

## High-speed rail accessibility: a comparative analysis of urban access in Los Angeles, San Francisco, Madrid, and Barcelona

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This paper is intended to set the context for policy discussion on HSR feasibility from the perspective of station accessibility. We compare the proposed Los Angeles – San Francisco HSR corridor to the functioning HSR line between Madrid and Barcelona to assess relative station 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 methodology that allows us to assess relative station accessibility in the four compared metropolitan areas. We find urban structure limits the potential accessibility of HSR in the California context, and warn HSR planners they should proceed with caution.

*Keywords: High speed rail, station accessibility, mono-centric vs polycentric cities, urban structure*

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### 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 and Horvath, 2010; Westin and 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 (see Albalade and Bel, 2012, for a worldwide review). This is a very well-known bias affecting all types of investment projects, (Flyvbjerg et al., 2005), but its consequences may be critical in HSR, because of the importance of high demand density and high air transport replacement.

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Demand forecasts can be very challenging and have been criticized for overly optimistic projections (Albalade and Bel, 2012; Brownstone et al., 2010, Lovallo and Kahneman, 2003). Our contribution to the debate is to assess HSR station accessibility based on an analysis of urban structure that gives explicit attention to a geographically disaggregated analysis of the major demand drivers: population, density, employment and income within reasonable catchment areas of HSR stations. Urban planners are keenly involved in planning for HSR stations and our analysis provides an explicit discussion of urban structure and its implications for HSR accessibility.

Discussion of high-speed rail in the US has been ongoing for more than two decades and the public and scholarly debate has progressively become more intense, with visions favouring HSR building (i.e. Johnson, 2012; Lane, 2102) and others expressing negative views (i.e. Button, 2012; Levinson, 2012). An interesting difference between the discussion on HSR worldwide and in the US is that elsewhere HSR designates speeds above 155 mph (De Rush and Nash, 2007), whereas in the US the federal government (DOT, 2009) distinguishes between three different categories of HSR: HSR-Express, HSR-regional, and Emerging HSR. Only the first one, HSR-Express, is equivalent to the conventional meaning of HSR worldwide. Throughout this paper we refer to the standard international meaning of HSR.

In the US, the most intense public policy debate and analysis of costs and benefits of building an HSR system has focused on the California High Speed Rail. Cost estimates for the California line have grown through the successive business plans, while ridership forecasts have been reduced (CHSRA 2009, 2011a, 2012). Furthermore, the States of Wisconsin and Ohio in 2010, and Florida in 2011 rejected subsidies offered by the US Federal government based on the claim that the project placed strong financial requirements on them. However, the fact that the federal government was requiring states to pay a percent of the cost of HSR similar to federal road projects suggests strong political motivation to oppose the agenda of the U.S. President.<sup>4</sup>

Demand forecasts accepted by CHSRA have been subject to criticism (i.e. Brownstone et al., 2010). Among the aspects not adequately assessed in demand forecasts is the role of urban structure, especially as regards accessibility of HSR. The competitive advantage of HSR stations with respect to airports is a key issue regarding potential ridership (Martín et al, 2012). HSR's ability to draw traffic from highways is limited. HSR is most likely to draw traffic away from highways when the distance is from 150 km to 450 km and the travel time is under 3 hours. Research has found the main absorption is from air transit (see Klein, 1997 for France, de Rus and Inglada, 1997 for Spain, and Börjesson, 2011 for Sweden). Estimates for 2030 for the CHSRA indicate that attraction from road trips will be around 2%, much lower than attraction from air trips, which is expected to be higher than 33% of air trips (CHSRA, 2012a).

Interest in accessibility analysis is quickly growing in the literature (Martín and van Wee, 2011). In this paper we draw on international experience to compare HSR accessibility in two large European cities with already functioning HSR, Madrid and Barcelona, with that of two major cities in California with proposed HSR, Los Angeles and San Francisco, and we develop and illustrate a methodology for assessing HSR accessibility in the studied metropolitan areas. Our methodology looks at socioeconomic and spatial characteristics – mono-centric versus polycentric cities and the factors affecting HSR accessibility. By addressing challenges of unit (urban geography), data series (normalization), and identifying four key components of HSR accessibility (population, population density, income and employment) we contribute to the literature by providing a comparative analysis of HSR accessibility and urban access in California and Spain.

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<sup>4</sup> We thank a referee for encouraging us to consider this interpretation.

## 2. International Comparison – Why Compare Los Angeles, San Francisco, Madrid and Barcelona?

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, 2011a, 2012b), as well as in the public debate (see, for instance, Sheehan, 2012, in *The Sacramento Bee*). Spain provides the most relevant comparison to the California case because Madrid and Barcelona are similar sized cities, the HSR track is dedicated to passengers 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 km<sup>2</sup>), relatively similar population (38 and 47 million), and population densities (92 and 93 inhabitants per km<sup>2</sup>), 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 between the two city-pairs are also similar: 150 minutes for Barcelona-Madrid and 166 minutes for LA-San Francisco.

One possible objection to the appropriateness of comparing California and Spain could be that HSR in Spain has a different gauge from conventional lines, so that it is not easy to combine HSR and conventional services, which is the most recent direction taken by the HSR project in California, particularly near the metropolitan areas. However, this is just a weak problem, because the Spain rail operator uses rolling stock with adjustable gauge, so that HSR and conventional services can be combined without changing vehicles and with little loss of time. With respect to freight traffic, neither Spanish nor California HSR is compatible with freight. An important difference however is that California plans to share tracks with commuter trains in some less dense metropolitan areas along the corridor which may increase ridership.<sup>5</sup>

Other comparisons seem to be less appropriate. The only two profitable lines in the world are Tokyo-Osaka and Paris-Lyon. But Tokyo-Osaka passes through several densely populated large cities, 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. In Germany, the most important HSR corridor, Köln-Frankfurt, is less than 115 miles and the population of both German cities and surrounding metropolitan areas is lower than that in the Spanish cities considered in our comparative analysis. In addition, most German lines are compatible with freight, leading to lower speeds (120-130 mph), whereas the proposed California HSR line is not compatible with freight.

This is why we believe a comparison of California and Spain is appropriate for our analysis. Madrid-Barcelona corridor is the most heavily travelled route 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 construction costs for Madrid-Barcelona corridor was \$12.4 billion in 2010 US dollars.<sup>6</sup> 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. 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

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<sup>5</sup> Note however that the California plans to share tracks with commuter trains could affect scheduling and cause congestion, thus additionally affecting its attractiveness. We thank a referee for bringing this point to our attention.

<sup>6</sup> 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 were obtained from RENFE and Iberia -main airline in the corridor- web pages in June 2012. Recall also that investment in most HSR corridors in Spain has been significantly subsidized by the European Union. In the case of the Madrid-Barcelona corridor, subsidies from the EU funded 38% of total construction costs until 2010 (Albaladejo and Bel, 2011: 184).

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.<sup>7</sup> Shifts in modal share from air travel to HSR in the Madrid-Barcelona corridor were 48% by 2010, and are around 50% in 2012.<sup>8</sup> The average round trip HSR ticket price in the Madrid-Barcelona corridor ranges from \$186-\$244 (2012 prices), more than competing low cost airfare (\$88 - \$220). CHSRA (2012) predicts an average price of \$81 one way (in 2011 dollars) in its plan, which is about the same cost as a plane ticket on this route.

While the comparison above 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 HSR in polycentric cities such as those in California.

### 3. Urban Geography and Transportation: Determining Accessibility

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

HSR shifts investment attention towards passengers and the role of their mobility from one metropolitan region to another. HSR changes the relative accessibility of places and impacts economic development (Haynes, 1997; Van den Berg and Pol, 1998; Givoni, 2006). To the extent HSR connects downtowns and central business districts directly, it may lessen the centrifugal effects airports and automobiles have on urban growth, although absorption by HSR of road trips in long distances is minimal (Klein, 1997, Börjesson, 2011), and improvements in metropolitan transit systems would have much stronger effect in this regard.

Urban structure has important implications for HSR competitiveness. Although cities throughout the world are becoming more polycentric (Bruegmann, 2005), still large differences in city density exist, and HSR has proved to work best in corridors with populous and dense urban centres, such as Paris and Tokyo (Albalade and Bel, 2012). HSR requires new infrastructure requirements in non dense cities for parking at terminals and improvements in intermodal connectivity (Cheng, 2010). Polycentric cities with low population density will not reap the benefits of city centre connection that HSR offers. For polycentric cities, HSR presents a difficult trade-off: build several stations to attract suburban riders or limit stations to maintain the high speed advantage. 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

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<sup>7</sup> The ridership in 2013, the 5th year of full HSR operation on this corridor, is still below initial expectations of ridership for 2010. This divergence can be explained by traffic forecasting that Lovallo and Kahneman (2003) argue was influenced by 'delusions of success'. This included lack of attention to urban structure, as shown by the protracted discussions on where to locate the main HSR station in Barcelona, based on the possibilities for residential and commercial development that could raise revenues for the project rather than on urban structure and connectivity to the existing subway and regional transportation network. It is also worth noting that development of the HSR network in Spain was made without the aid of cost benefit analysis -properly speaking- of the different projects (Albalade and Bel, 2012: 102)

<sup>8</sup> Cambridge Systematics (2005, pp. 4.4 and 4.5, table 4.1) provides a summary of recommended evaluation measures for travel demand models. They do not consider explicitly urban structure as such. They only mention as evaluation measures related to our paper: (a) Population & employment (by county); (b) Population & employment (by subregion and transit planning area). Indeed, an independent review conducted for CHSRA (CHSRA, 2011b, p.4) criticizes the limited discussion of socioeconomic and land use forecast inputs. Furthermore, no international comparative analysis was conducted.

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 (Small and Song, 1994; Anas et al., 1998). Giuliano and Small (1991) identified seven employment centres in the Los Angeles Metro area in 1970 and later with a modified methodology, Giuliano et al. (2007) identified 36 employment centres 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-centres (Davoudi, 2003). The San Francisco Bay Area is only slightly less polycentric; Cervero and Wu (1997) found 22 employment centres in the Bay Area in 1990. Available data on employment location in the metropolitan areas of Madrid and Barcelona<sup>9</sup> is not homogeneous to that available for Los Angeles and San Francisco, making comparison difficult. However, employment concentration in the two Spanish cities is much higher. Data for 2009 in the metropolitan area of Barcelona show that the three districts in the central city surrounding the HSR station (Eixample, Sants-Montjuic and Les Corts), concentrate more than 17% of total employment in the metro area, a percentage that is 78% higher than their share in total population. In 2009, concentration of employment in the metro area of Madrid is still higher: the four districts in the central city surrounding the HSR station (Salamanca, Retiro, Chamberí, and Centro) concentrate more than 20% of total employment in the metro area, a percentage that is 132% higher than their share in total population.

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 centres (Dittmar et al., 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).

Urban structure and transportation come together in assessments of accessibility. In transportation studies, travel time is usually broken down into several components: access, egress, wait, and in-vehicle time (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, 2008a). 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. Although there is little research done on how HSR station locations affect ridership and market share (Clever and Hansen, 2008b), most authors agree that access and egress time are more onerous than in-vehicle time, so access to the terminal is a greater determinant of intercity travel mode choice (Forinash and Koppelman, 1993; Wen and Koppelman, 2001).

#### **4. Methodology: Case comparisons**

We compare the cities of Los Angeles and San Francisco in California with the cities of Madrid and Barcelona in Spain to assess relative accessibility of stations as determined by urban structural factors. International comparison is important for HSR, as it is for other types of infrastructure, because research shows important differences across countries due to topography, demographics, nature of transit demand and government investment schemes (Campos and de Rus, 2009; Albalade and Bel, 2012).

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<sup>9</sup> Sources for data of employment in the central districts and the metro areas of Barcelona and Madrid are: Catalonia Statistics Institute, 2009; Departament d'Estadística de l'Ajuntament de Barcelona (Barcelona Dep. of Statistics); Spanish National Statistics Institute 2009; Area de Estadística del Ayuntamiento de Madrid (Madrid dep. of Statistics).

International research is complicated by differences in data systems that make direct comparisons difficult. We present a methodology that addresses these differences. 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 Province of Madrid as our areas of study (land size 7,733 and 8,030 km<sup>2</sup> respectively; population 4.96 and 6.45 million respectively; population density 641.4 and 803.2 inhab/km<sup>2</sup> respectively). 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 (land size 13,527 km<sup>2</sup> and population 6.17 million; population density 456.2 and 562.0 inhab/km<sup>2</sup> respectively), 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 (land size 30,783 km<sup>2</sup> and population 17.3 million), 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 into the city to use HSR. The larger study areas for the US cities reveal the sprawling nature of the California cities.

The geographic unit of analysis within each metro area is based on comparable sizes and data availability. For the Spanish cities, it is the municipality and district; for Californian cities, we use Zip Code Tabulated Areas. The Municipality of Madrid and the Municipality of Barcelona are broken down to the district level, because they are much larger in size than other municipalities and it is desirable to have smaller units for the municipalities that encompass the downtown area where the HSR station is located. In total, there are 322 units in the Province of Barcelona, 199 in the Community of Madrid. In Greater Los Angeles, there are 529 units; in the Bay Area, there are 248 units. The municipalities and districts in Spain and the Zip Codes in Los Angeles and the Bay Area are comparable in size, mostly less than 50 km<sup>2</sup>.

**Table 1. Definition of Study Areas**

Name	Metro Area Definition	Area (km <sup>2</sup> )	Population (million)	Density (inhab/km <sup>2</sup> )
Barcelona	Province of Barcelona	7,733	4.96	641.4
Madrid	Community of Madrid	8,030	6.45	803.2
San Francisco Bay Area	San Francisco-Oakland-Fremont MSA and San Jose-Sunnyvale-Santa Clara MSA	13,527	6.17	456.2
Los Angeles	Los Angeles-Long Beach-Riverside CSA (modified)	30,783	17.30	562.0

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

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 HSR corridor. 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 Bay Area) will serve urban or regional trips in large part. We focus on the nonstop service of these three central stations of the Los Angeles - San Francisco route because they are more comparable to that of the Barcelona and Madrid route.

#### *4.1 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 (Mallet, 1997; Garrison and Levinson, 2005; Chang and Lee, 2008). 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 their locations relative to the HSR stations.<sup>10</sup> 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).<sup>11</sup>

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 downtown Los Angeles and San Francisco much smaller than those in Barcelona and Madrid, the colour also fades much more slowly from the centre to the periphery. This shows that 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. Population density measures the concentration of potential riders whereas total population measures 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 as well.

Business trips usually make up a significant proportion of HSR trips (Garrison and Levinson, 2005; Chang and Lee, 2008). Many business trips originate or terminate at office districts where employment concentrates. Hence a major employment centre is a major area of potential HSR riders (see Figure 3 and Figure 4). In addition, as 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 differences in purchasing power. 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 5.

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<sup>10</sup> An interesting issue is that of potential complementarity between airports and HSR in the main metropolitan areas of California. Prospects for complementarity are weak in the case of Los Angeles, because planned stations do not have an adequate intermodal connection with the LAX international airport. The case of San Francisco could be different, as plans exist to place a HSR station next to the SFO international airport. A more detailed analysis of this issue can be found in Albalade, Bel and Zhong (2013)

<sup>11</sup> 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 Estadística 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).

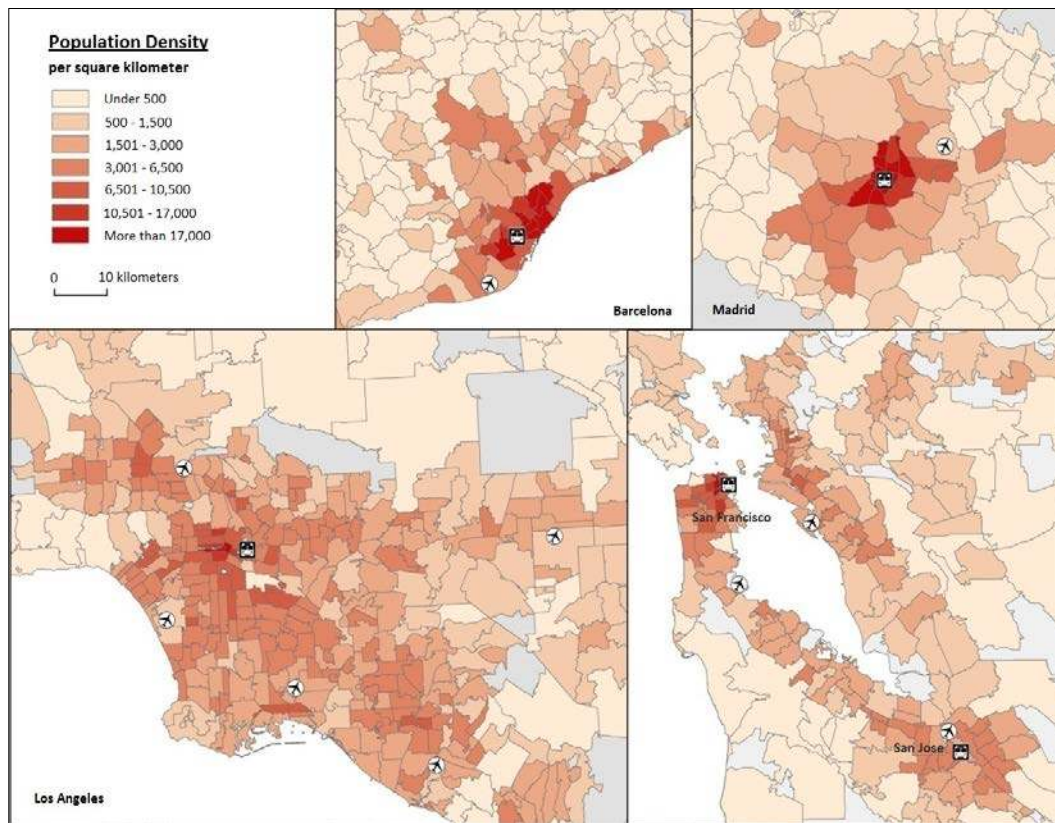


Figure 1 Population Density Comparisons: Barcelona, Madrid, Los Angeles and San Francisco Bay Area

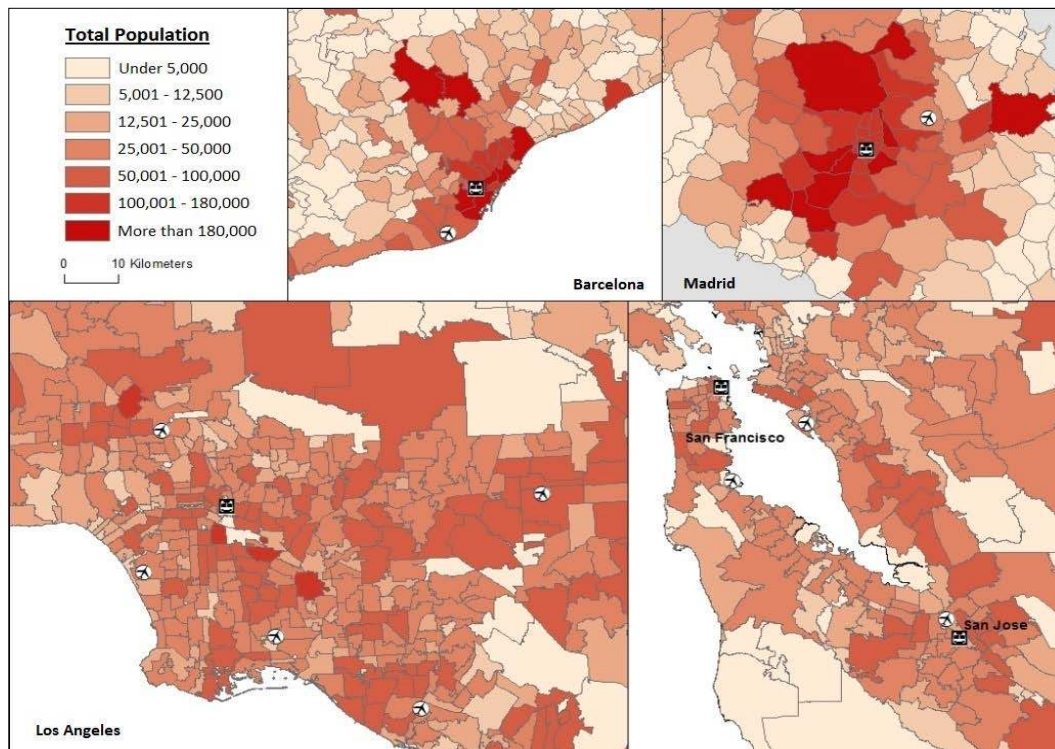


Figure 2 Total Population Comparisons: Barcelona, Madrid, Los Angeles and San Francisco Bay Area



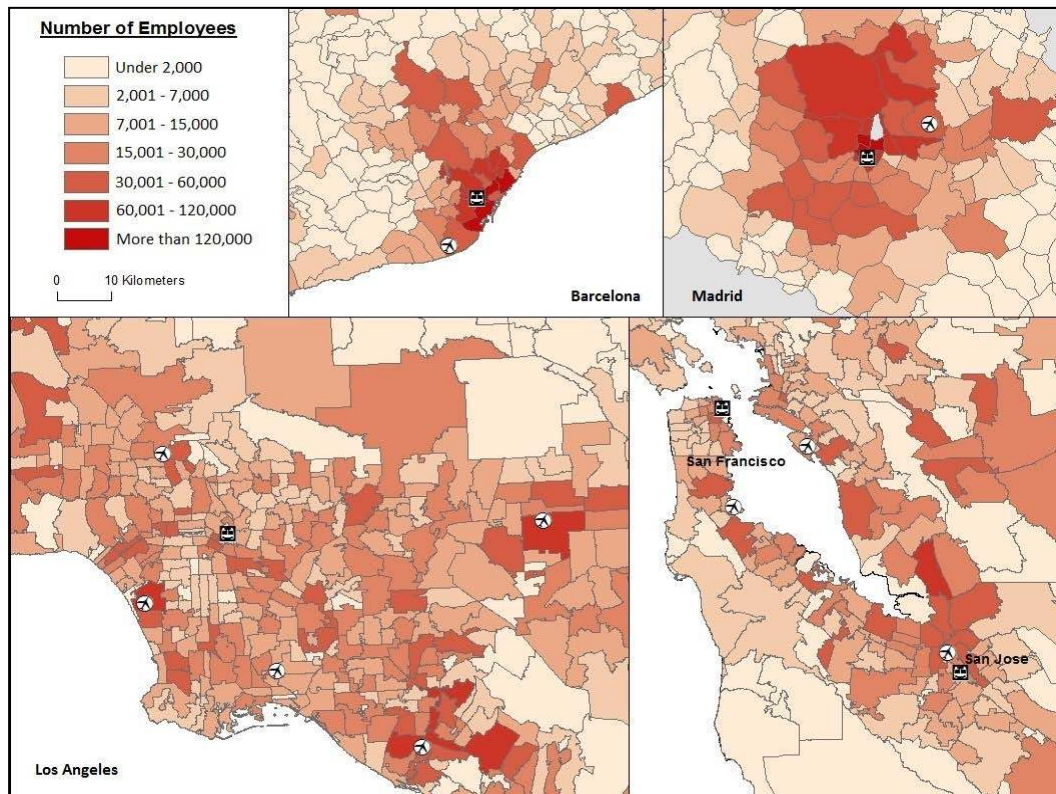


Figure 3 Employment Comparisons 1: Barcelona, Madrid, Los Angeles and San Francisco Bay Area

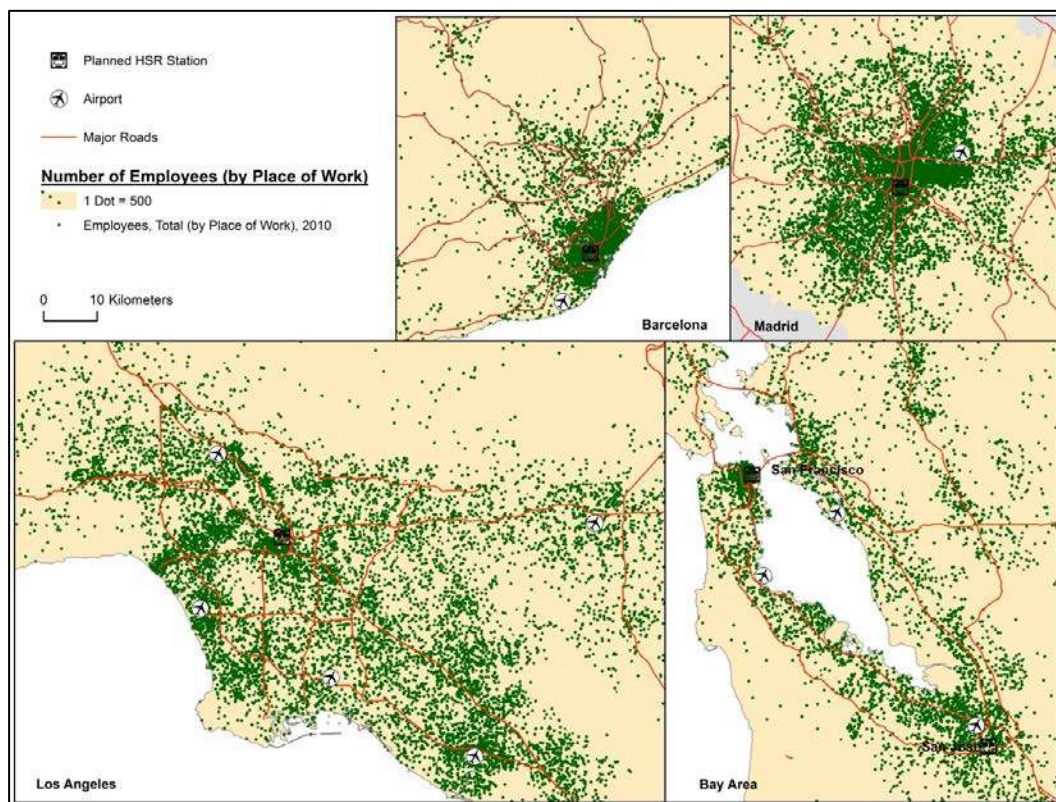


Figure 4 Employment Comparisons 2: Barcelona, Madrid, Los Angeles and San Francisco Bay Area

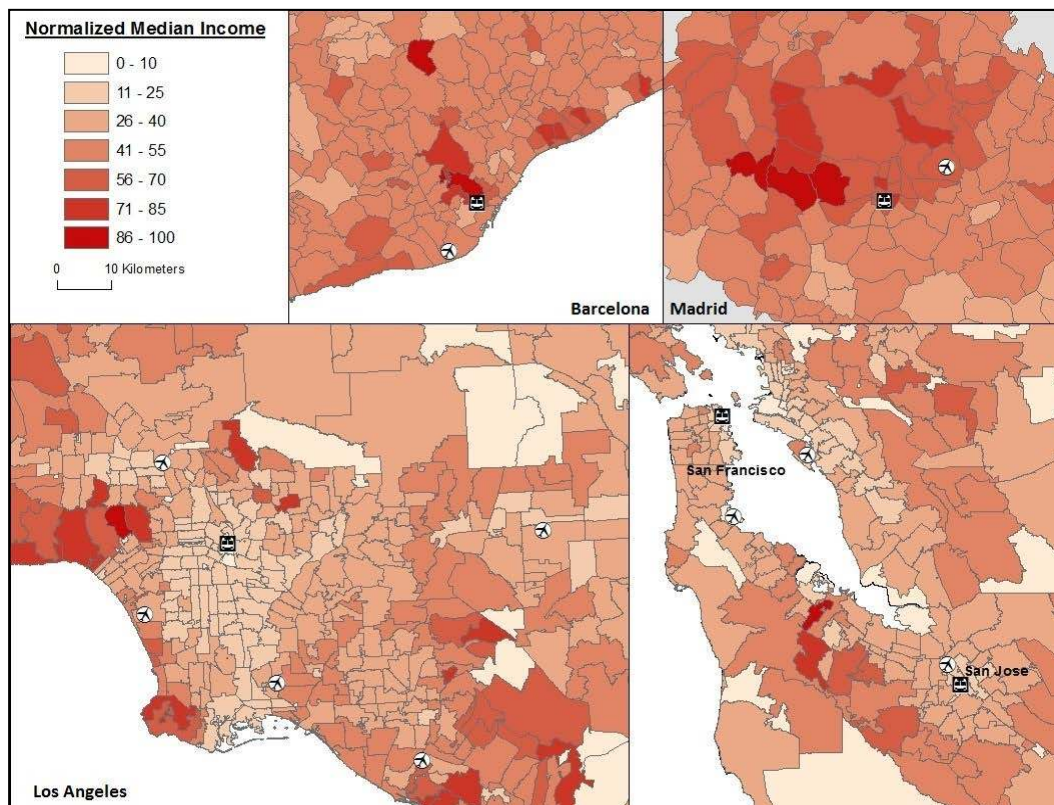


Figure 5 Normalized Median Household Income Comparisons: Barcelona, Madrid, Los Angeles and San Francisco Bay Area

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

We derive a new variable, 'Aggregate Score', which considers the four variables, population, population density, employment, and relative income, simultaneously. The aggregate score is a weighted sum of the four variables after normalization, each given an equal weight of 0.25<sup>12</sup>. The normalized variables all fall in the range of 0 to 100, as do the aggregate scores. The aggregate score maps of Los Angeles and the Bay Area look very different from their population density maps (see Figure 6). The downtowns can barely be recognized as 'centres' in the aggregate score maps, while some other areas emerge as 'centres'. Moreover, most of the areas in Los Angeles and the Bay Area have similar scores not much lower than the 'centres'. As Gordon and Richardson (1996) described, the spatial pattern of population and economic activities of the Californian cities is beyond polycentric.

<sup>12</sup> For the purpose of sensitivity analysis, another weighing method was carried out to test the results. The sensitivity analysis showed that altering the weights does not change our conclusions. For details of the sensitivity analysis, please see Appendix A.

The highly dispersed nature of the aggregate score maps reflects the fact that population centres do not coincide with employment centres 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 centres of population, employment and income all overlap in Barcelona and Madrid. This makes the downtowns of Barcelona and Madrid even more favourable for sitting an HSR station. In absolute terms, the contrast between Californian and Spanish cities is also sharp. The highest aggregate score for a subunit area 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.

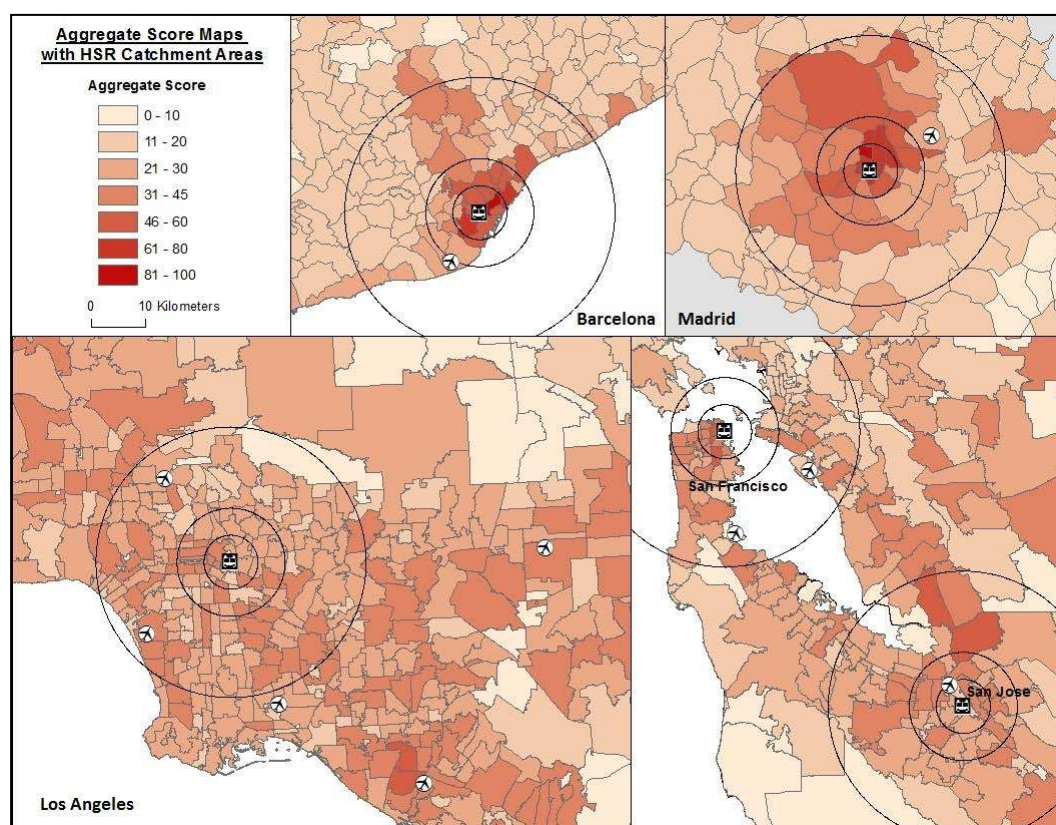


Figure 6 Aggregate Scores of HSR Accessibility with 5, 10 and 25 km Catchment Areas

#### 4.2 Aggregate Score Gradient

Next we move beyond the visual presentation via maps, to measure urban structure with the density gradient, a method pioneered by Clark (1951), and advanced by Alonso (1964), Ebertz (1981), Madden (1985), etc. The density gradient measures the rate at which population density, or other indicators, decreases as the distance from the centre increases.

$$D(u) = D_0 e^{-\gamma u \epsilon} \quad (1)$$

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 centre, in this case the centre being the geographic unit where the HSR station is located.  $D(u)$  will be the

aggregate score of the geographic unit that is  $u$  kilometres away from the centre, and  $\varepsilon$  is the error term. 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  $\gamma$  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**

	Bay Area				
	Los Angeles	San Francisco	San Jose	Barcelona	Madrid
$\Gamma$	0.00363***	0.00622***	0.00063	0.02862***	0.03473***
$R^2$	0.238	0.317	0.006	0.888	0.924

\*\*\* significant at 1%

The aggregate scores fitted with the gradients for each city are mapped in X/Y space in Figure 7. 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 the degree of concentration of potential HSR riders is much lower in the Californian cities than in the Spanish cities. These results confirm what we observed in the maps. A similar graph is made with gradients estimated with aggregate scores calculated in the sensitivity analysis, which can be found in Appendix A.

#### 4.3 Measuring Accessibility of HSR Stations

To compare the accessibility of HSR in the four cities 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 the accessibility function to quantify the accessibility of HSR stations across the four metropolitan areas in our study.

A catchment area is the area within a reasonably accessible distance from a transit station. The existing literature on 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, Catz and Christian (2010) argued that the catchment areas of intercity travel terminals, like HSR stations, should be much larger than those of transit stations. They suggested a catchment area of 1.5 – 5 km, depending on the feeder system of the HSR station. Murakami and Cervero (2010) 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 km, 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 km, depending on the feeder system. In all four cities of our study, there is a metropolitan light rail system that is or will be linked to HSR. In the Spanish cities, the metro system is a dense network within 10 km of the city centre. In the Californian cities, the metro system is less dense but more extensive, roughly within 25 km of the city centre. Therefore we select 10 and 25 km as the radius of catchment areas for the accessibility analysis to reflect the extent of the existing feeder systems. We believe 10 km is a more reasonable radius for Spanish cities, while 25 km is more reasonable for Californian cities but we analyze both 10 and 25 km catchment areas for all cities, as well as the 5 km catchment area proposed by Murakami and Cervero (2010) as a reference.

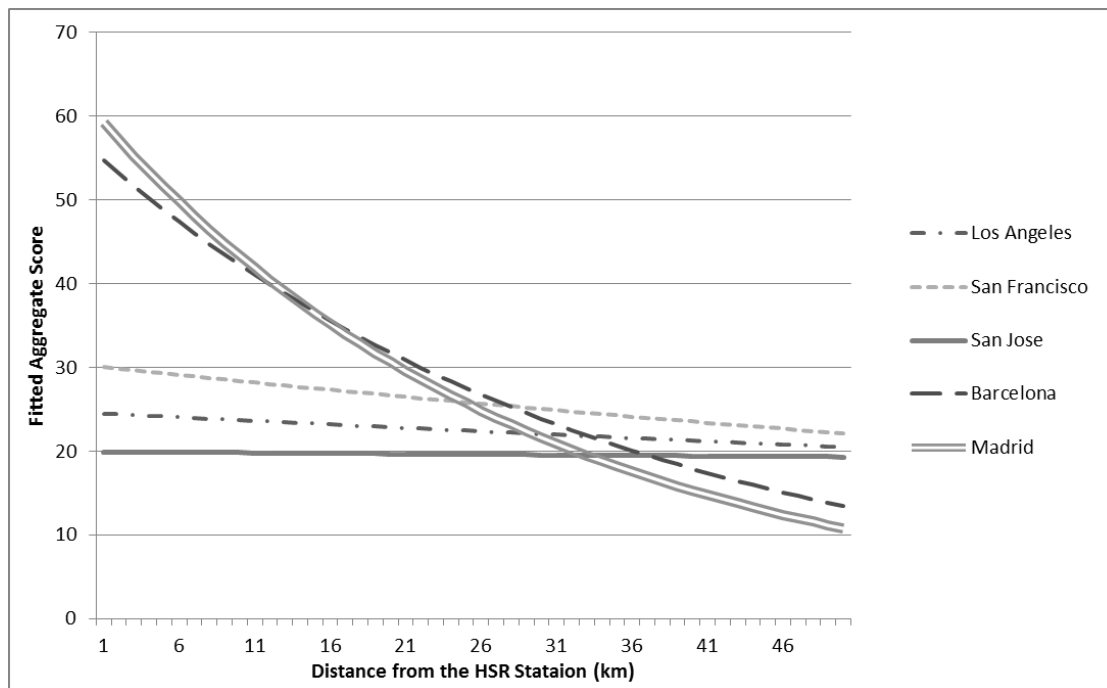


Figure 7 Aggregate Score Gradient for HSR Accessibility of Study Cities

The catchment areas are shown in Figure 6 above as overlays on the aggregate score maps. It is clear that the 10 km catchment area captures the darker areas in Barcelona and Madrid, where most of the HSR riders are. However in California, even the largest 25 km catchment area leaves out many of the dark-coloured areas. That implies 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.

#### 4.4 Modelling Accessibility

We adopt the commonly used accessibility function (Sanchez, 1999; Baradaran and Ramjerdi, 2001; Chang and Lee, 2008) with modifications specific to our research:

$$A_i = \sum_{j=0}^J O_j d_{ij}^{-b} \quad (2)$$

$O_j$  will be the aggregate score calculated with the four socio-economic variables 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 centre. A larger  $b$  will favour the Spanish cities, because of their compact nature; and a smaller  $b$  will favour 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 the nearest airports.

**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
Population Density (pop/km <sup>2</sup> )	Barcelona	14808		7464		2037	
	Madrid	18831		9164		2791	
	Los Angeles	5895		5576		3144	
	Bay Area	7690		5388		2036	
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		52.4		50	
	Madrid	61.6	N.A.	60.1	N.A.	57.1	N.A.
	Los Angeles	15		17.9		26.1	
	Bay Area	23.9		27.9		30	
Aggregate Score*	Barcelona	63.2		56		44.7	
	Madrid	61.4	N.A.	56.1	N.A.	45.9	N.A.
	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

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.

Second, if a unit is less than 1 kilometre from the centre, 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 centre is only about 0.2 kilometres from the centre. To eliminate this bias we drop the zip codes in San Francisco that are less than one kilometre away from the HSR station and average the two accessibility values for the two stations in the Bay Area.

In Barcelona and the Bay Area, where the HSR stations are very close to the coast, the catchment areas are only partial circles. This puts Barcelona and the Bay Area at a disadvantage if we compare them with cities with full-circle catchment areas, like Los Angeles and Madrid. But in

reality, this is a limitation of HSR accessibility in those two metropolitan areas as a result of the natural environment.

The results in Table 4 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 the aggregate score drops very quickly as distance increases from the urban centre. But in Los Angeles, the 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.

Comparing 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.

**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

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 favour 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 Spanish cities have much higher gradients and aggregate scores at the centre, which indicates that potential HSR riders are highly concentrated in the Spanish cities, but highly dispersed in the Californian cities.

## 5. Discussion and Conclusion

We have presented a methodology for looking at the relationship between urban structure and HSR accessibility. Our methodology assesses socioeconomic and spatial characteristics of mono-centric versus polycentric cities that may affect HSR accessibility. We show that low density polycentric cities such as Los Angeles and San Francisco are less attractive candidates for HSR than higher density more mono-centric cities such as Madrid or Barcelona, although a limitation of the methodology is the difficulty in determining an accurate radius for HSR's catchment area. The critical importance of urban spatial form on the accessibility of HSR reflects spatial patterns of population, employment and income across the metropolitan region. Policy makers and

transportation planners should give full consideration to urban structure and its effects on HSR competitiveness.

An alternative option, and one proposed in California, is to have numerous stations in each metropolitan area. However, having too many stations places a challenge in operating frequent and high-speed services. This issue was addressed in a separate study that compared and evaluated the eleven proposed HSR stations in the Los Angeles metro area by demography, employment and connectivity to mass transit (Zhong, 2011). The results show that Union Station and Anaheim HSR stations are best located in terms of their accessibility. Burbank, Norfolk, Ontario Airport, and Riverside HSR stations are the next best located stations, while the rest are significantly less accessible. Zhong recommended to downgrade the less accessible stations to commuter or urban rail stations and serve as feeders to the more accessible HSR stations. This 'blending' of intercity and inter-regional operations can maximize coverage of less densely populated metropolitan areas while still offering high-speed intercity performance between cities. Future studies could determine the optimal number of HSR stations to build in Greater Los Angeles, to maximize accessibility while maintaining competitive service speed and frequency.

Updating and improving rail services offers the possibility that an alternative urban structure may emerge that could be denser and more focused around transit-oriented development at nodal centres (Dittmar et al., 2004). Some argue HSR could be the means of 'sprawl repair' by re-centering both residential and commercial development and creating the opportunity to scale up from local to regional to inter-regional transportation needs. In fact the network model of many stations that is being proposed in California could promote such nodal development- attracting population and employment to a network of dense centres throughout the metro region. However, well designed plans for expansion of metropolitan and regional transit could achieve more powerful effects at much lower investments than HSR. 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: population, density, employment and income. Beyond these, future research should explore public investment alternatives, economic development impacts and implications for carbon footprint of HSR development. International experience suggests HSR is a costly and rigid approach to achieving such goals. Less costly and more flexible approaches to inter-urban transit that better utilize air travel, conventional rail, car sharing and bus travel may better match the polycentric urban form of US cities.

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## Appendix A.

### Sensitivity Analysis for Socio-Economic Variable Weights in the Aggregate Score Calculation

A sensitivity analysis was performed to test the weights of the four socio-economic variables used to calculate the aggregate score. In the original analysis, each of the four variables was given an equal weight of  $\frac{1}{4}$ . For the sensitivity analysis, the weights for the variables were changed to  $\frac{1}{3}$  for total population and employment, and  $\frac{1}{6}$  for population density and income level. The rationale is that absolute numbers (total population and employment, as base of potential passengers) are more important than relative numbers (population density and income level, as concentration of potential passengers and likelihood to travel long-distance) in terms of HSR station accessibility.

As a result of the new weights, the aggregate scores are now different from the original analysis; so are the estimated gradients. Table A-1 shows the gradients estimated with the new aggregate scores. Compared with Table 2 the changes are subtle and they do not change the relative conclusion that Spanish cities have a far more concentrated passenger base surrounding the HSR stations in the two metropolitan areas studied.

**Table A-1. New gradients estimated with aggregate scores based on altered weights in sensitivity analysis**

	Bay Area				
	Los Angeles	San Francisco	San Jose	Barcelona	Madrid
$\gamma$	0.00575***	0.00756***	0.00247***	0.03705***	0.04089***
R <sup>2</sup>	0.351	0.308	0.066	0.883	0.924

The aggregate scores fitted with the estimated gradients are graphed in Figure A-1 showing five curves representing the spatial trend of aggregate scores of the five cities with a major HSR station. As in the original gradients reported in Figure 7, Figure A-1 shows that the Spanish cities have much greater gradients, which means potential HSR riders are more concentrated in Spanish cities than in California cities.

**Figure A-1. Aggregate Score Gradient for HSR Accessibility of Study Cities (based on gradient estimates of the sensitivity analysis)**

