ population)	✓	✓	✓	✓
NUTS1 decade trends	✓	✓	✓	✓	2011-1961 Δln(LUZ pop.)	✓	✓	✓	✓
LUZ FE	✓	✓	✓	✓	Country FE	✓	✓	✓	✓
					History	✓	✓	✓	✓
					Geography	✓	✓	✓	✓
Adj. R-squared	0.85	0.84	0.90	0.97	R-squared	0.59	0.72	0.62	0.81
Observations	3,474	3,474	3,474	3,474	Observations	579	579	579	579

Notes: The estimates presented in Columns [1] to [4] include 579 cities in 6 decades (1961-2011). The historical transport variables are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. Standard errors are clustered by LUZ and are in parenthesis. In Columns [5]-[8], geography is controlled by the logarithm of the CC and the LUZ area, the mean and range of CC elevation, the mean surface ruggedness for each LUZ and the logarithm of the distance to the closest coast from the CC centroid. History is controlled by the inclusion of dummy variables for historical major cities (in 1000 and 1450) and for the logarithm of city population in 1850, for cities with universities between the 12th and 15th century, for cities with Roman settlements, for cities with bishoprics (in 600 and 1450), for cities with medieval monasteries and for cities with historical city centres or another landmark denominated by UNESCO. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

In order to validate the relevance of our instruments, in Panel B, we show the first-stage of a long-difference specification that includes a number of historical and geographical control variables. By including a series of historical variables, we show that even when explicitly controlling for past economic development and political influence[27], the historical transport variables we use as instruments are still highly statistically significant and positively related with the modern transport infrastructure. A further concern for the first-stage estimation is that geographical features may have affected the location of both modern and historical transport infrastructure. The literature has reported a negative relationship between surface roughness and transport

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[27] Europe's biggest cities in 1000, 1450 and the logarithm of 1850 populations can be used as proxies for economic development in earlier centuries. As Tabellini (2010) suggests, in the past, cities were the centre of commerce and the Industrial Revolution further concentrated economic activity around major urban areas. For this reason, several studies have relied on city size as a measure of past economic development (De Long and Shleifer, 1993, Acemoglu et al., 2005). The inclusion of dummies for cities with bishoprics, medieval monasteries, Roman settlements and monasteries can be regarded as proxies for political influence in the past.

infrastructure (Ramcharan, 2009), which appears to be consistent with the road construction literature. The estimates suggest an exponential impact of terrain grade variation on the cost of building and maintaining roadways and rail lines, as well as on the time and energy required to move goods within a country and to maintain transport networks[28]. Panel B in Table 4 confirms the relevance of our instruments after controlling for the role of history and geography.

3.3 *Second-stage results: The "drivers" of suburbanization*

Table 5 shows our main average results when estimating equation (1) for the whole sample of cities. Column [1] shows the results of a simple OLS regression in which we estimate the joint effect of highway and railway rays on suburbanization. The highway ray coefficient appears to be highly significant and negative while the railroad ray coefficient is zero. However, as discussed above in Section 3.1 and in the literature, this OLS regression might suffer from bias. Therefore, hereinafter we use TSLS estimations.

The method used to select the specifications that we finally include in each output table was the following. First, we estimate individual specifications for both highway rays and highway ramps. If both coefficients are significantly different from zero, we estimate the joint effect of highway rays and ramps. We proceed in the same way for railways (rays and stations). Then, we estimate the joint highway-railway effect for all the couples of jointly or individually statistically significant variables (if any). If, for example, highway rays are statistically significant in a joint highway rays-ramps specification but highway ramps are not, we only include the highway rays in the joint highways-railways specification (that is if any railway coefficients are statistically significant). If, on the other hand, none of the highway rays or ramps are statistically significant in the joint highway rays-ramps specification, we estimate the joint highway-railway specifications (again, if any railway measure is statistically significant) for both highway rays and ramps. It should be stressed that the first-stage F-statistic tests in Section 4 are not always above the Stock and Yogo (2004) 10% critical values. Nonetheless, for the sake of completeness and consistency, we prefer to show all the results and interpret them with caution when the instruments are not strong.

Column [2] shows the results of the TSLS regression when we use the highway rays as our main variable of interest. The estimated highway coefficient is highly statistically significant and its value is -0.045. Column [3] includes the logarithm of suburban highway ramps as a measure of suburban[29] highway accessibility and as an alternative measure of highway infrastructure. The coefficient for the highway ramps is highly significant and negative and its value is -0.054. These results are in line with the negative effect of highways on CC population that has been found in the related literature (Baum-Snow, 2007a, Baum-Snow et al., 2015, Garcia-López et al., 2015). Column [4] includes both highway rays and the logarithm of suburban ramps in order to separate CC highway penetration and the impact of suburban accessibility. It appears that highway rays

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[28] See for example Aw (1981), Highway Research Board (1962) and Paterson (1987).

[29] Suburban ramps and stations are very highly correlated with the total number of ramps and stations in the LUZ. However, suburban nodes are not so strongly correlated with the number of rays. For this reason and in order to mitigate the collinearity issues between our highway/railway measures, we chose to include the suburban counts of nodes instead of the LUZ counts.

constitute the only statistically significant measure and its value is not statistically different from its value in Column [2]. However, the increase in standard errors due to the high correlation between the rays and the ramps measures suggests that the effects of the different measures of highway infrastructure are not easily disentangled. This is another reason why we opted to show all these different specifications in all the estimation output tables.

Table 5: Suburbanization and transportation in Europe, 1961–2011: Average results

Dependent variable:	ln(Central city population)									
								Robustness		
	1961–2011 Main results							Endog LUZ pop	Algorithm rays	Smoothed rays
	OLS [1]	TSLS [2]	TSLS [3]	TSLS [4]	TSLS [5]	TSLS [6]	TSLS [7]	TSLS [8]	TSLS [9]	TSLS [10]
Highway rays	-0.031^a (0.008)	-0.045^a (0.008)		-0.036^b (0.016)			-0.042^a (0.008)	-0.022^a (0.008)	-0.038^a (0.012)	-0.046^a (0.008)
ln(suburban ramps)			-0.054^a (0.012)	-0.017 (0.023)						
Railroad rays	0.004 (0.005)				-0.038^a (0.015)		-0.021 (0.013)	-0.015 (0.012)	-0.001 (0.006)	-0.005^c (0.003)
ln(suburban stations)						0.007 (0.011)				
ln(LUZ population)	✓	✓	✓	✓	✓	✓	✓	Lagged	✓	✓
LUZ fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year×NUTS1 dummies	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
First-Stage F-statistic	-	249.6	261.6	25.6	33	162.6	16.5	16.6	65.6	103
S. & Y. 10% critical values	-	16.4	16.4	7	16.4	16.4	7	7	7	7
Observations	3,474	3,474	3,474	3,474	3,474	3,474	3,474	2,895	3,474	3,474
Instruments:										
1810 post road rays		✓		✓			✓	✓	✓	✓
ln(1810 post road km)			✓	✓						
1870 railroad rays					✓		✓	✓	✓	✓
ln(1870 railroad km)						✓				

Notes: The estimates presented in Columns [1] to [9] include 579 cities in 6 decades (1961-2011). Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. S. & Y. refer to Stock and Yogo (2004). Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Columns [5] and [6] present the results for railway rays and stations, respectively. Column [5] indicates that the railway ray coefficient is also highly significant and negative. In addition, its value is similar to the value of the highway ray coefficient. Yet, Column [6] shows that in the case of railways, the measure of suburban accessibility (stations) is not significant for suburbanization. Therefore, in accordance with our method for selecting the most meaningful specifications, we do not include a joint specification for rail measures[30]. Finally, Column [7] is our preferred specification for the average results, where both highway rays and radial railways are included. This specification indicates that when the two types of transport infrastructure are jointly considered, railways are not statistically significant, while the highway ray coefficient is hardly unchanged compared to the individual specification in Column [2]. The finding that the effect of railway rays on suburbanization is biased when railways are considered individually is

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[30] In any case, the resulting output is approximately a reproduction of the railway ray and station coefficients and p-values from Columns [5] and [6].

crucial and highlights the importance of jointly considering highways and railways in the study of suburbanization.

Column [7] indicates that an additional highway ray displaced on average 4.2% of the European CC population in the period 1961-2011. This is a somewhat lower[31] estimate than that provided by previous empirical findings in the related literature (Baum-Snow, 2007a, Baum-Snow et al., 2015, Garcia-López et al., 2015). This can be attributed either to the differences between Europe, on the one hand, and the US, China and Spain, on the other, or to the different estimation strategies used. The following section (Section 4) highlights the heterogeneity in terms of history, geography and other specific characteristics of the groups of cities and countries. However, when comparing the results obtained without using regional (or country) trends, it seems that the NUTS1 interaction dummies used in Table 5 capture a significant part of the CC population variation. Omitting these regional trends raises the values of the estimated coefficients.

Columns [8] to [10] include some alternative specifications that serve to confirm the robustness of the previous findings. Column [8] uses the lag of the LUZ population variable in order to control for reverse causality issues. The value of the highway coefficient is -0.022; however, this change of the coefficient could be entirely attributed to the exclusion of the first year of our data when we include the lag of the LUZ population since we do not have population data prior to 1961[32]. Column [9] uses the number of rays based on the algorithm count that we described in Section 2. Using this alternative measure for highway rays, we confirm the results in Column [7]. Finally, Column [10] includes the ”smoothed rays” measure of highways and railways[33]. Here, they are computed by multiplying the number of 2011 highway/railway rays by the fraction of the highway/railway mileage in each LUZ completed in each decade. The fractional values of the rays measure allows even small suburbanization effects to show up in the coefficient. This could be the case if, for example, it takes twenty years for residential location patterns to fully respond to changes in highway infrastructure. The results of our preferred specification using the smoothed rays remain unchanged.

4. Heterogeneous effects

4.1 Suburbanization by time period

According to urban economic theory, households respond to the increase in accessibility to the CBD by relocating from the central city to the suburbs. However, the reaction of households to improvements in transport infrastructure appear to have varied considerably during our 50-year study period. There are a number of circumstances that point out to this variation. In Table 1, we saw that the LUZ population growth was highest in the decade 1961-1971 and almost twice that of the second highest period of growth which occurred between 1971 and 1981. In addition, Table 2 indicates that during this first decade, small cities experienced intense urbanization while their

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[31] In absolute values (hereafter).

[32] The value of the estimated highway ray coefficient when we exclude 1961 is exactly 0.022. This drop in the coefficient is discussed in detail in Section 4.1.

[33] Smoothed rays were first introduced in Baum-Snow (2007a).

bigger counterparts underwent extensive suburbanization. However, this pattern became more balanced in terms of suburbanization across all city sizes towards 2011. Finally, in Column [8] of Table 5, when we exclude the first year of our study period (1961) in order to include the lag LUZ population, the estimated coefficient fell considerably. As mentioned in Section 3.3, this fall was not caused by the endogenous variable, but rather by the change in the period of study.

In this section[34], we first split our period of study in two in order to test whether the effect of transportation infrastructure on suburbanization differed between these subperiods. Panel A of Table 6 shows the results when we split the study period (1961-2011) into two subperiods: 1961-1981 and 1991-2011[35]. There is a statistically significant difference between the higher highway coefficient in the period 1961-1981 (Column [1]) and the lower and less statistically significant highway coefficient in the period 1991-2011 (Columns [12] and [13]). This finding could imply that our average results were mainly driven by the first subperiod or by the cities in which highways were constructed during the early years. This is the main reason why in Panels B and C, we use two subsamples of cities based on the existence of one or more highways by 1981 and we also split the whole 50-year period in the two subperiods used in Panel A.

Panel B in Table 6 shows that for the cities with highways in 1981, the highway effect on suburbanization in the whole period of study is roughly the same as in our preferred specification (Column [7] in Table 5). However, for these cities, rail seems to be an important driver of suburbanization too, although it is only marginally statistically significant. Columns [7] to [10] and Columns [11] to [14] show the effect for each of the two subperiods. As can be seen, there is a highly significant effect of highways on suburbanization during the first period but no effect in the period 1991-2011. This first result suggests that the early highways that were opened in 1961 fostered the suburbanization of the cities in which more highways were constructed during this first period. In contrast, the latter result suggests that in the cities with some highway endowments by 1981, the additional highways built after 1981[36] did not result in more suburbanization during that second period.

The group of cities used in Panel B comprises by high population cities, located primarily in Central-Northern Europe. Although these cities experienced relative suburbanization on average during the period 1991-2011, this process does not seem to be the result of improvements to their transport infrastructure. There are many potential explanations for this finding. We discuss these explanations in detail in Sections 4.2 and 4.4, where we estimate the effect of transport infrastructure for big cities and for the cities in the Central-Northern Europe.

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[34] The output tables in Section 4 are included after the references at the end of the paper.

[35] The results are similar when other subperiods were considered (1961-1991 and 1991-2011 as well as 1961-1981 and 1981-2011).

[36] In cities with highways built by 1981, many new highways were also constructed after 1981 (47% increase in the total number of highways in the period 1981-2011 in these cities).

Table 6: Suburbanization and transportation in Europe, 1961–2011: Time periods

Dependent variable:	ln(Central city population)														
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]
Panel A: Subperiod results															
	1961–1971–1981 Panel					1991–2001–2011 Panel									
Highway rays	-0.038^{a}		-0.030^{c}			-0.012^{c}		-0.004				-0.012^{c}	-0.012^{c}		
	(0.007)		(0.017)			(0.006)		(0.014)				(0.006)	(0.006)		
ln(suburban ramps)		-0.030^{a}	-0.009				-0.039^{c}	-0.033						-0.043^{c}	-0.053^{a}
		(0.009)	(0.018)				(0.023)	(0.037)						(0.025)	(0.019)
Railroad rays (smooth)				-0.061					-0.003^{b}		-0.005	-0.002^{c}		-0.006^{b}	
				(0.046)					(0.001)		(0.005)	(0.001)		(0.002)	
ln(suburban stations)					-0.155					-0.008^{c}	0.011		-0.008^{c}		0.004
					(0.098)					(0.004)	(0.020)		(0.004)		(0.011)
First-Stage F-statistic	199.9	205.9	20.9	8.0	41.6	60.1	11.1	1.4	140.7	151.9	4.7	31.2	30.4	4.9	131.2
Observations	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	3,474
Panel B: 327 LUZs with highways prior to 1961 or built between 1961 and 1981															
	1961–2011 Results						1961–1981 Results				1991–2011 Results				
Highway rays	-0.046^{a}		-0.048^{b}			-0.039^{a}	-0.030^{a}				0.002				
	(0.014)		(0.020)			(0.014)	(0.009)				(0.006)				
ln(suburban ramps)		-0.041^{b}	0.008					-0.016				-0.008			
		(0.020)	(0.029)					(0.012)				(0.062)			
Railroad rays*				-0.050^{b}		-0.037^{c}			-0.013				-0.006		
				(0.022)		(0.019)			(0.026)				(0.006)		
ln(suburban stations)					-0.008					-0.006				-0.004	
					(0.015)					(0.050)				(0.006)	
First-Stage F-statistic	154.9	107.4	22.2	18.7	69.7	9.4	91.1	91.7	744.1	8222	26.9	1.3	21.6	61.7	
Observations	1,962	1,962	1,962	1,962	1,962	1,962	981	981	981	981	981	981	981	981	
Panel C: 252 Other LUZs (no highways until 1991)															
	1961–2011 Results					1991–2011 Results									
Highway rays	-0.032^{c}		0.006			-0.022^{b}				-0.019^{b}					
	(0.018)		(0.051)			(0.009)				(0.010)					
ln(suburban ramps)		-0.053^{b}	-0.059				-0.051								
		(0.022)	(0.068)				(0.034)								
Railroad rays				-0.006				-0.021^{c}		-0.016					
				(0.027)				(0.0123)		(0.0121)					
ln(suburban stations)					0.022				-0.006						
					(0.017)				(0.007)						
First-Stage F-statistic	31	34	1.3	9.8	58.4	29.2	7.3	13.9	67.2	6.2					
Observations	1,512	1,512	1,512	1,512	1,512	756	756	756	756	756					

Notes: *The coefficient of Column [7] is obtained using the smoothed railway rays. The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Panel C in Table 6 includes only those cities that had no highways up until 1981. We created this subsample in order to test whether our average results were solely attributable to those cities in which highways were constructed in an earlier period. The results for the whole period suggest a highway coefficient that is statistically significant at the 10% level. In contrast, the results for the 1991-2011 subperiod present a -0.022 statistically significant highway coefficient. This result suggests that highways also caused suburbanization in the cities with highways constructed after 1981.

The results in this section suggest that the average results presented in Section 3.3 hold in general for all the cities and for the whole period of our dataset. In particular, considering the whole sample of cities, we find a reduced but significant effect in the later period. In addition, we find that highways caused suburbanization in the cities in which highways were constructed only after 1981. However, in all these results, the estimated effect of transport infrastructure on suburbanization declined over time. Finally, as the effect of highways on suburbanization seems to have reduced over time, the effect of railways on suburbanization seems to have become significant. One explanation for this latter finding could be that railways do not suffer from the time losses associated with traffic congestion and that traffic congestion became more severe during more recent decades.

4.2 *Urban form and suburbanization*

The descriptive statistics of suburbanization in Section 2.1 indicate that the process of suburbanization in Europe differed for cities of different population sizes. In addition, in Map A.1 we observe a mixed pattern of urbanization/suburbanization in Europe's cities. Based on these stylized facts, we investigate the effect of highways and railways on suburbanization when we split our sample based on different characteristics of the cities' urban form.

Panel A in Table 7 presents the results when we split the total sample of cities based on the median LUZ population in 1961 (177,158 inhabitants). Our preferred specification for the big cities (Column [5]) shows that both highways and railways are jointly significant and the value of their rays coefficients is exactly the same. This result suggests that an additional highway in big cities displaced as much population as an additional railway ray. In contrast, for small cities, only highway rays are statistically significant. This result makes intuitive sense as highway congestion in Europe is considerably more severe in the big cities (Christidis and Rivas, 2012) and as railways mainly facilitate the journeys of daily travellers in big cities, where average commuting distances are longer. Finally, suburbanization in big cities could be the result of firm (and therefore employment) decentralization (Baum-Snow, 2010).

Table 7: Suburbanization and transportation in Europe, 1961–2011: City size and density

Dependent variable:	ln(Central city population)													
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]
Panel A: Size by population														
	290 Big LUZs (1961 pop≥177,158 inhab.)					289 Small LUZs (1961 pop<177,158 inhab.)								
Highway rays	-0.020^{b}				-0.017^{b}	-0.032^{c}								
	(0.008)				(0.008)	(0.019)								
ln(suburban ramps)		-0.022					-0.011							
		(0.014)					(0.020)							
Railroad rays			-0.024^{a}		-0.017^{c}			-0.026						
			(0.009)		(0.009)			(0.046)						
ln(suburban stations)				0.016					0.011					
				(0.011)					(0.017)					
First-Stage F-statistic	134	162.1	26.5	131.4	14.2	102.5	102.7	5.2	80.1					
Observations	1,740	1,740	1,740	1,740	1,740	1,734	1,734	1,734	1,734					
Panel B: Size by area														
	289 Big LUZs (area≥1,170 km^2)				290 Small LUZs (area<1,170 km^2)									
Highway rays	-0.032^{c}				-0.039^{a}		-0.018			-0.034^{a}				
	(0.019)				(0.009)		(0.019)			(0.010)				
ln(suburban ramps)		-0.011				-0.059^{a}	-0.042				-0.066^{a}			
		(0.020)				(0.014)	(0.027)				(0.017)			
Railroad rays			-0.026					-0.052^{c}		-0.030	-0.068^{b}			
			(0.046)					(0.028)		(0.025)	(0.034)			
ln(suburban stations)				0.011					0.014					
				(0.017)					(0.014)					
First-Stage F-statistic	102.5	102.7	5.2	80.1	105.3	146.1	14.24	6.5	73.5	2.8	3.1			
Observations	1,734	1,734	1,734	1,734	1,734	1,734	1,734	1,734	1,734	1,734	1,734			
Panel C: 1961 Density														
	289 Dense LUZs (1961 LUZ den ≥178 inh/km^2)							290 Sparse LUZs (1961 LUZ den<178 inh/km^2)						
Highway rays	-0.043^{a}		-0.030			-0.041^{a}		-0.042^{a}		-0.034			-0.040^{a}	
	(0.014)		(0.025)			(0.014)		(0.011)		(0.021)			(0.011)	
ln(suburban ramps)		-0.062^{a}	-0.031				-0.062^{a}		-0.046^{a}	-0.013				-0.043^{a}
		(0.017)	(0.034)				(0.018)		(0.014)	(0.028)				(0.015)
Railroad rays				-0.042^{a}		-0.023^{b}	-0.047^{a}				0.000			
				(0.016)		(0.012)	(0.017)				(0.058)			
ln(suburban stations)					-0.011							0.031^{b}	0.026^{c}	0.026
					(0.013)							(0.015)	(0.014)	(0.016)
First-Stage F-statistic	181.7	104.6	12.7	25.9	107.5	14.6	13.6	63.2	112.1	6.7	1.6	63.5	39.1	58.1
Observations	1,734	1,734	1,734	1,734	1,734	1,734	1,734	1,740	1,740	1,740	1,740	1,740	1,740	1,740

Notes: The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Table 8: Suburbanization and transportation in Europe, 1961–2011: Degree of (sub)urbanization

Dependent variable:	ln(Central city population)									
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
Panel A: 1961 Degree of Centralization-suburbanization										
	280 Centralized LUZs (1961 CC share>1961 SUB share)						299 Decentralized LUZs (1961 CC share<1961 SUB share)			
Highway rays	-0.034^{a}		-0.005				-0.032^{c}			
	(0.006)		(0.014)				(0.019)			
ln(suburban ramps)		-0.071^{a}	-0.065^{a}			-0.062^{a}		-0.029		
		(0.012)	(0.025)			(0.016)		(0.022)		
Railroad rays				-0.071^{b}		-0.083^{b}			0.000	
				(0.030)		(0.033)			(0.058)	
ln(suburban stations)					-0.009					0.009
					(0.014)					(0.018)
First-Stage F-statistic	176.8	124.2	12.5	6.6	67.2	3.3	69.6	108.2	1.6	49.2
Observations	2,220	2,220	2,220	2,220	2,220	2,220	1,254	1,254	1,740	1,254
Panel B: Absolute suburbanization (90 LUZs with 1961–2011 ↓CC pop)										
Highway rays	-0.033^{a}		-0.032^{b}			-0.030^{b}				
	(0.012)		(0.014)			(0.013)				
ln(suburban ramps)		-0.024^{b}	-0.001							
		(0.013)	(0.016)							
Railroad rays				-0.015^{b}		-0.009				
				(0.007)		(0.007)				
ln(suburban stations)					0.030					
					(0.020)					
First-Stage F-statistic	41.0	39.7	6.5	14.3	16.6	16.7				
Observations	540	540	540	540	540	540				
Panel C: Relative (de)centralization (489 LUZs with 1961–2011 ↑CC pop)										
	218 Relative suburbanization (61–11 ↑CC pop & ↑SUB share)					271 Relative centralization (↑CC pop & ↑CC share)				
Highway rays	-0.012^{c}		0.001			-0.029^{b}				-0.028^{b}
	(0.007)		(0.013)			(0.013)				(0.013)
ln(suburban ramps)		-0.026^{b}	-0.027				-0.008			
		(0.012)	(0.021)				(0.020)			
Railroad rays				-0.148				-0.023		
				(0.253)				(0.048)		
ln(suburban stations)					-0.006				0.025^{c}	0.025^{c}
					(0.015)				(0.014)	(0.013)
First-Stage F-statistic	97.4	74.1	9.8	0.3	85.3	43.9	92.9	7.3	56.9	22
Observations	1,308	1,308	1,308	1,308	1,308	1,626	1,626	1,626	1,626	1,626

Notes: The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Panel B in Table 7 shows the results when cities are divided on the basis of their median LUZ area (1,170 km²). These results differ from those in Panel A. It seems that highways are the only significant transport infrastructure measure for the 'big' area cities. In the case of 'small' area cities, railway rays are also statistically significant individually at the 10% statistical significance level. However, the first-stage F-statistics reported in Columns [10] and [11] are too low to estimate a robust joint effect. The individually estimated coefficients of the highway rays between big and small cities in Panel B show that the magnitude of the highway effect did not differ between the two groups. Both Panel A and Panel B suggest that the average effects estimated in Section 3 are not crucially determined by city size. Nonetheless, the fact that in high population cities, highways and railways both affected suburbanization equally is a novel and interesting finding.

A further aspect of the urban form is urban population density. In order to control for the differences between densely and sparsely populated cities, in Panel C in Table 7, we split our sample according to the median LUZ population density in 1961 (178 inhabitants/km²). The results suggest that the effect of highways on suburbanization does not differ significantly between more and less dense (denominated sparse) cities. However, in the case of the dense cities, either of the two highway measures (rays or ramps) and railroad rays are jointly statistically significant, even though the railway coefficient is lower. For the sparse cities, it is not clear whether railways are also important since the first-stage of the railway rays specification is very weak.

In Panel A in Table 8, we separate the sample according to the share of population living in the CC and the share of population living in the suburbs of each city. We define as *centralized* cities those for which the CC population share is larger than the suburban population share and as *decentralized* all the rest. Although we find no differences in the highway coefficients of the two groups, railroad rays are statistically significant in the centralized cities. Moreover, ramps seem to drive highway suburbanization in the centralized cities. However, the low F-statistic of Column [6] suggests that the joint results should be interpreted with caution.

In Section 2.1, we defined relative (sub)urbanization. In addition, in Table 2, we saw that some cities experienced relative suburbanization while others experienced relative urbanization. At this juncture, we introduce the cities that experienced *absolute suburbanization*, that is, those whose CC population declined. In Panels B and C in Table 8, we have separate our sample according to these three different characterizations of (sub)urbanization. This is an important distinction for the relationship that we are investigating since the estimated negative coefficient of our main results could only be driven by the fact that the cities with little or no transport infrastructure urbanized. The estimated highway coefficients for the cities that experienced absolute suburbanization and those that experienced relative urbanization are virtually the same. The estimated highway coefficient for the cities that experienced relative suburbanization is also not statistically different from that of the other two groups. However, its value is lower and it is only statistically significant at the 10% level.

4.3 *Cities with history*

Table 9 presents the results when separating the sample according to the cities that were considered major urban centres during different historical time periods from those that were not. Here, we only find a statistically significant difference for the coefficient of the highway rays for cities that were major Roman cities. However, major cities in the Middle Ages and major cities in the pre-Industrial Revolution (1700-1750) also exhibit a lower highway coefficient than the rest of the cities. A possible explanation for these differences could be the availability of historical urban amenities, which are usually embedded in the central cities of historical European cities. Brueckner et al. (1999) define historical amenities as being ”generated by monuments, buildings, parks, and other urban infrastructure from past eras that are aesthetically pleasing to current residents of the city”. They also suggest that there is a positive correlation between historical and modern amenities. Therefore, urban amenities could explain the fact that transport infrastructure displaced less CC population in the Roman and other historical cities.

On the other hand, we find absolutely no difference between the highway coefficients of the post-Industrial Revolution cities and the rest of the sample. Industrialization in European cities frequently occurred in a disconnected fashion from any previous urban development, hence by-passing a city’s historic role as a convenient market-place, a safe bastion or a religious or political centre (Hohenberg and Lees, 2009). Some of these cities, such as London, Cologne or Amsterdam, served important functions, but many others had previously been merely villages or small towns (Plöger, 2013). The emergence of major cities during the Industrial Revolution in places with ”no history” might add to the previous explanation concerning historical urban amenities. Moreover, the marked impact of economic restructuring on many older manufacturing cities could explain why highways in Post-Industrial Revolution cities did not promote more suburbanization. Finally, the massive loss of employment in many manufacturing cities, as a result of economic restructuring (Plöger, 2013), may also have curtailed the demand for housing in post-Industrial Revolution cities.

Further evidence for the importance of historical urban amenities in central cities is provided in Table B.1 in Appendix B, where we split the sample between cities with a historical city centre or with a landmark recognized by UNESCO from all other cities. Note that most of these landmarks are located in central cities. The coefficient for highway rays is lower and not statistically significant in the UNESCO cities, while for the non-UNESCO cities, the estimated coefficient is in line with our average results. It should be stressed that only 59% of the UNESCO cities were Roman cities and that only 26% of the Roman cities were UNESCO cities.

Table 9: Suburbanization and transportation in Europe, 1961–2011: City history

Dependent variable:	ln(Central city population)													
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]
Panel A: The Roman Empire														
	225 Roman cities							354 Non-Roman cities						
Highway rays	-0.024^{a}		0.006			-0.023^{a}		-0.057^{a}		-0.066^{b}				
	(0.007)		(0.026)			(0.008)		(0.015)		(0.031)				
ln(suburban ramps)		-0.065^{b}	-0.072				-0.071^{b}		-0.045^{a}	0.013				
		(0.027)	(0.057)				(0.029)		(0.013)	(0.032)				
Railroad rays				-0.048^{c}		-0.035	-0.054^{c}				-0.018			
				(0.027)		(0.023)	(0.030)				(0.014)			
ln(suburban stations)					-0.005							0.016		
					(0.023)							(0.012)		
First-Stage F-statistic	142.2	74.7	7.4	8.4	100.3	4.4	4.2	68.3	147	9	17.6	94.3		
Observations	1,350	1,350	1,350	1,350	1,350	1,350	1,350	2,124	2,124	2,124	2,124	2,124		
Panel B: The Middle Ages														
	296 Major medieval cities						283 Other cities							
Highway rays	-0.035^{a}		-0.011				-0.049^{b}				-0.050^{b}			
	(0.008)		(0.017)				(0.020)				(0.020)			
ln(suburban ramps)		-0.061^{a}	-0.051^{b}			-0.065^{a}		-0.012						
		(0.014)	(0.026)			(0.016)		(0.019)						
Railroad rays				-0.053^{b}		-0.068^{b}			-0.027^{c}		-0.017			
				(0.024)		(0.029)			(0.014)		(0.013)			
ln(suburban stations)					0.006					-0.009				
					(0.016)					(0.015)				
First-Stage F-statistic	146.1	165.9	22.7	7.3	150.3	3.5	44.4	66.9	18.5	57.7	10.9			
Observations	1,776	1,776	1,776	1,776	1,776	1,776	1,698	1,698	1,698	1,698	1,698			
Panel C: Pre-Industrial Revolution														
	357 Major cities in 1700–1750 ($\geq$ 25,000 inhab.)							222 Other cities						
Highway rays	-0.036^{a}		-0.012			-0.030^{a}		-0.050^{a}		-0.058^{a}			-0.050^{a}	
	(0.008)		(0.020)			(0.010)		(0.015)		(0.021)			(0.016)	
ln(suburban ramps)		-0.064^{a}	-0.051				-0.068^{a}		-0.033^{b}	0.016				-0.034^{c}
		(0.016)	(0.033)				(0.018)		(0.015)	(0.023)				(0.017)
Railroad rays				-0.053^{b}		-0.030	-0.064^{b}				-0.047^{b}		-0.035^{c}	-0.050^{b}
				(0.027)		(0.025)	(0.030)				(0.022)		(0.019)	(0.023)
ln(suburban stations)					0.004							-0.013		
					(0.013)							(0.018)		
First-Stage F-statistic	139.2	121.5	13.4	7.3	98.4	3	3.6	110.3	104.4	10.1	19	72.3	9.9	9.6
Observations	2,142	2,142	2,142	2,142	2,142	2,142	2,142	1,332	1,332	1,332	1,332	1,332	1,332	1,332
Panel D: Post-Industrial Revolution														
	291 Major cities in 1850 ($\geq$ 25,000 inhab.)							288 Other cities						
Highway rays	-0.030^{a}		-0.010			-0.029^{a}		-0.029^{a}						
	(0.008)		(0.018)			(0.008)		(0.011)						
ln(suburban ramps)		-0.052^{a}	-0.041				-0.027		-0.024					
		(0.014)	(0.030)				(0.021)		(0.018)					
Railroad rays				-0.026^{b}		-0.011	-0.025			-0.023				
				(0.013)		(0.012)	(0.051)			(0.050)				
ln(suburban stations)					-0.005						0.032^{c}			
					(0.016)						(0.017)			
First-Stage F-statistic	124.6	101.2	9.2	14.2	72.5	7.1	2.2	72.4	109	4.6	78.4			
Observations	1,746	1,746	1,746	1,746	1,746	1,728	1,728	1,728	1,728	1,728	1,728			

Notes: The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

4.4 Common European grounds

In this section, we divide the cities according to the European region in which they are located (namely, Mediterranean, Eastern and Central-Northern Europe). We then separate the sample according to whether the NUTS1 region in which each city is located was characterised as Objective 1 region in 1995 or in 2000[37]. This also serves as a division between poorer and more wealthier regions, since the classification of Objective regions is based on regional GDP. We also divide our sample of cities according to the different phases of EU integration (for those results see Appendix B.2).

Table 10 presents the results when we separate our sample of cities on the basis of three greater geographical areas that shared common historical and development paths. For this reason, in the cases of France and Germany, we have divided the national territories of each country in two: Southern France (*"le Midi"*) and the rest of the France, and East and West Germany (based on its political division)[38].

The magnitude of the coefficient of highway rays for the Mediterranean cities in Panel A of Table 10 is similar to the estimates of Garcia-López et al. (2015) for the effects of highways for Spain. The results for Eastern European cities in Columns [6]-[11] of Panel A seem to be in line with the findings of Bertaud (1999, 2004) and Redfearn (2006). Following the transition, these ex-Soviet regions had poor and very limited infrastructure that could not support the high residential densities of their city centres. In addition, the expansion of office and retail space in their city centres at the expense of residential areas, together with increased motorization and the construction of new highways and railways, fostered greater rates of suburbanization in these cities than in cities in the rest of Europe. In contrast, the effect of transportation infrastructure on the suburbanization of the Central-Northern European cities (Panel B) can be almost equally attributed to highways and railways. Central-Northern European cities are characterized in general by high economic performance, high migration inflows and well-organized urban planning systems that seek to limit urban sprawl (Couch et al., 2008) and protect green areas around the city fringe. The resulting lack of developable land, together with the increasing demand for housing and congestion levels in cities with high population concentrations, are some of the factors that appear to account for these results.

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[37] For reasons of data availability, we use regional GDP per capita figures from 1995 for the EU15 states and from 2000 for the rest of the countries.

[38] We also used other groups that included the whole of France in the Mediterranean or in the Central-Northern groups and the whole of Germany in the Central-Northern group or even in the Eastern group. The results remained largely similar.

Table 10: Suburbanization and transportation in Europe, 1961–2011: Geographical and EU regions

Dependent variable:	ln(Central city population)										
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Panel A: Mediterranean and Eastern European countries' cities											
	193 Mediterranean LUZs					147 Eastern LUZs					
Highway rays	-0.052^{a}		-0.005			-0.056^{a}				-0.055^{a}	
	(0.019)		(0.040)			(0.019)				(0.019)	
ln(suburban ramps)		-0.123^{a}	-0.116				-0.011				
		(0.034)	(0.071)				(0.026)				
Railroad rays				-0.081				0.010			
				(0.051)				(0.028)			
ln(suburban stations)					-0.018				0.038^{b}	0.039^{a}	
					(0.029)				(0.016)	(0.015)	
First-Stage F-statistic	123.8	88.2	6.6	10.47	37.1	27.6	40.2	7.8	49.3	14.5	
Observations	1,158	1,158	1,158	1,158	1,158	882	882	882	882	882	
Panel B: Central-North European countries' cities											
	239 Central-North LUZs										
Highway rays	-0.038^{a}		-0.034^{a}			-0.032^{a}					
	(0.009)		(0.013)			(0.009)					
ln(suburban ramps)		-0.035^{a}	-0.007								
		(0.011)	(0.016)								
Railroad rays				-0.037^{a}		-0.025^{b}					
				(0.012)		(0.011)					
ln(suburban stations)					-0.005						
					(0.010)						
First-Stage F-statistic	114	134.2	20.1	17.1	82	8.2					
Observations	1,434	1,434	1,434	1,434	1,434	1,434					
Panel C: EU regional policy (Objective 1)											
	242 LUZs in 1996–2011 Objective 1					337 Other LUZs					
Highway rays	-0.044^{a}		-0.023			-0.031^{a}		-0.029^{b}			-0.028^{a}
	(0.017)		(0.072)			(0.006)		(0.013)			(0.007)
ln(suburban ramps)		-0.059^{b}	-0.032				-0.037^{a}	-0.006			
		(0.026)	(0.098)				(0.014)	(0.023)			
Railroad rays				-0.007					-0.033^{a}		-0.022^{b}
				(0.020)					(0.012)		(0.011)
ln(suburban stations)					0.020					0.006	
					(0.018)					(0.011)	
First-Stage F-statistic	67.3	104	1.6	11.9	56.7	164.5	149.1	19.7	18.3	104.4	9.3
Observations	1,476	1,476	1,476	1,476	1,476	1,632	1,632	1,632	1,632	1,632	1,632

Notes: The Mediterranean regions include Bulgaria, Croatia, Cyprus, the South of France, Greece, Italy, Malta, Portugal and Spain. The East European countries regions include Austria, Czech Republic, Estonia, Finland, Eastern Germany, Hungary, Latvia, Poland, Romania, and Slovakia. Finally, the Central-North regions include Belgium, Denmark, France (except for the South), Western Germany, Ireland, Iceland, Luxembourg, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom. Objective 1 cities are those whose NUTS2 regional GDP per capita was below the 75% of the EU average in 1995 or in 2000 (if data for 1995 are not available). The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

Finally, in Panel D in Table 10, we split the group of NUTS1 regions between Objective 1 regions and the rest. Objective 1 regions are those whose regional GDP per capita was below 75% of the EU average. This grouping is meaningful because an enormous amount of the EU Regional Funds were allocated to Objective 1 (considerably less to Objective 2) regions for the construction of transport infrastructure (mainly highways). The rest of the regions received almost no funds for transport infrastructure investments from the Regional and Cohesion Funds. While we find a higher highway coefficient for the cities of Objective 1 regions, it is not statistically different from that of the cities of non-Objective 1 regions. However, for these latter cities, the railway effect seems to be as important as that of the highways for suburbanization.

Table B.2 in Appendix B.2 presents the heterogeneous estimates when we split our sample based on various stages of integration in the EU. The countries that on each occasion joined the EU were those who at least fulfilled the accession criteria. As such, this represents another way of clustering countries with similar institutional and economic environments. Table B.2 was not included in the main text because of the small number of cities involved and the weak first-stage estimates. Nonetheless, the highway results for the EU founders and for those becoming members between 2004 and 2013 are in line with the results for the Central-Northern European cities and the Eastern European cities, respectively. In addition, we find a considerably higher highway coefficient for those becoming new members in 1973 (namely, Denmark, Ireland and the UK).

4.5 *Natural geography shapes cities*

A further source of heterogeneity among European cities is their natural geography. The geographical features that we consider in the heterogeneous estimates reported in Table 11 are contiguity to the coast, the median of the Riley et al. (1999) ruggedness index for each LUZ, the median temperature of each LUZ and whether a city is intersected by a navigable river. While we find more marked highway effects for coastal cities, for cities with a rugged terrain, for warm cities and for cities without a navigable river, only the difference in the highway ray coefficient in cities with navigable rivers is statistically significant. In the case of railways, in warm and those with a rugged terrain, highways and railways appear to be jointly significant.

Although we find no statistically significant differences between coastal and inland cities, the fact that the highway coefficient is much higher for coastal cities seems to be in line with the empirical findings of Baum-Snow (2007a) and Garcia-López et al. (2015) and with the literature that suggests that many city-dwellers move to the coast to enjoy consumption amenities (Couch et al., 2008). This latter studies catalogues families and entrepreneurs that choose to divide their time between a job in the city and their leisure activities in the countryside; artists, intellectuals and others that seek alternative lifestyles; and, retirement migrants moving to the Mediterranean coast and islands. It might be thought that highways fostered the suburbanization of coastal cities since they increase the accessibility of these already attractive suburban locations.

Table 11: Suburbanization and transportation in Europe, 1961–2011: City geography

Dependent variable:	ln(Central city population)												
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Panel A: Coastal vs. Inland cities													
	175 Coastal LUZs					404 Inland LUZs							
Highway rays	-0.061^{a}		-0.029			-0.035^{a}		-0.040^{a}			-0.033^{a}		
	(0.016)		(0.034)			(0.007)		(0.014)			(0.008)		
ln(suburban ramps)		-0.092^{a}	-0.061				-0.030^{a}	0.009					
		(0.020)	(0.049)				(0.012)	(0.021)					
Railroad rays				-0.036					-0.040^{c}		-0.028		
				(0.028)					(0.021)		(0.020)		
ln(suburban stations)					-0.007					0.018			
					(0.017)					(0.014)			
First-Stage F-statistic	54.7	84.5	8.3	5.2	33.4	162	144.9	16.5	21.5	167.7	11.1		
Observations	1,050	1,050	1,050	1,050	1,050	2,424	2,424	2,424	2,424	2,424	2,424		
Panel B: Temperature													
	289 Warmer LUZs (temperature≥18°C)							290 Colder LUZs (temperature<18°C)					
Highway rays	-0.050^{a}		-0.010			-0.043^{a}		-0.037^{a}		-0.042^{a}			-0.037^{a}
	(0.014)		(0.035)			(0.013)		(0.009)		(0.016)			(0.009)
ln(suburban ramps)		-0.108^{a}	-0.095				-0.104^{a}		-0.027^{b}	0.008			
		(0.026)	(0.064)				(0.027)		(0.011)	(0.019)			
Railroad rays				-0.055^{c}		-0.044^{c}	-0.065^{b}				-0.023^{c}		-0.005
				(0.029)		(0.026)	(0.031)				(0.012)		(0.010)
ln(suburban stations)					-0.015							0.015	
					(0.025)							(0.010)	
First-Stage F-statistic	147.1	101.4	6.7	17.1	60.5	8.5	9.1	109.1	156.1	15.9	15.4	119.1	7.7
Observations	1,734	1,734	1,734	1,734	1,734	1,734	1,734	1,740	1,740	1,740	1,740	1,740	1,740
Panel C: Navigable rivers													
	260 Cities with navigable river						319 Other cities						
Highway rays	-0.035^{a}		-0.039^{b}			-0.031^{a}	-0.064^{a}		-0.062^{c}			-0.065^{a}	
	(0.008)		(0.017)			(0.010)	(0.014)		(0.036)			(0.014)	
ln(suburban ramps)		-0.031^{b}	0.008					-0.065^{a}	-0.003				
		(0.015)	(0.027)					(0.020)	(0.048)				
Railroad rays				-0.033^{c}		-0.022				-0.037^{b}		-0.021	
				(0.017)		(0.017)				(0.018)		(0.015)	
ln(suburban stations)					0.007						0.004		
					(0.016)						(0.015)		
First-Stage F-statistic	133.4	101.8	11.3	10.4	95.9	5.3	111.3	111.2	8.8	26.2	62.8	13.9	
Observations	1,560	1,560	1,560	1,560	1,560	1,560	1,914	1,914	1,914	1,914	1,914	1,914	
Panel D: Terrain ruggedness index (by Riley et al. (1999))													
	289 Rugged LUZs (TRI≥38m)							290 Non-rugged LUZs (TRI<38m)					
Highway rays	-0.057^{a}		-0.027			-0.049^{a}		-0.034^{a}				-0.034^{a}	
	(0.014)		(0.029)			(0.014)		(0.008)				(0.008)	
ln(suburban ramps)		-0.077^{a}	-0.051				-0.088^{a}		-0.021				
		(0.016)	(0.036)				(0.021)		(0.015)				
Railroad rays				-0.094^{b}		-0.062^{c}	-0.108^{b}			-0.011			
				(0.039)		(0.032)	(0.044)			(0.010)			
ln(suburban stations)					-0.010						0.022^{c}	0.019	
					(0.021)						(0.012)	(0.011)	
First-Stage F-statistic	111.9	123.5	10.3	11.8	50.8	5.5	5.5	130.6	117.6	20.73	106.1	64.6	
Observations	1,734	1,734	1,734	1,734	1,734	1,734	1,734	1,740	1,740	1,740	1,740	1,740	

Notes: The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

The results for warmer cities (Panel B of Table 11) are in line with the previous results and discussion and are further supported by a study conducted in US cities (Rappaport, 2007). While the difference between the highway coefficients of warmer and colder cities is small, the fact that in warm cities the railway ray coefficient is statistically significant and almost identical to that for highways stresses the importance of transportation infrastructure for suburbanization in these cities.

In Panel C of Table 11, we present the estimation output for cities crossed by a navigable river and the rest of the cities. Today in Europe, more than 37,000 kilometres of waterways link up hundreds of cities and regions (PINE, 2004). There is a statistically significant difference between the estimated highway ray coefficients in the two groups. Navigable rivers were very important during and after the Industrial Revolution, when many cities that enjoyed access to these rivers developed as transportation hubs or markets for interregional trade. As the volume of trade in these hubs increased, population agglomerated to meet labour demands for shipping and the handling of commodities (Konishi, 2000). This is supported by the fact that 38% of the cities with navigable rivers were already suburbanized in 1961[39]. This means that many of these cities had already extended towards the suburbs before the beginning of our study period, probably because both firms and households were seeking locations along the river. As might be expected, in an already suburbanized city, highways tend to displace less fewer people. In addition, around 60% of these cities were major Medieval and pre-Industrial Revolution cities. Thus, the role of historical amenities (see Section 4.3) and the potential[40] natural amenity of rivers could account for these results. Finally, the fragmentation of space caused by the presence of a river could also limit potential for suburbanization in these cities.

Panel D in Table 11 shows the results for rugged and non-rugged cities. It seems that the highway ray coefficient is higher for rugged cities and that railways also fostered significant suburbanization in these cities. Finally, while our average results show that only highway rays caused suburbanization, in the case of rugged cities, and for many other subsamples in Section 4, we are unable to disentangle whether the effect of highway rays and highway ramps on suburbanization.

5. Conclusions

During the second half of the 20th and the beginning of the 21st centuries, European national governments and the EU have allocated a vast amount of resources to highway construction. Although the density of the highway network across the continent has increased enormously in these years, it is the railway network that has served as Europe's backbone since the beginning of the 20th century. While many studies have been conducted at the regional level, none has sought to address the impact of transportation infrastructure on city structure for a broad sample of European cities over an extended period of time. In this paper, we have estimated the joint effect of highways and railways on the suburbanization 579 cities located in 29 countries for the period

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[39] Based on the grouping used in Section 4.2 and presented in Panel A of Table 8.

[40] A clean river is regarded as a positive amenity while a polluted river is regarded as a disamenity.

1961-2011. To the best of our knowledge, this is the first paper to estimates this effect for such a unique sample of cities and countries. In addition, this is one of very few studies to consider the whole of Europe and in so doing, it offers valuable insights into the urban processes operating in European and US cities.

Drawing on a unique population and transport infrastructure dataset, we have used panel data methods and instrumental variables to identify a causal relationship. The data and the methodology employed allow us to estimate jointly the effects of highway and railway infrastructure; however, interestingly we find no effect of railways on suburbanization when the two modes are considered together. A major advantage of using this particular research setting is that we are able to control for both city-specific characteristics and for regional time trends, which enhances the validity of our identification strategy. Our estimates suggest that an additional highway ray displaced, on average, approximately 4% of the central city population in European cities during the period 1961-2011.

We further exploit our rich dataset to validate our main findings and to obtain heterogeneous estimates. We find evidence that the effect of transport infrastructure on suburbanization was significantly weaker in the period 1991-2011 than it was earlier in the period 1961-1981. Additionally, we confirm that the average suburbanization effect is driven both by those cities that had highways since the early years in our sample and by cities that built highways at the end of the 20th century too. However, we find that the effect of highways on suburbanization has decayed over time in the case of European cities. This is an important and novel result, which in part defends EU highway funding in recent decades. This position is further supported by the small difference in the estimated effect of highways on the suburbanization of cities that received most of the EU Regional and Cohesion Funds, when compared with the rest of the cities.

In line with the different patterns of suburbanization detected across Europe, we estimated separate effects for big and small cities and for cities characterized by different urban forms. In the latter case, no significant differences were found in the estimated effects; however, for big cities, we found highways had a lower effect on suburbanization, equal in fact to the statistically significant effect of the railways. This finding seems to be most relevant for the big, dense cities while for the small, 'sparsely' populated cities, transport-related suburbanization can be solely attributed to highways. One potential explanation for this result could be traffic congestion, which is more severe in Europe's bigger and denser cities.

In a study of other city characteristics, we tested whether the effect of transportation infrastructure on suburbanization varies when cities with different histories are considered. Our findings suggest that the effect of highways on suburbanization varies considerably in line with certain characteristics of historical cities. Specifically, we find significant variation in the estimated effect for highways in cities that were major centres during the Roman era. Moreover, we find that these differences are not so notable for cities with "less history". These results appear to be related to the historical urban amenities embedded in the city centres of many historical European cities. This finding points to marked differences between European and US cities.

We also find differences between cities located in different geographical regions of Europe. Specifically, cities in the Mediterranean and the Eastern European regions were more markedly affected by highways than were those in Central-Northern Europe. Additionally, in the cities of Eastern and Central-Northern Europe, railways were also important drivers of suburbanization. Finally, when grouping cities according to their natural geography, we obtain higher estimates of the effect of highways on suburbanization for coastal and those with a warmer climate. Similar coefficients have been reported in the literature for the US and Spain and they reflect the consumption amenities that coastal and warmer locations have to offer. Finally, we find that highways caused significantly less suburbanization in the cities with navigable rivers. This result seems to provide further support for the importance of amenities – not only historical, but natural – in central cities. All these findings are especially relevant and shed further light on results published in the related literature and provide valuable insights for the European regional and transport policies.

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Appendix A. Maps

Figure A.1: Average relative (sub)urbanization in European cities (1961-2011).

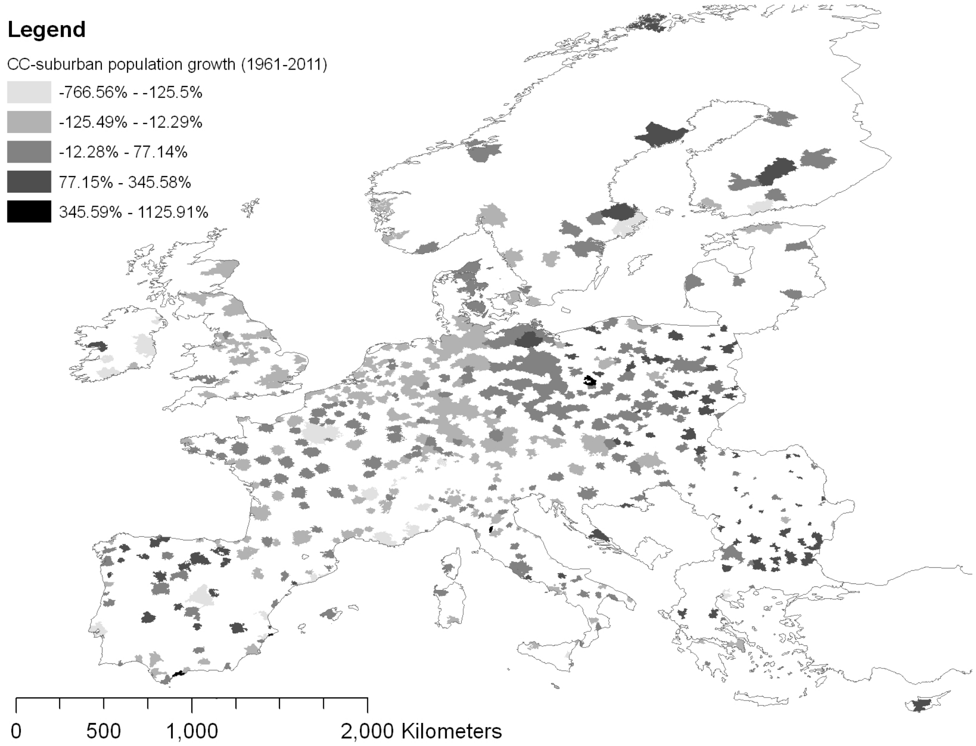

Figure A.2: Evolution of highways (1961-2011)

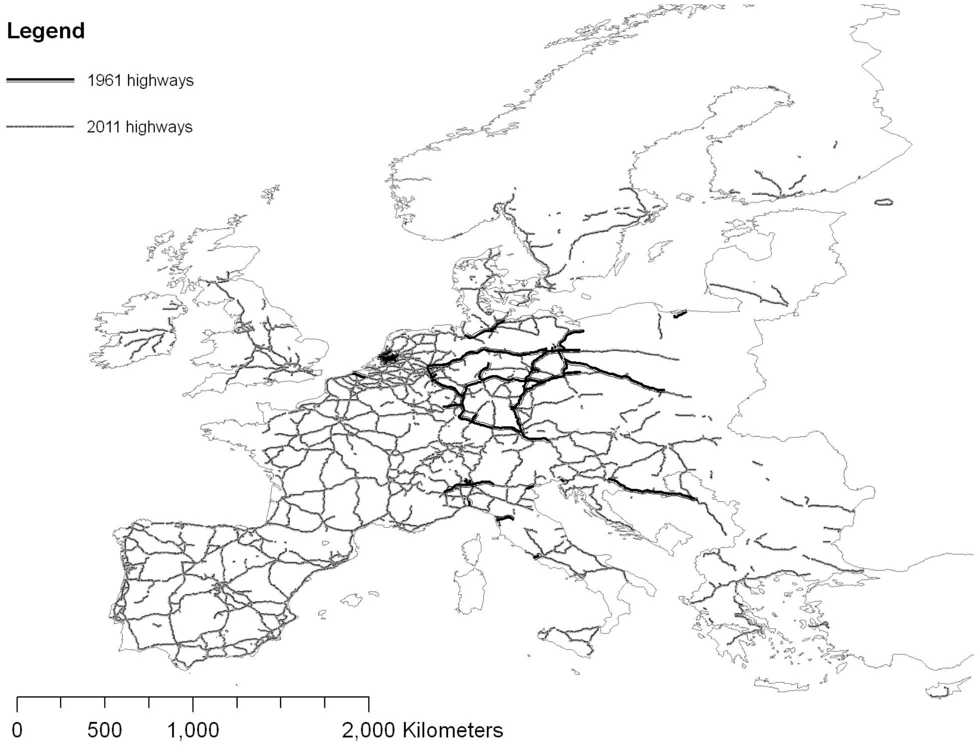

Figure A.3: The railway network in 1870.

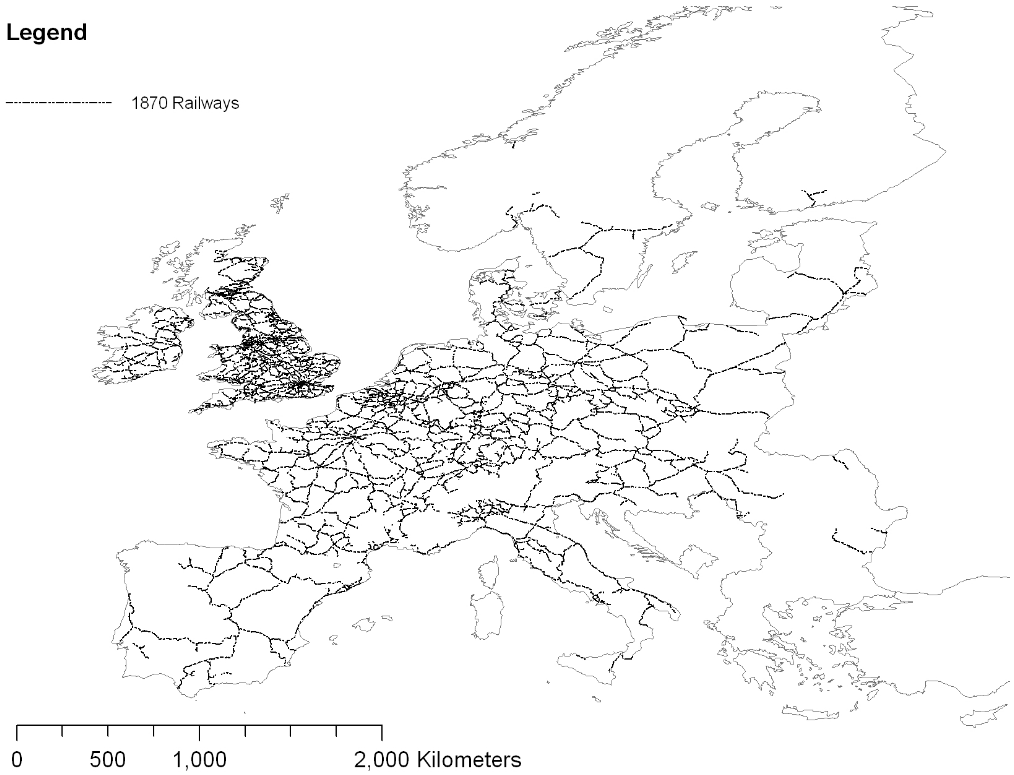

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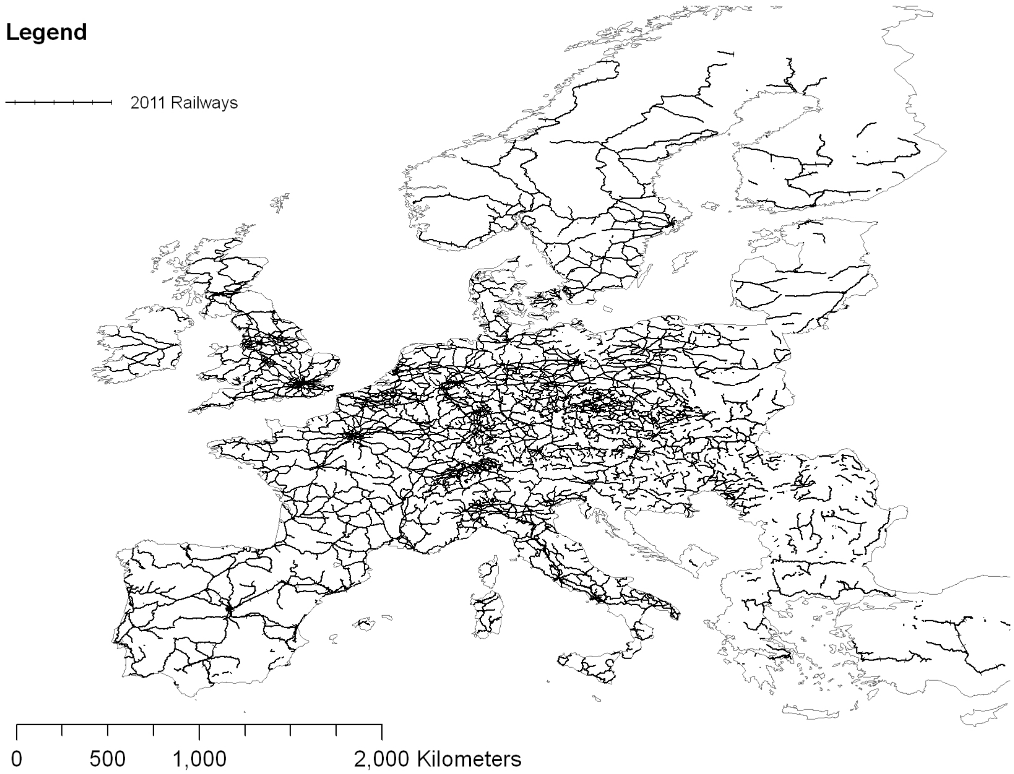
Figure A.4: The railway network in 2011.



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Appendix B. Additional heterogeneous results

B.1 UNESCO cities

For the UNESCO cities, the estimated coefficient for highways is not statistically significant, while, owing to the strength of the instrument, we are unable to plausibly estimate the effect of railway rays. However, railway stations, with a high first-stage F-statistic, are not statistically significant. In contrast, the results for the cities without any landmark recognized by UNESCO are very similar to our average results, where the highway ray coefficient is approximately -0.04 and the railways are not statistically significant in a joint highway-railway specification. These results support our intuition that highways caused less (in this case no) suburbanization in cities with historical amenity endowments.

Table B.1: Suburbanization and transportation in Europe, 1961–2011: UNESCO cities.

Dependent variable:	ln(Central city population)									
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]
	106 LUZs in UNESCO cities				473 LUZs in Non-UNESCO cities					
Highway rays	-0.021				-0.039^{a}		-0.034^{c}			-0.037^{a}
	-0.016				(0.009)		(0.019)			(0.009)
ln(suburban ramps)		-0.125^{a}				-0.038^{a}	-0.008			
		-0.04				(0.011)	(0.024)			
Railroad rays			1.007					-0.027^{b}		-0.015
			-6.979					(0.012)		(0.011)
ln(suburban stations)				0.015					0.008	
				-0.032					(0.010)	
First-Stage F-statistic	82.3	46.4	0.0	193.1	150.5	191	17.27	33.80	128.2	16.83
Observations	636	636	636	636	2,838	2,838	2,838	2,838	2,838	2,838

Notes: UNESCO cities are denominated to the cities with an historical city centre or another landmark denominated by UNESCO (most of these landmarks are located in the central cities.). The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.

B.2 *EU integration stages*

For the EU integration stages, we find much higher highway rays coefficients for Denmark, Ireland and the UK (1973 EU integration), for Austria, Finland and Sweden (1995 EU integration) and a relatively higher coefficient for the 2004-2007 entrants new members. However, the paucity of observations for the 1973 group of states and the low first-stage F-statistic for the 1995 group do not allow us to interpret these results. The states joining between 2004 and 2007 and the EU founders correlate highly with the Eastern European and the Central-Northern European regional groups in Section 4.4, respectively. The results confirm previous results in Table 10.

Table B.2: Suburbanization and transportation in Europe, 1961–2011: EU integration and policy

Dependent variable:	ln(Central city population)												
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Panel A: EU founders, and 1973 EU enlargement new members													
	272 LUZs in 1952 EU founders						48 LUZs in 1973 new EU members						
Highway rays	-0.035^a		-0.040^b			-0.029^a	-0.073^b						
	(0.011)		(0.017)			(0.010)	(0.031)						
ln(suburban ramps)		-0.030^b	0.011					-0.028					
		(0.015)	(0.024)					(0.021)					
Railroad rays				-0.055^b		-0.045^c			-0.007				
				(0.026)		(0.023)			(0.007)				
ln(suburban stations)					0.004					0.010			
					(0.016)					(0.012)			
First-Stage F-statistic	186	143.1	16.9	15.0	98.2	7.4	22.2	45.5	20.3	35.8			
Observations	1,632	1,632	1,632	1,632	1,632	1,632	288	288	288	288			
Panel B: 1981–1986, 1995 and 2004–2013 EU enlargement new members													
	72 LUZs in 1981-86 new EU members				24 LUZs in 1995 new EU members					146 LUZs in 2004–2013 new EU members			
Highway rays	-0.020				-0.078^a				-0.089^a	-0.056^a			
	(0.023)				(0.018)				(0.021)	(0.017)			
ln(suburban ramps)		-0.157^a				-0.037					-0.039		
		(0.055)				(0.037)					(0.029)		
Railroad rays			-0.186				0.201					-0.031	
			(0.653)				(0.188)					(0.044)	
ln(suburban stations)				0.021				-0.304^b	-0.136				0.003
				(0.072)				(0.128)	(0.087)				(0.022)
First-Stage F-statistic	25.4	41	0.1	3.2	6.1	11.5	1.4	4.9	2.7	27.	34.1	5.5	41.6
Observations	876	876	876	876	432	432	432	432	144	144	144	144	144

Notes: EU founders (1952) are Belgium, France, Germany, Italy, Luxembourg, The Netherlands. The 1973 new members are Denmark, Ireland, UK. The 1981–1986 new members are (1981): Greece; (1986): Spain, Portugal. The 1995 new members are Austria, Finland, Sweden. The 2004–2013 new members are (2004): Czech Republic, Cyprus, Estonia, Latvia, Lithuania, Hungary, Malta, Poland, Slovenia, Slovakia; (2007): Bulgaria, Romania; 2013: Croatia. The selection of the specifications included is explained in Section 3.3. All regressions include the log of LUZ population, LUZ fixed effects, decade fixed effects and NUTS1 decade trends. Our historical instruments are smoothed; i.e. they are time varying and they are computed by multiplying the number of historical rays/length by the fraction of the highway/railway mileage in each LUZ completed at each decade. The smoothed 1810 post road rays and the smoothed 1870 railroad rays instrument for highway and railroad rays, respectively. The log of smoothed 1810 post road km and the log of smoothed 1870 railroad km instrument for the log of ramps and the log of stations, respectively. The Stock & Yogo (2004) 10% critical values are 16.4 and 7 for one and two instrumented variables, respectively. Robust standard errors are clustered by LUZ and are in parenthesis. ^{a}, ^{b} and ^{c} indicates significant at 1, 5, and 10 percent level, respectively.