High-Speed Rail Accessibility: What Can California Learn from Spain?

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Abstract

Discussion on High Speed Rail (HSR) station accessibility is attracting increasing attention in the literature. We compare the proposed Los Angeles – San Francisco HSR corridor to the functioning HSR line between Madrid and Barcelona to assess relative accessibility based on urban structure. Our methodology assesses socioeconomic and spatial characteristics of mono-centric versus polycentric cities that may affect HSR accessibility. By addressing challenges of unit (urban geography), data series (normalization) and identifying four key components of HSR attractiveness (population, population density, income and employment) we have created a straightforward methodology that could be used to compare HSR corridors around the world. We find urban structure limits the potential accessibility of HSR in the California context and warn HSR planners they should proceed with caution.

Key words: High-speed rail; station accessibility; mono-centric vs polycentric cities; urban structure.

1. Introduction

After almost five decades of international experience with High-Speed Rail (HSR), several lessons have been learned. Although HSR is a very convenient transportation technology, implementation incurs huge investment costs, which make demand density crucial for HSR to provide benefits that compensate these huge costs (De Rush and Nash, 2007). Very high levels of demand and high HSR replacement of air transit are needed to obtain a positive environmental balance, because emissions of pollutants when the HSR line is constructed are huge (Chester & Horvath, 2010; Westin & Kageson, 2012).

Although demand is crucial for HSR to deliver financial and socio-economic benefits, ridership projections have been overly optimistic in most countries with operating HSR, particularly in China, Spain (Albalate and Bel, 2011), Italy (Beria and Grimaldi, 2011), Taiwan (Johannesson and Kien-Hong, 2010), and Korea (Suh et al, 2005). This is a very well known bias affecting all type of investment projects, (Flyvbjerg, Holm, & Buhl, 2005), but its consequences may be critical in HSR, because of the importance of high demand density and of high air transport replacement.

Several factors are critical for HSR demand density and intermodal competition, and in this paper we develop and illustrate a methodology for assessing HSR accessibility, which we apply to the proposed Los Angeles and San Francisco line in California compared to the actual Madrid and Barcelona line in Spain. Discussion of high-speed rail in the US has been ongoing for more than two decades, as shown by Schwieterman and Scheidt (2007), and the public and scholarly debate has progressively become more intense, with visions favoring HSR building (i.e. Johnston, 2012; Lane, 2102) and other expressing negative views (i.e. Button, 2012; Levinson, 2012). The most important institutional step toward HSR was made with the American Recovery and Reinvestment Act (17 February 2009), which provided funds for the Federal Railroad Administration to assign to intercity and high-speed rail projects. On 16 April 2009, President Obama made public his blueprint for a national network of high-speed passenger rail lines, including several corridors in the East Coast, the Midwest, the South and the Pacific Coast (FRA 2009). The purpose of this plan is to reduce traffic congestion, cut dependence on foreign oil, and foster livable urban and rural communities. Among all the considered corridors, the most intense analysis of costs and benefits of building a HSR system has been devoted to the California High Speed Rail (CHSRA 2009, 2011, 2012). This is the most important HSR project currently under consideration in the US.

Cost estimates for the California line have grown from $35.7 billion (2009 dollars) (CHSRA, 2009) to between $65.4 and $74.5 billion in the 2012 Phase 1 Business Plan (CHRSA, 2011). This sharp increase in costs led CHRSA to change its strategy for HSR implementation, resulting in a less ambitious project ('blended' strategy) and obtaining projected costs of between $53.4 and $62.3 billion (2011 dollars) (CHSRA, 2012). In contrast, ridership forecasts have been reduced. The 2009 Business Plan forecasted 41 million riders per year in 2035, but the 2012 Business Plan (CHSRA, 2011) projected between 23 million to 34 million by 2035 and the revised version 2012 Business Plan (CHSRA, 2012) has further reduced ridership projections for 2035 to between 20 to 32 million. California voters approved the HSR with the expectations of much lower costs (Proposition 1A 2008) and a 2012 poll shows the majority of voters now oppose the plan (Orski, 2012). However, in most systems around the world costs have exceeded expectations and ridership has fallen below expectations (Albalate and Bel, 2012; Campos & de Rus, 2009). Almost all corridors in the world have required important subsidies, and the amount of subsidies offered by the US government places strong financial requirements on US states. This has led the States of Wisconsin and Ohio to reject federal subsidies for HSR in 2010, and Florida to do the same in 2011.

Demand forecasts accepted by CHSRA have been subject to criticism (i.e. Brownstone, Hansen and Madanat, 2010). Among the aspects not correctly dealt with in demand forecasts is the absence of an airport/station choice model, as the competitive advantage of HSR stations with respect to airports is a key issue regarding potential ridership.

In this paper we draw on international experience to compare a functioning HSR corridor (Madrid-Barcelona) with the California proposed corridor, and we develop and illustrate a methodology for assessing HSR accessibility which can be used for future international comparative urban research. Our methodology looks at socioeconomic and spatial characteristics – mono-centric versus polycentric cities and the factors affecting HST accessibility (attractiveness). By addressing challenges of unit (urban geography), data series (normalization) and identifying four key components of HST attractiveness (population, population density, income and employment) we contribute to the literature by creating a methodology that could be used to compare HSR corridors around the world.

2. Review of the Literature

2.1 International Comparison – Why Compare California to Spain?

Almost half a century has passed since the first HSR line went into service between Tokyo and Osaka in Japan in 1964. The great success of this line of the *Shinkansen* was followed by successive expansions of new lines in Japan. In 1981 HSR arrived in Europe with the opening of the *Train à Grande Vitesse* line between Paris and Lyon, in France. The extension of HSR in Europe accelerated since the late 1980s with lines opening in Germany and Spain, while the network in France continued to expand. In the last decade a more accelerated expansion of high-speed rail networks occurred in Spain, China and Italy. Lines on the principal routes in Korea and Taiwan also entered into service.

In the case of California's HSR, a comparison with the Spanish case can offer something to the debate, as emphasized in CHSRA business plans (2009, 2011, 2012), as well as in the public debate (see, for instance, *The Sacramento Bee*, January 15, 2012 http://www.sacbee.com/2012/01/15/4188592/spains-high-speed-rail-syste-offers.html). Other comparisons seem to be less appropriate. The only two profitable lines in the world are Tokyo-Osaka and Paris-Lyon. But Japan has greater urban density than California, and Paris-Lyon is an unbalanced network (large city, small city) with very limited air service for a trip of little more than 250 miles. On the other hand, Germany and Italy represent more balanced networks but they connect medium sized cities where the distances are much shorter than in the California case, and they do not usually use dedicated HSR rail lines.

Spain provides the most relevant comparison to the California case because Madrid and Barcelona are similar sized cities, the HST rail is dedicated to passenger only (no freight) and the air service is excellent (it was the densest air shuttle service worldwide until 2009). California and Spain have similar surface areas (423,970 and 505,645 Square Km), relatively similar population (38 and 47 million), and population densities (92 and 93 inhabitants per Square km), and the same distance (430 miles) between their main metropolitan areas: Los Angeles and San Francisco in California, and Barcelona and Madrid in Spain. Projected travel times in the two HSR corridors are also similar: 150 minutes for Barcelona-Madrid and 166 minutes for LA-San Francisco.

Another similarity between the US and Spain is the importance of political drivers in the decision to invest in HSR (Bel, 2012; Button, 2012). Political considerations may influence the structure of the network, the number and location of stations, and the extension of the networks to less populated rural zones. In Spain, for example, 'HSR political supply' from the national government has been fostered by huge foreign subsidies for construction from the European Union, which have accounted for between 20% and 25% of total investment costs until 2010 (Albalate and Bel, 2011, p. 184). In addition to this, 'HSR political demand' from regional and local governments has been encouraged by the fact that the full costs of construction have been borne by the central government budget (with the help of those foreign subsidies). Spanish HSR does not recover even operating costs when all relevant factors are properly taken into account (Albalate & Bel, 2011).

In the US the case for HSR has been strongly pushed forward by President Obama (Perl, 2012) by offering important federal subsidies to the states to build HSR lines. Concern over the need for huge subsidies from State budgets has been a crucial factor in the decision by the states of Wisconsin, Ohio and Florida to renounce federal subsidies to build HSR. Obama's has responded to these setbacks by strengthening his commitment to HSR development, proclaiming the goal of giving 80 percent of Americans access to high-speed rail within 25 years (Obama, 2011).

This is why we believe a comparison of California and Spain is appropriate for our analysis. The Madrid-Barcelona corridor is the most heavily travelled corridor in Spain, and thus provides actual data on costs and ridership, which we can compare with proposals for the San Francisco - Los Angeles line. The expected construction costs for Madrid-Barcelona corridor is $12.3 billion in 2010 US dollars, while the actual costs amounted to $16.3 billion. California high-speed rail has a projected cost of $53.4 -

$62.3 billion in 2011 US dollars (CHSRA, 2012), much higher than its Spanish counterpart. In terms of ridership, the estimated ridership for Madrid-Barcelona corridor is 6.9 million in 2010, but the actual ridership in 2010 was only 5.8 million. The estimate for California HSR in 2035 is between 20 and 32 million (CHSRA, 2012). The number of HSR passengers in the Madrid-Barcelona corridor in 2011 (the fourth year in which the service was operating), has still only reached 70 - 75% of demand forecasts. Shifts in modal share from air travel to HSR in the Madrid-Barcelona corridor were 48% by 2010, and are around 50% in 2012. The average HSR ticket price in the Madrid-Barcelona corridor ranges from $186-$244 (2012 prices), more than competing low cost airfare ($88 - $220).[1] CHRSA (2012) predicts an average price of $166 (2011 dollars) in its plan, but many low cost airlines also serve the LA – San Francisco corridor making substitution between air travel and HSR uncertain.

While the analysis suggests costs are underestimated and ridership over estimated in both contexts, our analysis will explore the unique impacts of urban structure on the accessibility of HSR that may create even more challenges for polycentric cities in California.

2.2 Urban Geography

While other studies look at HSR with transportation demand models (Brand, et al., 1992; Wardman, 1997; Yao and Morikawa, 2005; Brownstone, Hansen and Madanat, 2010), our focus is on factors of special concern to urban transportation scholars - how does HSR relate to urban structure and settlement patterns?

[1] Costs and demand for Madrid-Barcelona corridor were obtained by the Spanish Infrastructure Operator ADIF and the Spanish Rail services operator RENFE. Actual price and travel time for Madrid-Barcelona have been obtained from RENFE and Iberia –main airline in the corridor- web pages in June 2012.

HSR changes the relative accessibility of places, and enlarges economic and social disparity spatially (Givoni, 2006; Van den Berg and Pol, 1998; Haynes, 1997). HSR improves connectivity of the largest cities it serves, but having a HSR station does not guarantee more economic growth. Research has shown the largest nodes benefit more from HSR services, while the smaller nodes benefit less or even suffer. For cities with unfavorable economic conditions compared to other cities in the HSR network, connection to the network may even drain away economic activities and result in an overall negative impact (Givoni, 2006; Van den Berg and Pol 1998). In Japan, Tokyo and Osaka are the winners, Nagoya lost jobs (Plaud, 1977). In France, trips to Paris increased much faster than trips originating from Paris to other cities (Bonnafous, 1987; Arduin, 1991). For the cities by-passed by HSR, they suffered worsened accessibility and economic prospects (Vickerman, 1997), a phenonmenon referred to as the tunnel effect (Gutierrez Puebla, 2005). HSR does not seem to improve regional inequality, but rather polarizes the regional economy.

HSR shifts investment attention toward passengers and the role of their mobility on the metropolitan region. To the extent that HSR connects downtowns and central business districts directly, it may counteract the centrifugal effects airports and automobiles have on urban growth. Urban structure has important implications for HSR competitiveness. HSR has proved to work best in populous, dense, and mono-centric urban centers, such as Paris and Tokyo (Albalate and Bel, 2012a). HSR requires new infrastructure requirements in cities for parking at terminals and improvements in intermodal connectivity (Marti Hennenberg 2000; Cheng, 2010). Polycentric cities with low population density will not reap the benefits of city center connection that HSR offers (Albalate and Bel, 2012b). For polycentric cities, HSR presents a difficult tradeoff. Build several stations to attract suburban riders or limit stations to maintain the high speed advantage. German cities generally lack a mono-centric configuration and are low in density. Low population densities require high regional transportation costs and shorter distances between stations, which result in lower speed (Vickerman, 1997). This is a major challenge facing HSR development in the US, as most American cities have a highly dispersed urban spatial structure.

Los Angeles is the prime example of a polycentric city (Bertaud & Malpezzi, 2003; Anas, Arnott, & Small, 1998; Small & Song, 1994). Giuliano and Small (1991) identified 7 employment centers in Los Angeles Metro area in 1970 and later with a modified methodology, Giuliano et al. (2007) identified 36 employment center in 1990 and 48 in 2000. The Los Angeles metro area is arguably more of an unorganized urban sprawl rather than an organized system of sub-centers (Davoudi, 2003). The Bay Area is only slightly less polycentric; Cervero and Wu (1997) found 22 employment centers in the San Francisco Bay Area in 1990.

Looking forward however, there are several drivers that could make HSR an attractive transportation alternative in sprawling metropolitan corridors. In the US the challenges with regard to congestion, air quality, interstate highway expansion and finance, etc. raise the possibility of the emergence of an alternative urban structure in the future that could be more dense and focused around transit oriented development at nodal centers (Dittmar, Belzer, & Autler, 2004). If such a development pattern were to occur, HSR stations could be a logical nexus for such transit oriented development, and indeed this is part of the California proposal (CHSRA, 2012).

History had shown us that urban structure is responsive to changes in technology. Witness the unique spatial development patterns of LA – the first major post car city rose in the early 20th century as the automobile became prevalent (Hall, 2009), as compared to San Francisco, which grew in the late 19th century with significant influences from the street car (Jackson, 1985; Warner, 1978). Whereas transportation has accommodated itself to the historical built environment of the city in old European capitals (Vance, 1990), transportation also has the ability to transform urban space over time (Hanson, 2004). It is this dynamic of transportation being retrofitted into a city form and simultaneously changing that form that makes ridership hard to predict.

However, changes in travel behavior do not occur quickly as has been shown in the overly optimistic ridership projections in most HSR corridors around the world (Flyvbjerg, Holm, & Buhl, 2005). One of the problems with HSR is that it reduces the metro region's flexibility (via multi-modal systems such as bus, air, conventional rail, truck and auto) to respond to shifting locational demand. HSR is costly, fixed in space and offers limited nodes for regional economic connectivity (Albalate and Bel, 2012a). These features limit its appeal even in a carbon sensitive, highly interconnected and dynamic urban economic system.

2.3 Transportation Geography – Determining Accessibility

Urban structure and transportation technology come together in assessments of accessibility. In transportation studies, travel time is usually broken down into several components: (1) Access - time a traveler needs to get to a terminal from her departing point. (2) Egress - time a traveler needs to get to her destination from a terminal. (3) Wait - time a traveler spends waiting in a terminal. (4) In-vehicle - time a traveler spends in a traveling vehicle (Hanson, 2004). HSR has advantages of shorter access, egress and wait time over air travel, while air travel usually has shorter in-vehicle time (Clever and Hansen, 2008). Therefore in order to make HSR competitive, its advantages on access, egress and wait time must be large enough to offset its disadvantage of longer in-vehicle time. We are concerned with the access and egress time of a trip, as these two components of travel time are where urban structure comes into play.

Few recent studies of intercity travel mode choice have focused exclusively on access or egress issues (i.e. Tapiador, Burckhart and Martí-Henneberg (2009); Martín, Román, García-Palomares and Gutiérrez, 2012), and these have focused on intermodal connections, although the last study also considers socioeconomic factors. There is very little research done on how HSR station locations affect ridership and market share (Clever & Hansen, 2008). In the limited literature that deals with these issues, most authors agree that access and egress time are more onerous than in-vehicle time (Forinash and Koppelman, 1993; Wen and Koppelman, 2001; Vrtic and Axhausen, 2003). Capital investments to improve in-vehicle time are unlikely to significantly increase ridership. Access to terminal, including time and ease, was found to be a much greater determinant of mode choice.

There are established methods to measure urban structure and transportation accessibility. Clark's population density gradient is commonly used to measure the degree of concentration and mono-centrism of a city (Clark, 1951).

$$\boldsymbol{D(u) = D_0 e^{-\gamma u \varepsilon}}$$

where D is population density at distance u from the center of a city; D_0 is the density at the center; e is the base of natural logarithm; $\gamma = {[\ln D_0 - \ln D_u]}/{u}$, is the gradient, or the rate at which density falls from the center. The final error term, ε, is included when the formulation is stochastic.

Studies on transportation accessibility use different modifications of the following equation (Sanchez, 1999; Baradaran & Ramjerdi, 2001; Chang & Lee, 2008):

$$A_i = \sum_{j=0}^{J} O_j f(d_{ij})$$

where O_j is the locational attractiveness of zone j, which is generally represented with zonal population, employment and gross domestic product (GDP); d_{ij} is the transport impedance, which can be measured by distance, travel time or generalized cost of travel; f is a function of d. Commonly used functional forms for $f(d_{ij})$ include inverse function and exponential function (Chang and Lee 2008). This measure of accessibility suits our study of HSR.

Catchment area is another concept used by researchers to study transportation accessibility. A catchment area is the area within a reasonably accessible distance from a transit station. The existing literature on transit stations catchment areas is mainly focused on urban transit for commuters. The distance in the catchment areas determined by studies on urban transit is very small. For instance, Alshalafah and Shalaby (2007) found access distance, i.e. the radius of a catchment area of transit stations, to be less than 400 meters. However, these distances are too small for intercity travel terminals. Catz and Christian argued (2010) that the catchment areas of HSR stations should be much larger than those of transit stations. With the assumption that HSR will mainly service inter-urban trips, they suggested a catchment area of 1.5 – 5 kilometers, depending on the feeder system of the HSR station. Murakami and Cervero (2010) also used a 5-km catchment area in their study of California and Japanese HSR. Yet another study (Leinbach, 2004) suggests the service coverage areas of Amtrak to be 25 miles, about 40 kilometers, radiance from a railroad station. Since our study focuses on intercity travel, we consider a reasonable HSR catchment area will fall in the radius range of 5 – 40 kilometers, depending on the feeder system. We explore a new methodology to measure the accessibility by combining the traditional measure of accessibility and the concept of catchment area.

3. Methodology: Case Comparisons

We compare the proposed San Francisco - Los Angeles HSR corridor with the Madrid – Barcelona HSR corridor to assess relative accessibility of potential demand as determined by urban structural factors. We give special attention to the demographic and spatial structure of population, density, employment and income across these four metro regions because prior research on HSR has shown these to be important factors. The polycentric nature of the California cities (especially Los Angeles) creates a strong contrast with the Spanish cities. We first map these demographic features using Arc-GIS and then conduct density gradient and accessibility analyses using an aggregate score of these four factors (population, density, employment and income). We show the sensitivity of the accessibility analysis to different distance impedance levels and catchment area calculations.

International comparison is especially important in HSR because the research shows important differences across countries due to topography, demographics, nature of transit demand and government investment schemes (Albalate and Bel, 2012a, 2012b; Campos and de Rus, 2009). The Los Angeles - San Francisco corridor in California is considered the most viable of the US HSR routes, and we find that of the candidates for international comparison, it is most comparable to the Barcelona – Madrid route in terms of distance, competing air and highway alternatives and population size relative to their regions.

International research is complicated by differences in data systems that make direct comparisons difficult. We present a methodology that addresses these differences. Decisions regarding data choices within each study area are described below.

We define the study areas of the four metro areas by the largest metropolitan planning regions that are relevant to intercity travel. For the Spanish cities, we take the Provinces of Barcelona and the Community/Province of Madrid as our areas of study. For the California cities, we modify the boundary of Metropolitan Statistical Areas (MSA) and Consolidated Statistical Areas (CSA) to make the areas more relevant to the study of HSR intercity travel and more comparable to the Spanish counterparts. San Francisco-Oakland-Fremont MSA and San Jose-Sunnyvale-Santa Clara MSA are combined as the study area for the Bay Area, with San Francisco and San Jose as the two core cities with non-stop HSR service to Los Angeles. For Los Angeles, we take the Los Angeles-Long Beach-Riverside CSA, but leave out the vast and sparsely populated inland area east of San Bernardino Mountain, because residents from this area would be less likely to come all the way into the city to use HSR. The larger study areas for the US cities reveal the sprawling nature of the California cities. Table 3 summarizes some basic features of the four study areas.

Table 1. Definition of Study Areas

Name	Metro Area Definition	Area (km²)	Population (million)
Barcelona	Province of Barcelona	7,733	4.96
Madrid	Community of Madrid	8,030	6.45
San Francisco Bay Area	San Francisco-Oakland-Fremont MSA and San Jose-Sunnyvale-Santa Clara MSA	13,527	6.17
Los Angeles	Los Angeles-Long Beach-Riverside CSA (modified)	30,783	17.30

Source: United States Census Bureau, 2010; Spanish National Statistics Institute 2009; Catalanoia Statistics Institute, 2009.

The choice of the geographic unit of analysis within each metro area is based on comparable sizes and data availability. For the Spanish cities, the geographic unit for analysis is the municipality; for Californian cities, the unit for analysis is Zip Code Tabulated Areas. The Municipality of Madrid and the Municipality of Barcelona are further broken down to the district level, because they are much larger in size than other municipalities in the respective metropolitan regions and it is desirable to have smaller units for the municipality that encompasses the downtown area where the HSR stations are located. In total, there are 322 units in the Province of Barcelona; and there are 199 units in the Community of Madrid. In Greater Los Angeles, there are 529 units; in the Bay Area, there are 248 units. The sizes of municipalities and districts in Spain are mostly less than 50 square kilometers. The sizes of most Zip Codes in Los Angeles and the Bay Area also fall into that range.

Our analysis focuses on five HSR stations in the four study areas. The stations in Barcelona and Madrid are currently in operation, and they are the only station in either metropolitan area offering service to the Barcelona-Madrid corridor.[2] The three HSR stations in California, Los Angeles Union Station, San Francisco Transbay and San Jose are chosen from a number of planned stations because they will have frequent and non-stop service to the opposite end of the corridor. These non-stop services will likely become the true high-speed service between the two metropolitan areas, whereas the other planned stations (10 in the LA area and 3 in the San Francisco/San Jose area) will largely serve an urban or regional transportation purpose. We focus on the nonstop

[2] Besides the Atocha HSR station in Madrid (where trains to Barcelona leave from), another station in this metropolitan area (Chamartin) is the base point for services to Segovia and Valladolid (Madrid to North-West). These services have a marginal dimension within the HSR from Madrid, and currently Atocha and Chamartin stations are not connected for HSR services.

service of these three central stations because it is more comparable to that of the Barcelona and Madrid HSR corridor.

3.1 Measuring Urban Structure: Concentration of Potential HSR Riders

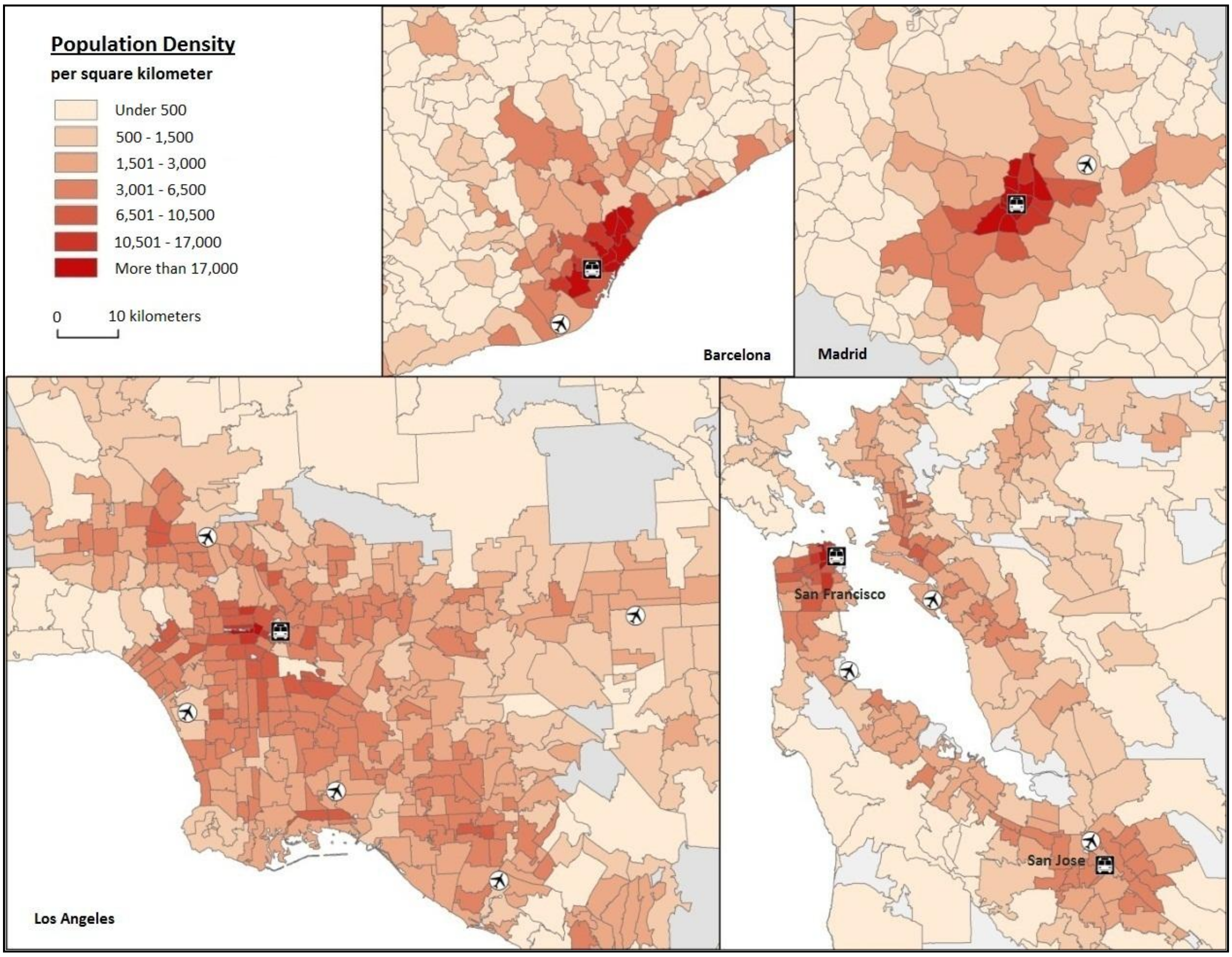
We assess accessibility using four measures defined as critical in the international HSR literature: population, population density, employment and income. We map these to visually demonstrate the different urban structures of our study cities in California and Spain. With ArcGIS, we use an identical scale to map the population density of each geographic unit of analysis for the four metropolitan areas. In order to show more important details around the HSR stations, the sparsely populated areas near the edge of the study areas in LA and San Francisco are not shown. Major airports are marked to show the relative locations of HSR stations to their airport competitors.

Population, income and employment data are drawn from the most recent available data (US Census 2010 for the California cities, and the Spanish National Statistics Institute - INE- and the Catalan Statistics Institute–IDESCAT- for Spain for 2009 – the first complete year of HSR operation between Madrid and Barcelona in Spain).[3] The population density maps in Figure 1 show that Barcelona and Madrid have a distinct urban core with population concentrated in the downtown area. There is a narrow ring of suburbs with moderate density surrounding the downtown, and beyond that, suburban areas with low density. In the San Francisco Bay Area and Los Angeles, the urban core is much less distinguishable. Not only are the dark areas (high density) in

[3] Sources for the shape files and data for all maps are: Geographic Research, Inc., 2011; United States Census Bureau, 2010; Museum of Vetebrate Zoology & International Rice Research Institute, University of California, Berkeley; Instituto de Estadistica de la Comunidad de Madrid (Madrid Statistics Institute); Department d'Estadística de l'Ajuntament de Barcelona (Barcelona Dep. of Statistics); Area de Estadística del Ayuntamiento de Madrid (Madrid dep. of Statistics).

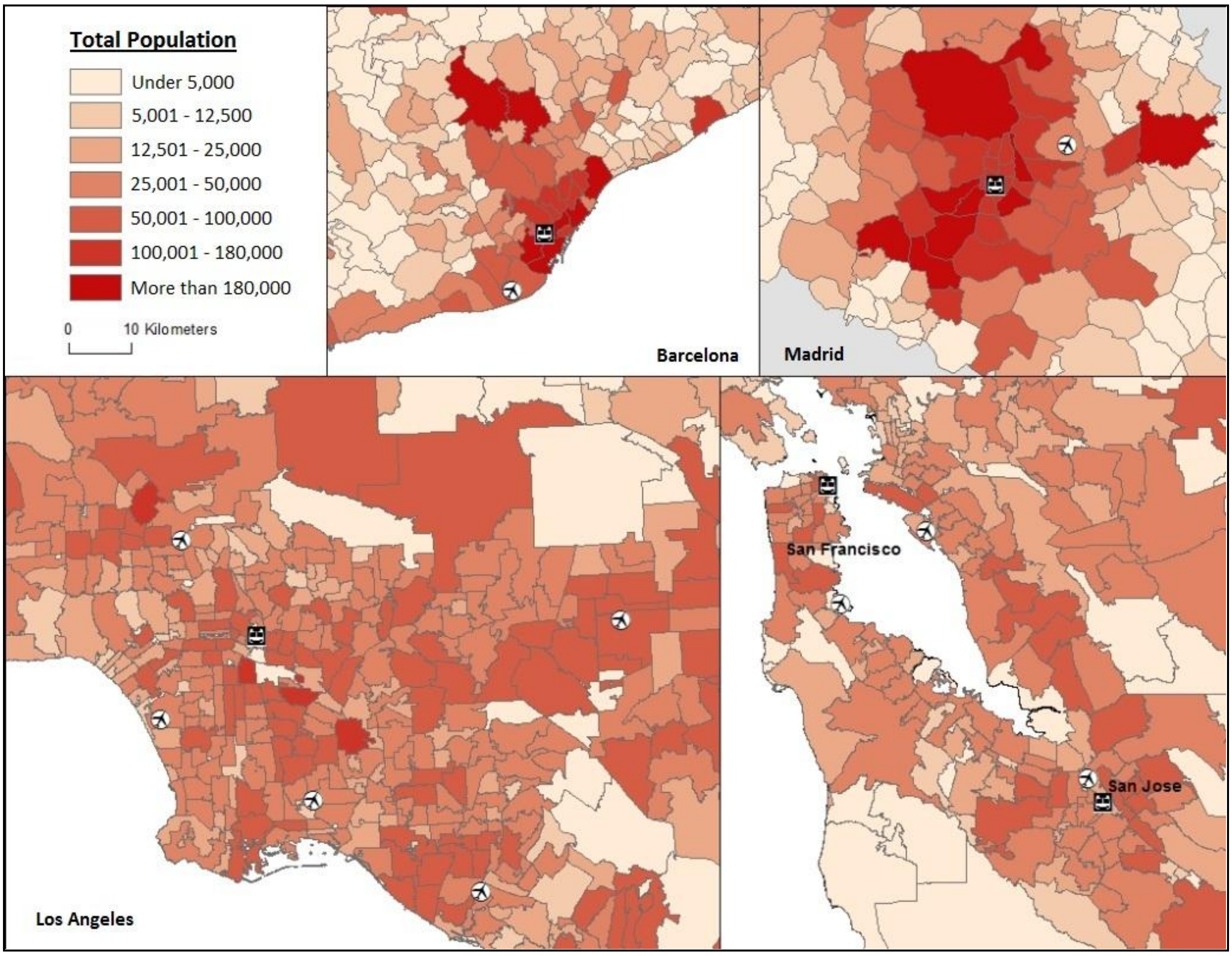
downtown Los Angeles and San Francisco much smaller than those in Barcelona and Madrid, the color also fades much more slowly from the center to the periphery. This shows population is much more spread out in the Californian cities. Suburbs with moderate density extend continuously for dozens of miles from the downtowns. Dense areas can be spotted outside the downtown area, for example, Oakland and Berkeley in the East Bay, and Long Beach and Anaheim to the south of downtown Los Angeles. This dispersed urban structure makes it very difficult to place a central HSR station that captures the majority of residents in Los Angeles and the San Francisco Bay Area.

Figure 1. Population Density Comparisons: Barcelona, Madrid, Los Angeles and San Francisco Bay Area



In addition to population density, we also take into account three other factors: total population, total employment and median household income of each geographic unit. Population density measures the concentration of potential riders. Total population is a measure of the total stock of potential riders. A large stock of potential riders is essential for HSR viability. Figure 2 shows that total population is more dispersed across the California cities.

Figure 2. Total Population Comparisons: Barcelona, Madrid, Los Angeles and San Francisco Bay Area



Business trips usually take up a significant proportion of HSR trips (Chang & Lee, 2008; Levinson, 2004). Many business trips originate or terminate at office district destinations where employment concentrates. Hence a major employment center is also a major area of potential HSR riders. Figure 3 maps employment comparisons across the four cities. In addition, because individuals with higher incomes tend to make more intercity trips (Mallet, 1999), an area with higher income is likely to generate more intercity travel trips. Unlike the other three variables, income is not comparable across different metropolitan areas, because of the differences in purchasing power and so on. Our interest is in the spatial pattern of relative income levels within a metropolitan area, so we normalize income to a scale of 0 – 100 *within* each metropolitan area as show in Figure 4.

Figure 3. Employment Comparisons: Barcelona, Madrid, Los Angeles and San Francisco Bay Area

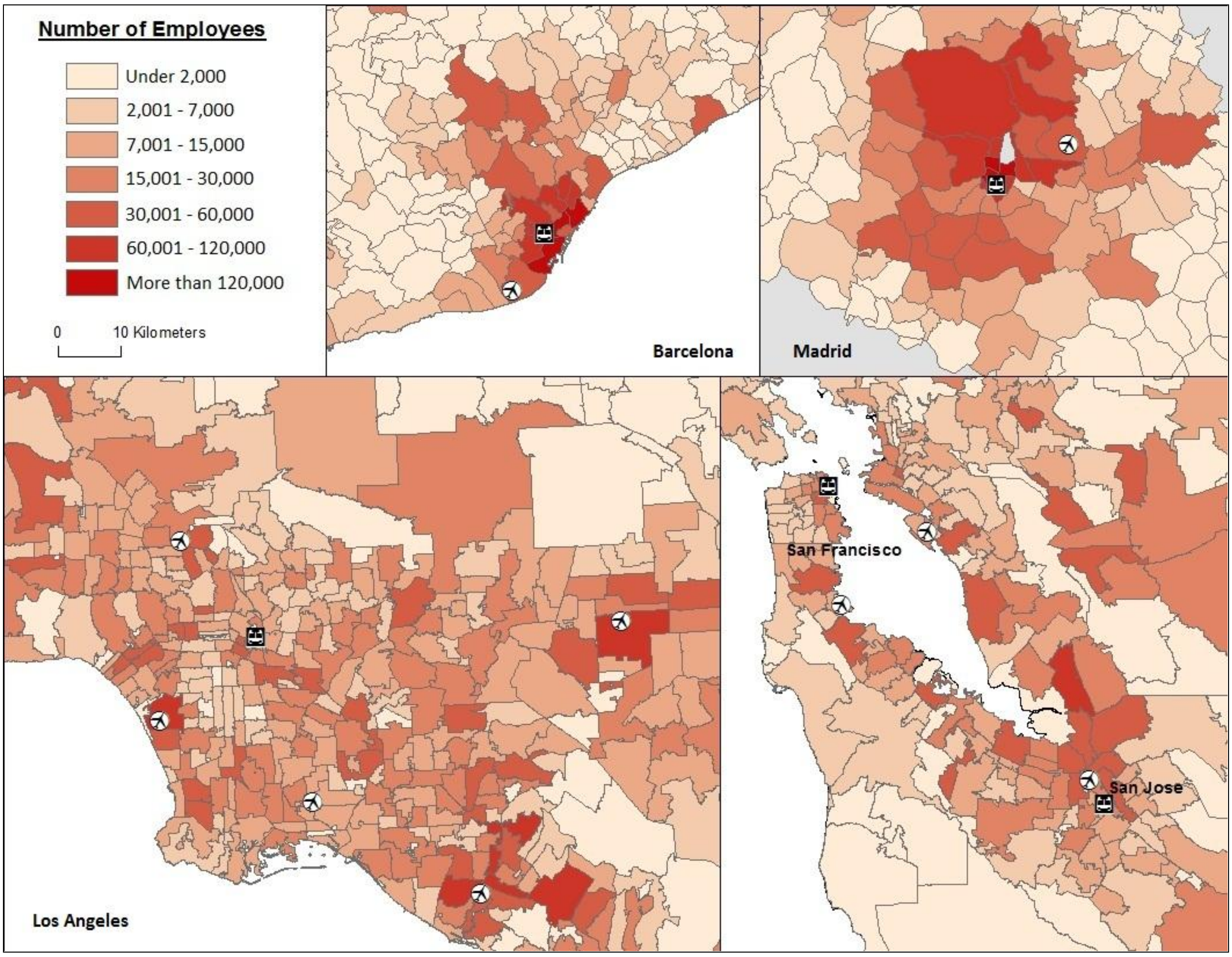
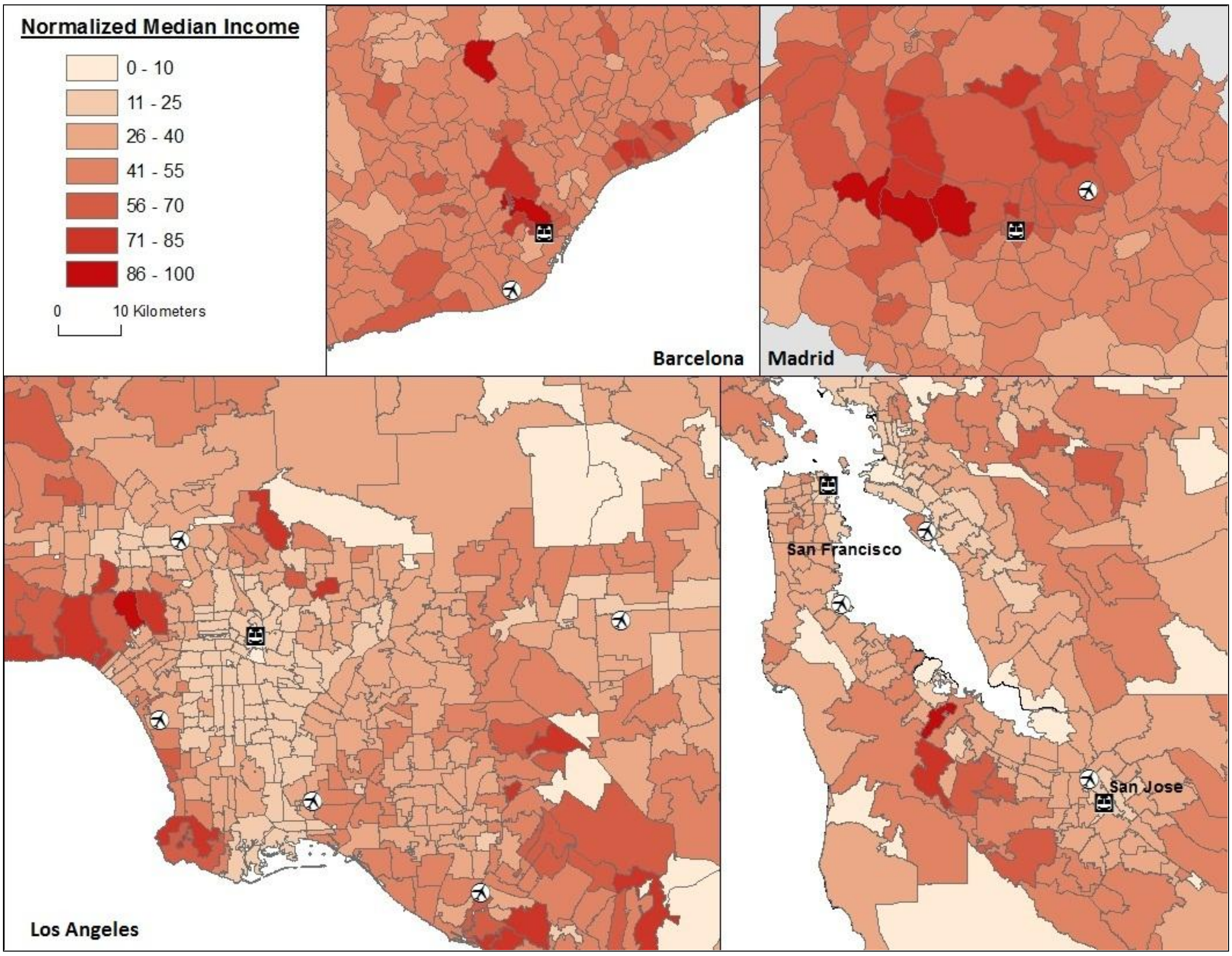


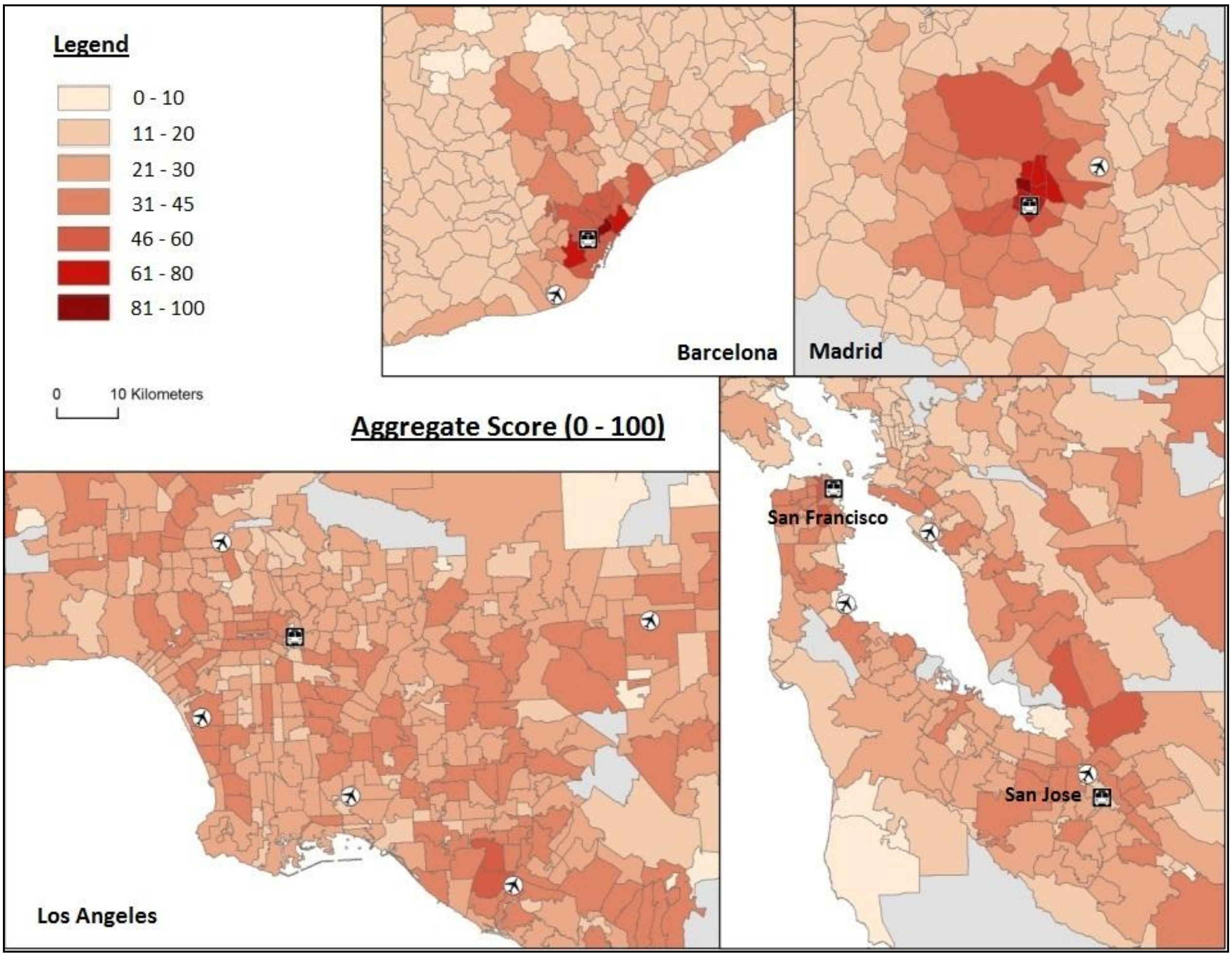
Figure 4. Normalized Median Household Income Comparisons: Barcelona, Madrid, Los Angeles and San Francisco Bay Area



The spatial patterns of these variables differ markedly between the Californian cities and the Spanish cities. In Barcelona and Madrid, the employment centers coincide with the population centers in the downtown areas. Downtown Barcelona and Madrid residents tend to be relatively wealthier, although there are obviously some very wealthy neighborhoods in the immediate suburbs. However, in Los Angeles and the Bay Area, employment centers do not coincide with population centers. Although downtown San Francisco and Los Angeles are large employment centers, their relative importance within the metropolitan areas is challenged by the suburban office districts. Population concentration is not where income level is high.

In order to consider the four variables simultaneously, we derive a new variable, which we denote as 'Aggregate Score'. The aggregate score is a weighted sum of the four variables after normalization, each given an equal weight of 0.25. The normalized variables all fall in the range of 0 to 100, as do the aggregate scores. The maps of aggregate scores (Figure 5) show a more dramatic contrast between the California and Spanish cities.

Figure 5. Aggregate Scores of HSR Accessibility: Barcelona, Madrid, Los Angeles and San Francisco Bay Area



* Aggregate Score = (Total Population + Population Density + Total Employment + Normalized Income) / 4

The aggregate score maps of Los Angeles and the Bay Area look very different from their population density maps. The downtowns can barely be recognized as ‘centers’ in the aggregate score maps, while some other areas emerge as ‘centers’. Moreover, most of the areas in Los Angeles and the Bay Area have similar scores not much lower than the ‘centers’. As Gordon and Richardson (1996) described, the spatial pattern of population and economic activities of the Californian cities is beyond polycentric. The highly dispersed nature of the aggregate score maps reflects the fact that population centers do not coincide with employment centers or the areas with relatively high incomes in the California cities. In contrast, for the Spanish cities, the aggregate score maps do not look much different from the population density maps. This is because the centers of population, employment and income all overlap in Barcelona and Madrid. This makes the downtowns of Barcelona and Madrid even more favorable for siting a HSR station. In absolute terms, the contrast between Californian and Spanish cities is also sharp. The highest aggregate score in Madrid is 76.48, and 85.30 in Barcelona; whereas in the Bay Area and Los Angeles, the highest scores are 26.88 and 27.75 respectively.

3.2 Aggregate Score Gradient

Next we move beyond the visual presentation via maps, to calculation of the density gradient, using the method first proposed by Clark (1951) to measure and compare urban spatial structure across cities. The density gradient measures the rate at which the population density decreases as the distance from the center increases.

$$D(u) = D_0 e^{-\gamma u \varepsilon}$$

For our purpose of studying the impact of urban structure on HSR accessibility, we substitute our aggregate score variable for population density in the equation. Therefore, D represents the aggregate score of a given geographic unit. Thus D_0 will be the aggregate score of the center, in this case the center being the geographic unit where the HSR station is located. D(u) will be the aggregate score of the geographic unit that is u kilometers away from the center. We differentiate San Jose and San Francisco in the subsequent analysis as each has a unique central station D_0. Table 2 shows the estimated gradient γ for each metropolitan area. We see the R^2 is larger for the Spanish cities showing the model fit is better for mono-centric cities.

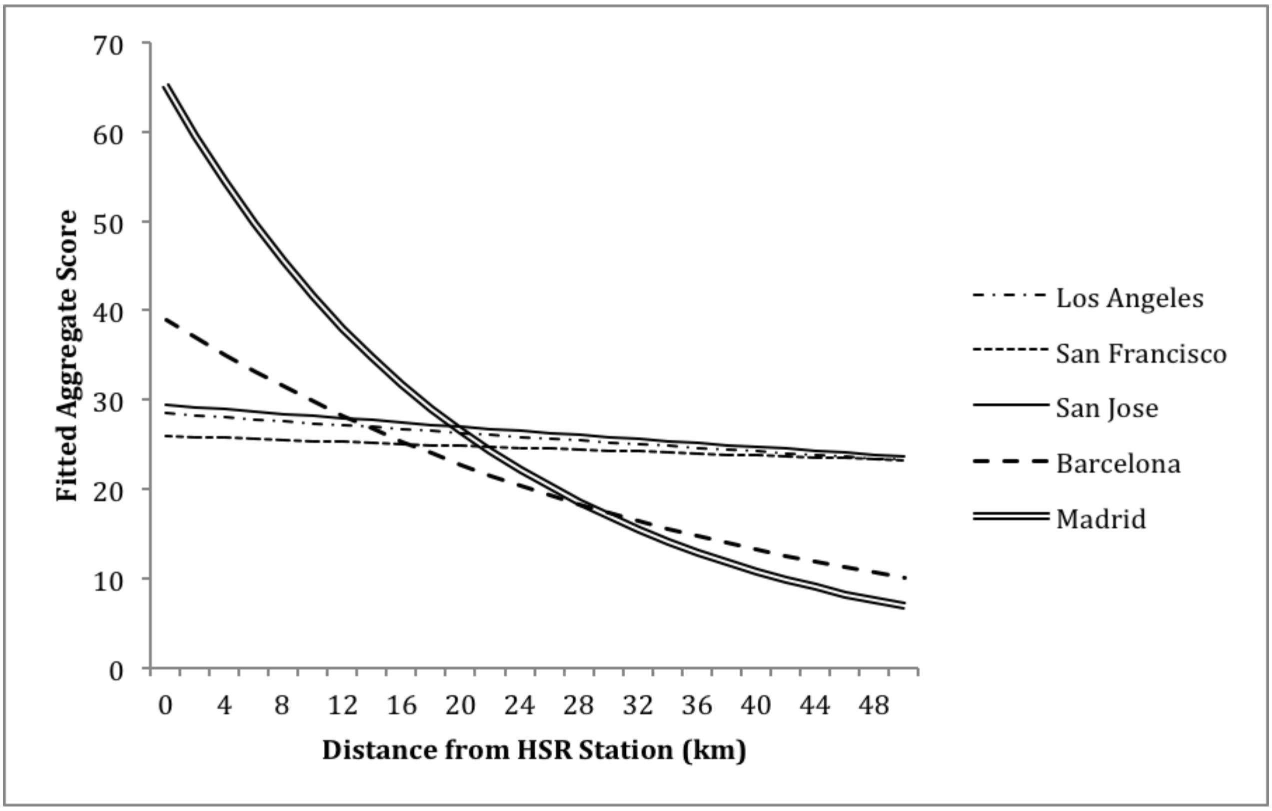
Table 2. Summary of Estimated HSR Aggregate Score Gradients for Study Areas

	Los Angeles	Bay Area		Barcelona	Madrid
		San Francisco	San Jose		
γ	0.00409***	0.00218**	0.00436***	0.02704***	0.04481***
D_0	28.5847***	25.9102***	29.4525***	39.0097***	65.2001***
R^2	0.908	0.873	0.884	0.827	0.910

*** significant at 1%; ** significant at 5%

The aggregate scores fitted with the gradients for each city are mapped in X/Y space in Figure 6. We see that the aggregate score decreases at a much slower rate in Los Angeles and the Bay Area than in Barcelona and Madrid. That suggests that the degree of concentration of potential HSR riders is much lower in the Californian cities than in the Spanish cities. Within Spain, Madrid is more compact than Barcelona. These results confirm what we observed in the maps.

Figure 6. Aggregate Score Gradient for HSR Accessibility of Study Cities



3.3 Measuring Accessibility of HSR Stations

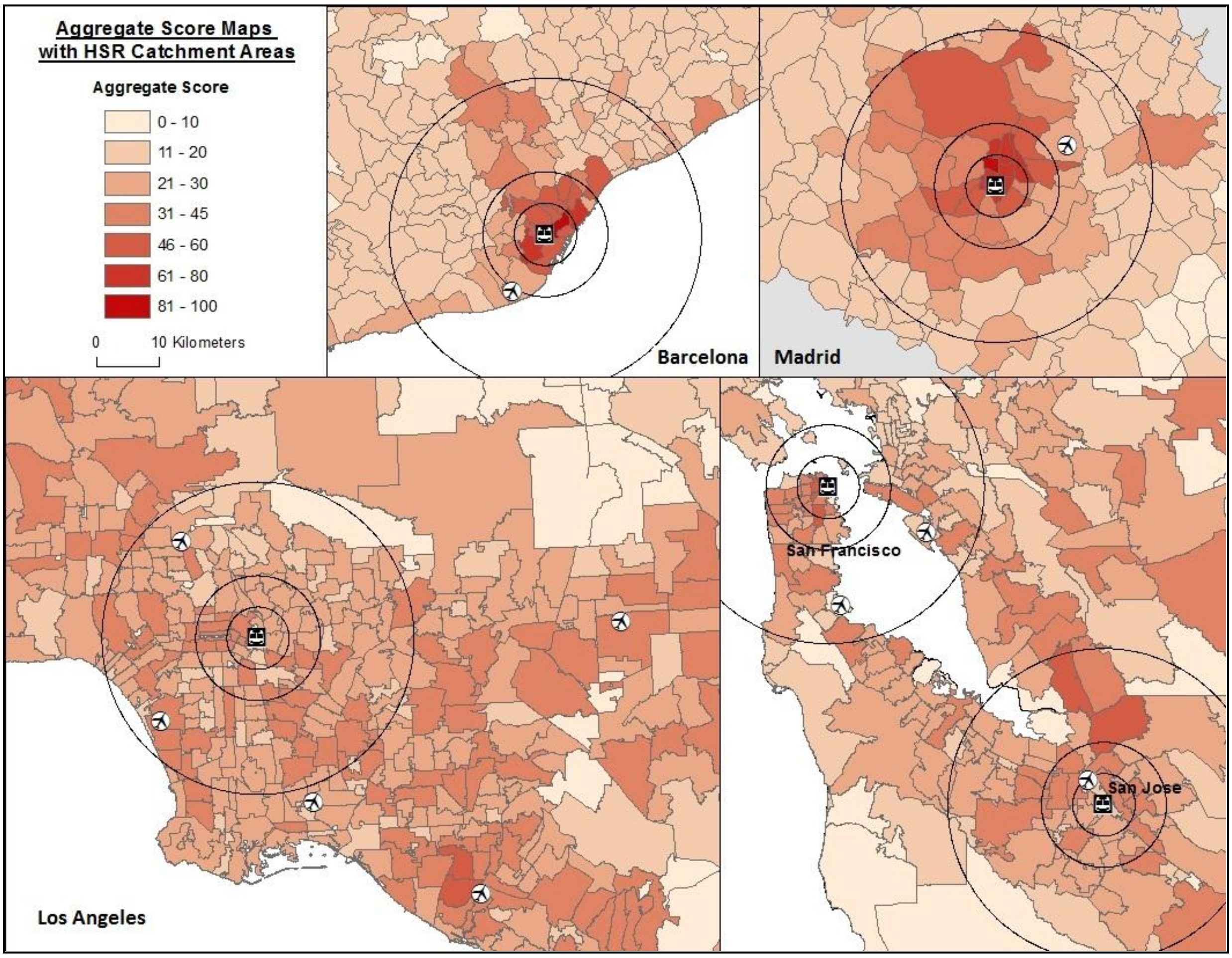
To compare the accessibility of HSR in California and Spain we first define the HSR catchment areas and compare the demographic and social-economic characteristics of the catchment areas in the four metropolitan areas. Second, we use an accessibility function to quantify the accessibility of HSR stations across the four metropolitan areas.

Based on prior studies on catchment area of a transit terminal we conclude that a reasonable HSR catchment area for intercity trips will be between 5 and 40 kilometers, depending on the station's connectivity to the local transportation system (Catz and Christian, 2010; Murakami and Cervero, 2010). There is a metropolitan light rail transit system in all four cities. In the Spanish cities, the metro system is a very dense network within 10 kilometers of the city center. In the Californian cities, the metro system is less dense but more extensive, roughly within 25 kilometers of the city center.

Bus service coverage is much larger than coverage by light rail, but beyond 10 or 25 kilometers from the HSR station, it is unlikely people will take a bus to access the HSR. This is because bus transport is much slower than light rail, travel time is unpredictable due to potential congestion on urban highways and transferring across modes is troublesome. Using a personal automobile or taxi is unlikely to affect the catchment areas as HSR stations are located downtown and it is difficult to provide sufficient parking space, and congestion on urban highways will deter driving to the downtown station. Hence, we assume travelers who live in suburbs will be more likely to drive or take a taxi to the nearby airports to avoid congestion and parking difficulty.

We select 10 and 25 kilometers as the radius of catchment areas for the accessibility analysis. Ten kilometers is a more reasonable radius for Spanish cities, while 25 kilometers is more reasonable for Californian cities. We analyze both the 10 and 25 kilometer catchment areas for both regions, as well as the 5 kilometer catchment area proposed by Murakami and Cervero (2010) as a reference. These catchment areas are shown in Figure 7 as overlays over the aggregate scores.

Figure 7. HSR Aggregate Score with 5, 10 and 25 km Catchment Areas



It is clear that the 10 kilometer catchment area captures the darker areas in Barcelona and Madrid, where most of the HSR riders are. However in California, even the largest 25 kilometer catchment area will leave out many of the dark-colored areas. That implies that HSR service is not very accessible to many potential riders in California.

Table 3 provides a closer look at the features of the catchment areas and tells a similar story to the maps; no matter which catchment area we use, the HSR stations in Spain better capture the potential HSR riders than the Californian counterparts across all dimensions of our accessibility analysis and the aggregate score.

Table 3. Population, Employment, Income and Aggregate Scores by HSR Catchment Areas

		5-km		10-km		25-km	
		Count	Percent	Count	Percent	Count	Percent
Total Population	Barcelona	1,163k	21.2	2,345k	42.7	3,999k	80.6
	Madrid	1,479k	23.1	2,879k	45	5,480k	85
	Los Angeles	463k	2.7	1,752k	10	6,174k	35.4
	Bay Area	604k	9.4	1,693k	26.4	3,997k	62.2
Total Employment	Barcelona	548k	29	1,086k	57.4	1,522k	80.5
	Madrid	786k	33.3	1,343k	56.9	2,149k	91.1
	Los Angeles	225k	3.5	540k	8.4	2,403k	37.5
	Bay Area	535k	19.3	890k	32.11	1,846k	66.6
Normalized Medium Household Income	Barcelona	55.4	N.A.	52.4	N.A.	50	N.A.
	Madrid	61.6		60.1		57.1	
	Los Angeles	15		17.9		26.1	
	Bay Area	23.9		27.9		30	
Aggregate Score*	Barcelona	63.2	N.A.	56	N.A.	44.7	N.A.
	Madrid	61.4		56.1		45.9	
	Los Angeles	30.5		30		28.2	
	Bay Area	36.9		33.2		30	

* Aggregate Score = (Total Population + Population Density + Total Employment + Normalized Income) / 4

3.4 Modeling Accessibility

We adopt the commonly used accessibility function with modifications specific to our research question.

$$A_i = \sum_{j=0}^{J} O_j d_{ij}^{-b}$$

O_j will be the aggregate score of location j, d_{ij} is the distance between location j and HSR station i, and the parameter b is a measure of distance impedance and will take the values 0.5, 1 and 2 for sensitivity analysis purposes. A higher value of b means a greater punishment for distance – less weight for units far away from the center. A larger *b* will favor the Spanish cities, because of their compact nature; and a smaller *b* will favor the Californian cities, as the suburban units get higher weights. The accessibility will be calculated for areas within catchment areas only, because it is unlikely that someone outside the catchment areas, especially the 25 km catchment area, will choose the downtown HSR station over suburban airports.

There are several potential biases in this method that we address in the following ways. First, the accessibility function treats the area of concern as discrete units, e.g. Zip Codes or Municipalities, when in fact the catchment areas are continuous areas. Thus for the same catchment area, the more units it is subdivided into, the higher its accessibility value. For example, in the 10 km catchment area, Madrid has 19 units, while Los Angeles has 41 units. In the 25 km catchment area the range in units is a low of 53 for Madrid and a high of 87 for Los Angeles. Therefore the reader should be aware that the results for Los Angeles have positive biases compared to Madrid. This makes Los Angeles appear more favorable than it really is.

Second, if a unit is less than 1 kilometer from the center, the accessibility value of that unit could be infinitively high due to the inverse functional form. This is the situation of San Francisco, where the unit nearest to the center is only about 0.2 kilometer from the center. To eliminate this bias we drop the zip codes in San Francisco that are less than one kilometer away from the HSR station and average the two accessibility values for the two stations in the Bay Area.

In Barcelona, where the downtown and HSR station are located very near the coast, the catchment areas are only partial circles. This puts Barcelona (and the Bay Area) at a disadvantage if we compare them with other cities with full-circle catchment areas, like Los Angeles and Madrid. We cannot resolve this by modifying the calculation method, so we simply compare Barcelona with the Bay Area, and Madrid with Los Angeles. The results of our analysis are described in Table 4.

Table 4. Bias-adjusted HSR Accessibility Measures by Distance Impedance

		5-km	10-km	25-km
Low Distance Impedance (b = 0.5)	**Madrid**	377.3	529.4	745.1
	Los Angeles	211.1	475.6	1261.1
	Barcelona	265.3	430.1	686.5
	Bay Area	212.1	388.9	580.1
Medium Distance Impedance (b = 1)	**Madrid**	252.1	308.9	361.8
	Los Angeles	127.0	222.3	415.1
	Barcelona	152.4	213.7	275.7
	Bay Area	136.3	184.3	245.0
High Distance Impedance (b = 2)	**Madrid**	139.8	147.9	151.2
	Los Angeles	57.2	69.9	82.0
	Barcelona	53.3	62.0	65.8
	Bay Area	72.0	78.5	82.5

The results show that Madrid dominates in most scenarios, except for the 25 km catchment areas with low distance impedance b = 0.5 and 1, where Los Angeles takes over Madrid. That is because the urban area of Madrid is much smaller than Los Angeles, and aggregate score drops very quickly as distance increases from the urban center. But in Los Angeles, aggregate score does not drop much as distance increases. So the larger the catchment area, the better the accessibility of Los Angeles becomes relative to Madrid, especially when the discount effect, b, is small.

If we compare Barcelona with the Bay Area, we find Barcelona performs better in most scenarios except when distance impedance is high (b = 2). This shows that Barcelona’s advantage of concentration is not sufficiently great to compensate for its fewer units relative to the Bay Area if the discount effect, b, is large. Also, Barcelona is smaller in population size than the other three cities, which drives down its accessibility value in all scenarios.

In general, our analysis shows that HSR in Madrid and Barcelona have better accessibility for their potential riders than those in Los Angeles and the Bay Area, even though there are biases in favor of the Californian cities in the accessibility measures. The better HSR accessibility in the Spanish cities is largely due to their highly concentrated urban structure. The degree of concentration is indicated by the aggregate score gradient and the aggregate score at the 'center', i.e. the HSR station. As demonstrated previously, the Spanish cities have much higher gradient and aggregate scores at the center, which indicates that potential HSR riders are highly concentrated in the Spanish cities, but highly dispersed in the Californian cities.

4. Discussion

The accessibility analysis shows HSR is less attractive in Los Angeles and San Francisco than in Madrid or Barcelona, despite the upward biases in our estimates for Los Angeles. The critical importance of urban spatial form (mono-centric or polycentric) on the accessibility of HSR reflects spatial patterns of population, employment and income across the metropolitan region. Comparative analysis with the Spanish experience suggest that the California HSR demand estimates are overly optimistic, as the CHRSA analyses (2009, 2011, 2012) have not given sufficient attention to the disadvantages of a polycentric urban form on HSR accessibility.

Although HSR has been heralded as a low carbon, economic development generating approach to turn city attention back toward residents, comparative international experience, suggests that developers should proceed with caution. Our analysis of the impact of urban spatial form (mono-centric or polycentric) points to a broader set of dimensions that should receive the attention of urban and transportation scholars when considering the accessibility of HSR. These include: equity, public investment alternatives, economic development impacts and implications for carbon footprint. Research has shown that HSR promotes urban investment and concentrates economic activity in the nodes. This might help HSR stations become nodes of denser urban development in the future and could, if linked to the metro light rail system, encourage transit development nodes throughout the Los Angeles and San Francisco regions. However, given the current structure of population, income and employment, California HSR is unlikely to be able to achieve a level of ridership sufficient to cover its costs as currently planned. Will HSR ever be self sustaining? Again, the international research raises serious doubts.

Popular support for HSR in California was predicated on the notion that the State needed to find an alternative to continued congestion on its highways**.** The interstate highway system is approaching the end of its service life (Chan, Keoleian and Gabler, 2008), and the existing highway finance system in the U.S cannot afford to pay for the reconstruction and expansion of the interstate to meet the increasing travel demand (McMullen, Zhang and Nakahara, 2010). While our analysis suggests HSR is not the answer, future trends in transit, green house gas emissions and urban form may offer a different picture than we see today.

At present however, the international experience suggests HSR is a costly and rigid approach to achieving such goals. Less costly and more flexible approaches to inter-urban transit which better utilize air travel, conventional rail, car sharing and bus travel may better match the polycentric urban form of US cities.

5. Conclusion

We have presented a straightforward methodology for looking at the relationship between urban structure and HST accessibility, which can be used for other international comparisons of interest to urban scholars. Our methodology assesses socioeconomic and spatial characteristics of mono-centric versus polycentric cities that may affect HSR accessibility. We show that polycentric cities such as Los Angeles and San Francisco are less attractive candidates for HSR than mono-centric cities such as Madrid or Barcelona. Because demand projections give insufficient attention to urban structure, this can lead to overestimations of ridership. Policy makers and transportation planners should give full consideration to urban structure and its effects on HSR competitiveness.

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