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# Catchment areas of high-speed rail stations: a model based on spatial analysis using ridership surveys

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This paper focuses on the spatial influence of High-Speed Rail stations, based on the notion of catchment area. Given the features of High-Speed Rail, its operations can and must serve a role beyond the station and the city in which it is located. Using a spatial systemic approach, this paper proposes a method to analyse the factors that may affect the size and shape of the catchment areas according to the relationship between distance and ridership. This study employs data from surveys of six stations of the Spanish high-speed rail system to apply the model and demonstrates that the context is crucial for regional use. The outcome also proves that other relevant factors should be considered in addition to the network to extend the use of high-speed services and increase its profits, which is a potential approach for future research.

***Keywords***: *catchment areas, High-Speed Rail, Spain, stations.*

## 1. Introduction

Recent economic trends induce a rationalized strategy for the development of transport according to sustainable principles in economic, social and environmental terms (EC, 2011). With regards to the structure of a rail system, the location of a station emerges as an important issue related to transport policy and strategies (Bertolini, 1999; Verhetsel and Vanelsander, 2010) and the resultant functioning of the services.

This issue is closely related to the number and location of the stations, which can be reduced and distributed to achieve the optimal configuration for a better advantage (Givoni and Rietveld, 2014; Connoly and Payne, 2004) with minimum cost. A consequence of the station's location will be the resultant area of influence and the shape and extent of the catchment area: the access to the station, which is important to the potential use of the train (Brons et al, 2009). A consequence is the relevance of the context for the usefulness of the station (Zempf et al., 2011).

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High-Speed Rail (HSR) requires substantial investments, was primarily conceived for long-distance connections, and was derived in a system that promotes fewer stops (stations) by taking advantage of speed and reducing the economic requirements. These requirements partially threaten the European Union's proposal of tripling the length of the HSR network to encourage the majority of medium-distance passengers to use HSR by 2050, which is part of the strategy for seamless door-to-door travel without curbing mobility (EC, 2011, p. 9).

The focus is on the HSR passenger who travels from the local city in which the station is located and a better understanding of the regional influence of HSR. This investigation will improve the capacity to address the goals proposed by European policy and the majority of investments.

Thus, a reinterpretation of HSR in regional terms is justified. This study contributes to the spatial analysis of HSR by reflecting on its potential usefulness in a regional scope and discussing the spatial role of HSR via the influence of the stations as nodes. It also introduces a debate about whether HSR can serve a regional role beyond the stations and the factors that may be relevant for this role by comparing the stations and facilitating performance assessments via the analysis of current ridership using a sample of stations in the Spanish HSR system. This analysis enables the identification of the limitations and the potential for future adaptations of services and policies. A framework to explore the relation of demand according to distance is proposed to shape the catchment areas of HSR stations. Using several ridership surveys, this paper examines the regional influence of HSR beyond local use and the factors that shape the catchment areas of a transport mode that is spatially constricted.

The paper is structured as follows: Section 2 discusses the topics of connecting HSR and catchment areas, which develops the background and literature on the analysis of catchment areas and the spatial implications of HSR. Section 3 presents the case study and data employed in the analysis. The analysis results are presented in Sections 4 and 5. Section 6 includes the conclusions and final remarks.

## 2. Spatial influence of HSR and the analysis of catchment areas

HSR services are intended to be medium- and long-distance connections. HSR stations are usually distant, despite the large variability of situations across countries, systems and within national networks. The distribution of stations along an HSR network is considerably smaller than any other land transport mode attached to termini. Long-distance connections and the reduced number of termini indicate that these termini may have a broader spatial effect that is probably larger than conventional rail stations. This idea establishes the basis of this paper: the spatial influence of HSR and its connection to the use of HSR stations.

### *2.1 Spatial implications of HSR at the regional level.*

Considering scale, HSR studies have focused on three different scopes of interest: local, regional and national within three different interpretations (Ureña et al., 2009). The local perspective is probably the most prominent perspective in the literature due to its strong relationship with urban planning and city strategies. The national approach is related to the new interurban relations and opportunities for an urban network (Garmendia et al., 2012). Our focus is the regional scale as an intermediate framework between the local scale and the national scale.

HSR infrastructures consume large portions of land and only provide service to urban nodes with a station. When cities are small and/or located in low-density areas, the connection between the station and the surrounding territory is poor. This territory, which is crossed by the line, receives all problems but does not benefit or integrate the network. Since the beginning of the HSR, the need to articulate these twofold (Plassard, 1991) or "two-speed" (Troin, 1995) territories to compensate its polarizing effects has become evident.

The phenomenon known as the tunnel effect has been identified by Gutierrez et al. (2006), Zamorano (2005) and the European Commission (1998). HSR enables a discontinuous, polarized and hierarchic territory that can only be reduced by improvements in regional connections (Plassard, 1991). HSR is a national or international infrastructure in which trains cannot stop as frequently as trains of conventional rail. The network needs to be completed by a secondary network (regional railways, regional bus services, and private cars), which would allow the intermediate territory to be revitalized and drawn together. In addition to the equity and territorial balance perspective, the need for secondary network connections for HSR has been identified by Gutierrez (2004) from the perspective of guaranteeing adequate traffic volume in the HSR network.

Zembri (2005) described the first initiative against the tunnel effect by the Department of Yonne in 1995 for the area located southeast of the Ile-de-France region by claiming direct HSR connections and adding stations to the line. However, one of the most ambitious strategies to reduce the tunnel effect is the strategy developed by the Regional Government of Nord-Pas-de-Calais due to the construction of the TGV Nord. This strategy consisted of three measures to reorganize regional railways—compensation, irrigation and articulation (Menerault and Barré, 2005)—and the introduction of HSR regional services (TER-GV). The necessity of strategies to diminish the tunnel effect and to increase the integration of HSR benefits and accessibility throughout the territory increases with the distance between stations.

Although HSR can modify the relative position of particular cities in the urban hierarchy, the dominance of the main national metropolis tends to be reinforced (Vickerman et al., 1999). The characteristics of HSR are incompatible with a homogenous territory and reinforce the centrality of the urban system. Thus, HSR has aroused many doubts regarding its regional role (Mannone, 1995). Specific case studies have analysed the HSR catchment area (Menéndez et al., 2002a; Garmendia et al., 2011). However, no network or systematic studies (considering an entire line or network) have addressed the real diffusion of the HSR, including the sizes and shapes of the catchment areas. Thus, no information about the regional influence of HSR can be derived.

### 2.2 *Catchment areas and ridership.*

The catchment area of a public transport station can be defined as the zone that provides services to travellers. This zone is closely related to the service area approach and represents the core of seminal geographical studies, such as Christaller's Central Place Theory or contributions by Lösch (Malczewski, 2009). The empirical approach to the issue has been depicted by two main viewpoints: as a consequence of the market potential (Niérat, 1997; Maertens, 2012) or the interest in the spatial configuration of the influence (Anderson and Landex, 2008). This paper is linked to the second approach.

A catchment area is substantially dependent on distance and how far people are willing to travel to obtain access to a certain service (Guerra et al., 2011). The simplest method for defining service areas is to define a circular Euclidean buffer around a station (Parsons Brinckerhoff, 1996; Upchurch et al., 2004); this method has been extensively applied. Despite the strong scepticism about buffering regular areas around the stations, this method remains prevalent in many studies as an initial approach to the issue. The majority of these studies note the lack of accuracy when measuring and defining catchment areas due the disregard for real network distances to a station (Gutiérrez et al, 2011) and obstructions (Landex et al. 2006) and the lack of consideration of other variables that may affect the spatial distribution of users (e.g., trip purpose, parking facilities, gender, land use, safety, and conditions; Guerra et al., 2011; Chakour and Eluru, 2014). In addition to distance, the spatial context of the station is as important as the functionality of the mode. The notion of catchment area connects with the concept of ridership, which is a derivative of demand.

In the urban framework, studies usually propose a range of influence from 600 to 1,200 m with access by foot (Parsons Brinckerhoff, 1996). These thresholds are not applicable to HSR, as this mode is intended to serve a national role in long- (and medium-) distance travel, which may affect the scale of influence and extend the area of analysis beyond the city in which the station is located. The spatial approach is more convenient for the analysis of HSR stations, especially for medium or small cities for which HSR is probably the only choice for long-distance travel.

Focusing on rail stations, the literature presents different empirical studies about the relationship between stations and ridership. First, studies that discuss users have proven the correlation between demand and different variables, which demonstrates that a station's catchment area extends beyond the issue of distance and is highly influenced by spatial features (Ewing and Cervero, 2010), such as socioeconomic and transportation-related features (Kuby et al., 2004; Debrezion et al., 2009; Givoni and Rietveld, 2014). These analyses are usually framed using an urban/metropolitan scale; however, the relationship between context and station is crucial in understanding the functionality of the latter. A more extensive scope of these considerations creates a more extensive viewpoint about the area of influence as a spatial system, in which different aspects may affect the use of the station: the context of the station, including population (size, density, and income) and structural elements of the station (Brons et al., 2009). Indicators such as population, jobs or centrality (in terms of the urban network structure) exert a significant effect on the size, concentration and composition of the catchment areas (Zempf et al., 2011).

Second, from a station point of view, some studies have highlighted the relevance of different factors that affect the profile of the stations and how this profile affects the subsequent use of the terminals, which emphasizes the convenience of categorizing according to different factors (Zempf et al., 2011). The potential regional use of HSR stations can be affected by two main factors: the location in the city and the positioning along the network. Locating the station (central, edge or nearby) was extremely important when using the station (Menéndez et al, 2002b). Edge locations were traditional in cities that implemented rail for the first time; the evolution transformed these positions into central locations as cities grew. However, HSR introduced locations far from city centres for different reasons, such as sharing a station (Haute-Picardie, France) or avoiding detours in the configuration of a line, which would decelerate many of the operations (e.g., Macon and Vendôme, France).

### *2.3 Spatial approach to the analysis of catchment areas.*

From a regional viewpoint of the issue, the station location will influence the ease of access for different users, such as modal access to the terminal or the effect of congestion on central locations. The network position of the station can also influence the catchment area. This variable demonstrated the strong effect on subway and light rail services (Kuby et al., 2004) when they are intermediate, terminal or even run as hubs for different lines. Regarding the special conditions of HSR, the influence may derive from the case of terminal stations, which enlarges their area of influence in the opposite direction from the network. Intermediate stations will be affected by potential overlaps if they are sufficiently close. The proximity between stations or the appearance of a new station may influence the demand for station use (Blainey and Preston, 2013) and reduce their catchment area.

A catchment area can be defined as a function that is dependent on distance (Fig. 1a). Studies have proven that demand decays with distance and that the application of decay functions enables better adjustments to the ridership estimation models (Gutierrez et al., 2011), which seems to prove the results from previous sections. Our proposal introduces two different distance decay functions to analyse the distribution of the ridership. The power decay function (Fig. 1b) has been one of the most prevalent functions since the seminal work by Hansen (1959) and reflects how demand rapidly diminishes with distance. The log-logistic decay function, which also frequently appears (Bewley and Fiebig, 1988), is linked with accessibility analysis or spatial interaction models (Reggiani et al., 2011); its shape (Fig. 1c) shows a more constant demand in short distances and a more pronounced reduction for medium and long distances.

Potential areas analysed by distance functions are usually distorted with situational impacts that distort the expected effect of distance (Landex et al., 2006). We consider two different distortions: barriers and modulators. The spatial context of a station may introduce the effect of barriers, which are elements that limit the expected configuration of a catchment area. They can be absolute (a topographic constriction; Fig. 1d) or relative, which are more common.

Transport networks and infrastructures serve a crucial role in HSR demand. Moreover, in a regional scope, the use of a complementary transport mode is essential. In this case, complementary modes can show ambivalent profiles: reduction of the potential use of HSR (barriers) and distortion of the foreseeable configuration of the catchment areas (modulators).

In some cases, a motorway may feed a corridor towards an HSR station, which increases its regional effect (Fig. 1g); in other cases, it can reduce the effect by eliminating potential passengers (Fig. 1f). The competition with other alternatives may limit the extension of the influence of HSR.

A similar effect on rail with two different situations is observed. Along the rail line, the locations of the stations may affect the extent of the catchment areas; proximity can reduce the areas of influence (Fig. 1e).In a different configuration, the availability of stations can originate a tunnel effect along the railway line towards the HSR stations (Fig. 1h). This effect may occur when conventional and HSR services are conveniently combined. These network effects have been added to the analysis under the category of modulators as its potential impact usually distorts the expected effect of distance in a positive manner.

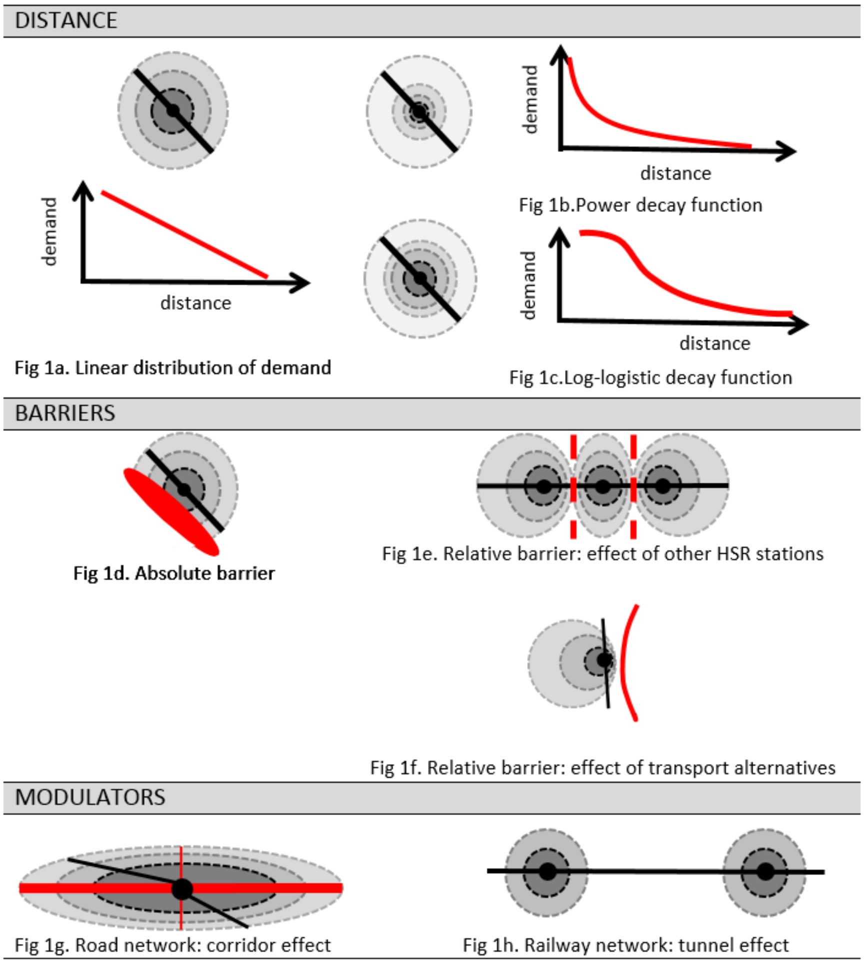
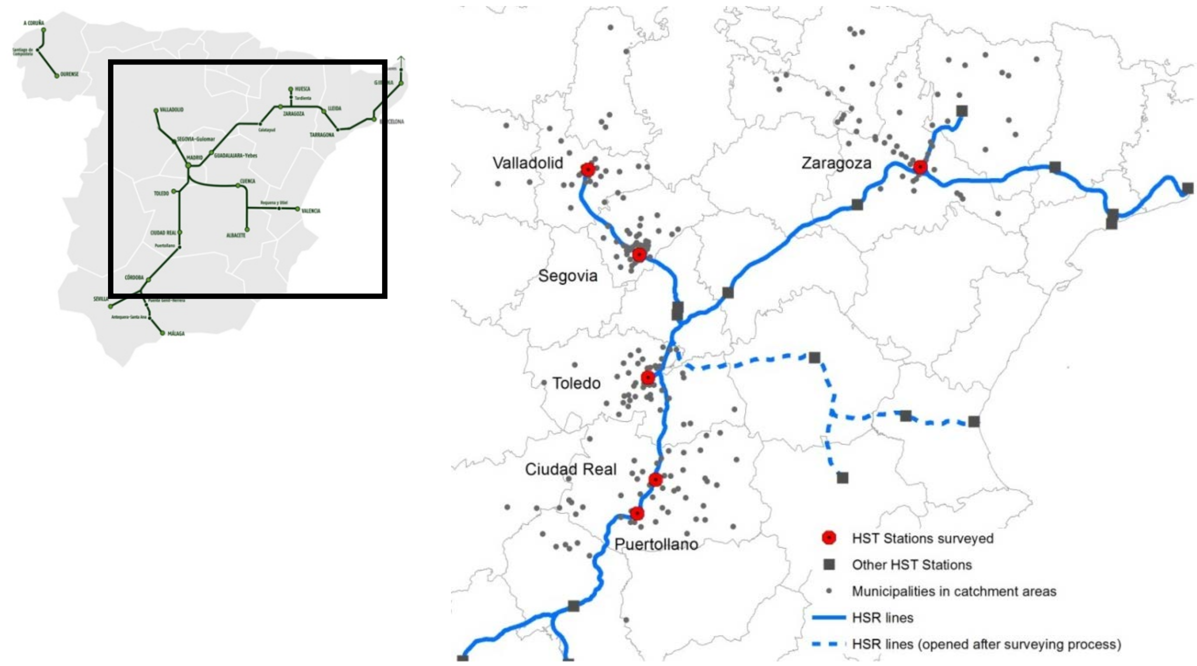



*Figure 1. Spatial approach to the analysis of catchment areas. Source: own elaboration.*

## 3. Case study and data

The Spanish HSR system, which exhibits a tree-shaped structure, is centred in Madrid and spreads towards the periphery, where Barcelona, Valencia and Seville are the main endpoints of the lines. The selection of the case study was determined by the available data, which are circumscribed to a ridership survey that was performed via a research project that is focused on analysing the role of intermediate cities in the HSR system. The result is a sample of six HSR stations (Fig. 2); 40% of the stations that were available when the survey was performed (15 stations). This sample is based on medium and small cities, with fewer options for long-distance travel; thus, they are expected to serve a more significant role in a larger scope than large cities and metropolises, in which HSR is one option.

In the sample, we include a variety of situations. As the HSR network has been developed from the centre and connects the main peripheral cities (Seville, Barcelona, Valencia), the analysed stations are not located far from the centre (Madrid) with intermediate locations within the urban system and different network positions, regardless of whether they are terminal (Toledo, Valladolid) or intermediate (Zaragoza, Segovia, Ciudad Real and Puertollano). These cities serve an administrative role as regional capitals (Zaragoza, Valladolid and Toledo) or provincial capitals (Segovia and Ciudad Real).




| | Station location | Network position | Population (HSR city)* | Starting operations | Comments |
|---|---|---|---|---|---|
| **Zaragoza** | Central | Intermediate | 679,624 | 2003 | Large regional capital halfway between Madrid and Barcelona |
| **Valladolid** | Central | Terminal | 311,501 | 2007 | Regional capital |
| **Segovia** | Nearby | Intermediate | 54,844 | 2007 | World's heritage city with a growing tourist profile. Near Madrid |
| **Toledo** | Edge | Intermediate | 84,019 | 2005 | Regional capital and world's heritage city with a combined administrative and touristic profile. Near Madrid. |
| **Ciudad Real** | Edge | Intermediate | 74,921 | 1992 | Small provincial capital in the first HSR Spanish line. |
| **Puertollano** | Central | Intermediate | 51,997 | 1992 | Similar to Ciudad Real with a more industrial labour profile. |

*Figure 2. Case study. Source: * www.ine.es; own elaboration.*

Background data have been computed in a geodatabase to combine information related to the stations and connect the HSR configuration with road access to these stations. The GIS (geographic information system) layers are developed as follows:

- Road network: Enables the calculation of ideal travel times towards stations by car. This layer was computed to construct an origin-destination matrix based on estimated maximum speeds of the road system with the following segmentation of stretches: motorways, national roads, regional roads, local roads, ring roads and streets. The latter category only includes access to the stations inside the urban area.
- HSR network: Includes both line and station. However, data on the latter are more important for analysis, as the configuration of the line is less relevant than the terminals, e.g., information related to the conditions of available service and other transport considerations, such as transit connections, interurban buses or available conventional rail.
- Municipal cover (point level): Includes two sensitive factors for the analysis: location and population.

The results derived from on-board ridership surveys are crucial data. These surveys were designed to analyse the use of the Spanish HSR and have been reinterpreted to satisfy the objectives of this study. They were conducted during different periods between April 2008 and December 2009; depending on the station, they were conducted on board every train in a single labour day. The survey has two main sections. The first section was oriented to define the user's profile and included questions related to age, labour situation, travel origin and destination, travel purpose, frequency of travel and the access mode to the HSR station. The second section exclusively addressed the commuters to determine the declared preferences of this type of user; however these data were not employed in this study.

Although the surveys were not designed to evaluate and measure demand, they are sufficient for examining the distribution of the user's origins within each HSR station.

## 4. External use of stations: factors and interpretation

This paper focuses on the spatial analysis of ridership surveys and employs distance as the main variable to determine how the results are distributed. The objective is twofold: assess the possible factors that affect the use of HSR stations and establish a station profile that enables interpretation of the second part of the method, which depicts the demand on the territory and analyses its distribution pattern.

Based on different studies about station features, we have constructed a table of characteristics (Table 1) that are clustered into different factors, including a preliminary analysis of the ridership survey and other variables that may affect the use of a station. Users and external relations conclude the surveys. The variable of external users is expressed as the percentage of passengers that originate from municipalities outside of the HSR city.

The surveys show that the range of users extends from nearly 700 passengers (Segovia, Puertollano) per day to 1,500 (Zaragoza) passenger per day with varying spatial distributions. We examine the external users, who originate in a city outside of the HSR city. These users establish the regional use and define each catchment. The maximum distance ranges from 62 km. for Segovia to 187 km. for Zaragoza, and the average distance is approximately 140 km. of travel time towards the station. The main users originate in the HSR cities, whereas the percentages of external use vary from 15% to 33%, which demonstrates different levels of regional use.

The first approach to the analysis of the catchment areas is to decompose the ratio of external users in quartiles according to distance to obtain three distance thresholds: 16, 35 and 75 km for the first quartile, the second quartile and the third quartiles, respectively. The first belt (16 km.) comprises approximately 70% in three stations and 50% in another station, which demonstrates that proximity is the crucial factor in these cases. The opposite situation is worth mentioning: Zaragoza holds 66% of its external demand in the fourth quartile, which are the more distant positions inside the catchment area.

Table 1 lists a set of variables that are linked to factors that may explain the external use of the HSR stations. The factors have been selected according to similar approaches to rail stations and urban transit (Kuby et al, 2004; Gutiérrez et al, 2011) and are adapted to this specific case of HSR and extensive regional areas of influence.

We consider two meaningful variables to assess the station characteristics: the distance from the station to the city centre expresses the location of the station and evaluates the three positions noted in the literature (central, peripheral and nearby; Menéndez et al, 2002b). The second variable is a Boolean expression for the network position of the station, where 1 indicates a terminal station and 0 indicates an intermediate station.

To analyse services, we introduced a single variable: the total number of stopping HSR trains. Note that the range of services is also considerable—from 9 services to 43—which reveals different situations.

A factor referred to as intermodality introduces the level of connectivity of the stations using two dummy variables that show the availability of conventional rail and/or bus (1 if positive or 0 if these services are not available).

**Table 1. HSR station characteristics and ridership results**

| Factors | Variables | | Zaragoza | Cum. | Valladolid | Cum. | Segovia | Cum. | Toledo | Cum. | Ciudad Real | Cum. | Puertollano | Cum. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Users* | Max (local) | | 1,210 | | 923 | | 462 | | 1,270 | | 1,491 | | 551 | |
| | Total | | 1,434 | | 1,063 | | 690 | | 1,682 | | 1,937 | | 697 | |
| | Mean | | 24.3 | | 32.2 | | 15 | | 9.4 | | 43.1 | | 30,3 | |
| | S.D. | | 155.8 | | 160.0 | | 67.7 | | 14.5 | | 229.0 | | 113.9 | |
| | External users | | 224 | | 140 | | 228 | | 412 | | 446 | | 146 | |
| | % external users | | 15.6 | | 13.2 | | 33.1 | | 24.5 | | 23.0 | | 20.9 | |
| External relations* | Number (no. municipalities) | | 59 | | 33 | | 46 | | 44 | | 42 | | 23 | |
| | Max distance (km.) | | 187 | | 186.7 | | 61.8 | | 123.9 | | 144.3 | | 160 | |
| | % users within distance thresholds | IQ: 16 km | 13.4 | 13.4 | 73.6 | 73.6 | 79.3 | 79.3 | 69.7 | 69.7 | 33.2 | 33.2 | 50.7 | 50.7 |
| | | IIQ: 35 km | 8.9 | 22.3 | 2.9 | 76.5 | 15 | 94.3 | 20.1 | 79.8 | 41.7 | 74.9 | 4.8 | 55.5 |
| | | IIIQ: 75 km | 11.6 | 33.9 | 15 | 91.5 | 5.7 | 100 | 8.3 | 98.1 | 13.7 | 88.6 | 11.6 | 67.1 |
| | | IVQ: max dist | 66.1 | 100 | 8.5 | 100 | --- | --- | 1.9 | 100 | 11.4 | 100 | 32.9 | 100 |
| Station characteristics** | Distance to centre | | 3.5 | | 1.3 | | 4.7 | | 1.7 | | 1.3 | | 0.4 | |
| | Terminal (1=yes) | | 0 | | 1 | | 0 | | 1 | | 0 | | 0 | |
| Services*** | Daily operations | | 43 | | 30 | | 23 | | 9 | | 29 | | 27 | |
| Intermodality*** | Bus (1=yes) | | 1 | | 1 | | 0 | | 0 | | 0 | | 1 | |
| | Rail (1=yes) | | 1 | | 1 | | 0 | | 0 | | 1 | | 1 | |
| Socioeconomic1 | Population (catchment area) | | 1,420,613 | | 625,932 | | 110,986 | | 404,674 | | 432,921 | | 204,738 | |
| | Population (HSR city) | | 679,624 | | 311,501 | | 54,844 | | 84,019 | | 74,921 | | 51,997 | |
| | Polarization (HSR/catchment) | | 47.8 | | 49.8 | | 49.4 | | 20.8 | | 17.3 | | 25.4 | |
| | No. municipalities | | 59 | | 33 | | 46 | | 44 | | 42 | | 23 | |

Sources: * Ridership survey, ** Calculations by the author, *** Renfe, 1 INE (www.ine.es)

The last factor is devoted to the socioeconomic variables and envisages the spatial settlement. The population in the catchment areas ranges from 200,000 inhabitants to 1.2 million inhabitants. The size of the HSR cities can be divided into two groups: medium cities (Zaragoza and Valladolid) and small cities. The effect of the polarization of each area is a variable that may affect the external use of the station.

To explore the influence and test the variables, an analysis of statistical significance among the explanatory factors is conducted and bivariate correlations among the variables are determined. The correlation coefficients in Table 2 show the significance of some variables, with minimal adjustment of the independent variables to explain the ratio of the users. This finding is partially attributed to the circumstances of the study due to the nature of the HSR services and travellers. As these services are high-quality services offered for medium and long distances, their use cannot be interpreted using the same parameters as urban transit. Stations are typically distributed and their catchment areas entail a large range of territory, in which similar factors may have different effects. For example, a motorway can be employed to feed a station or to reduce the potential demand of rail. Demand is less constricted to a predictive model. The survey conditions do not enable demand to be modelled; however, this analysis but would be necessary if a larger number of respondents participated in the survey.

**Table 2. Matrix of bivariate correlations among variables in the catchment area**

| | | Ratio of users | Distance to HSR | Motorway | Railway | Roadways | Distance HSR-centre | Intermodality | Terminal | Trains | Population | Polarization | Settlement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ratio of users | Users/1000 inh. | 1 | | | | | | | | | | | |
| Distance to HSR | km. | -,244** | 1 | | | | | | | | | | |
| Motorway | On origins (yes=1, no=0) | ,083 | -,099 | 1 | | | | | | | | | |
| Railway | On origins (yes=1, no=0) | ,039 | ,122 | ,381** | 1 | | | | | | | | |
| Roadways | nº of roads | ,182** | ,205** | ,373** | ,429** | 1 | | | | | | | |
| Distance to centre | m. | ,233** | -,059 | -,001 | ,031 | -,134* | 1 | | | | | | |
| Intermodality | Of HSR station (yes=1, no=0) | ,199** | ,393** | ,090 | ,225** | ,085 | -,125* | 1 | | | | | |
| Terminal | yes=1 | -,087 | -,165** | ,124 | -,120 | -,110 | -,427** | -,055 | 1 | | | | |
| Trains | nº of trains | ,115 | ,398** | ,099 | ,272** | ,216** | ,244** | ,712** | -,587** | 1 | | | |
| Population | inh. | ,240** | ,425** | ,175** | ,227** | ,159* | ,189** | ,662** | -,154* | ,761** | 1 | | |
| Polarization | % HSR city in the area | ,129* | ,079 | ,095 | ,139* | -,085 | ,686** | ,500** | -,150* | ,527** | ,378** | 1 | |
| Settlement | nº of municipalities | -,027 | ,173** | ,112 | ,102 | ,041 | ,696** | ,013 | -,310** | ,428** | ,695** | ,357** | 1 |

*. Correlation is significant at 0,05 level (bilateral).
**. Correlation is significant at 0,01 level (bilateral).

Table 3 lists the correlations among the variables and the ratio of users, which are segmented in distance quartiles. The closer the station is, the higher the adjustment is; the explaining capacity of the variables decreases as we move to the periphery of the catchment areas.

Distance, which is the most consistent variable, the distance from the station to the city centre and the size of the catchment area are the three variables that exhibit better adjustment for the sample. Other variables with fair adjustment are the intermodality and the number of daily trains in the HSR station; these variables exhibit a sharper decline with distance.

The distance to the station is the most reliable variable within the context in which a ridership model would probably not be useful for two reasons: data are not reliable and the use of HSR is probably beyond the scope of predictive models.

This ambivalence of some factors may partially explain why some correlations are lower than expected or not significant. For example, the availability of a rail station at the origin, which in some cases feeds the HSR station and can reduce the potential demand in other cases. Using spatial analysis, we can envisage the configuration of the areas of HSR influence.

**Table 3. Bivariate correlations between independent variables and the ratio of users, and distance thresholds within the catchment area**

| | | I Q 16 km | II Q 35 km | III Q 75 km | IV Q All |
|---|---|---|---|---|---|
| Distance to HSR | km. | -,384** | -,314** | -,211** | -,244** |
| Motorway | On origins (yes=1, no=0) | ,233 | ,161 | ,146* | ,083 |
| Railway | On origins (yes=1, no=0) | ,051 | ,120 | ,110 | ,039 |
| Roadways | nº of roads connecting origin | ,303* | ,180* | ,244** | ,182** |
| Distance to centre | m. | ,333** | ,334** | ,311** | ,233** |
| Intermodality | yes=1 | ,616** | ,368** | ,249** | ,199** |
| Terminal | yes=1 | -,249 | -,212* | -,173* | -,087 |
| Trains | nº of trains | ,441** | ,198* | ,122 | ,115 |
| Population | inh. | ,595** | ,440** | ,321** | ,240** |
| Polarization | % HSR city in the area | -,107 | ,116 | ,152* | ,129* |
| Settlement | nº of municipalities | ,028 | -,019 | -,006 | -,027 |

*. Correlation is significant at 0,05 level (bilateral).
**. Correlation is significant at 0,01 level (bilateral).

# 5. Distance and regional use of HSR: shaping catchment areas

Figure 3 shows the first outcome connecting results and spatial analysis. The size, extension and configuration of the catchment areas are shown using cartography, and each area is highlighted according to the proportion of external users. Table 1 reveals the considerable range of potential sizes for the areas, which are quantitatively expressed as the maximum distance of travel towards the station.

Extracting some findings from this circumstance, the two larger areas (Zaragoza, Valladolid) show a lower level of regional use, whereas the smallest area (Segovia) shows the greatest external use of the sample. These three cases have the same level of polarization and settlement structure (approximately 50%, Table 1). Thus, the size and level of external use are not directly related, which supports the idea that station location serves a key role in the subsequent functionality of the station (Menéndez et al, 2002b) as Segovia is the station that is located at a greater distance from the centre. It is located outside the urban built environment, which favours a regional use. Edge stations are more likely to promote both local use and external use as they combine sufficient access for both the local scale and the regional scale. Therefore, station location is a factor that affects the external rates.

Proximity is also a factor to consider. The limits tend to be established according to the two stations (Ciudad Real and Puertollano) and distinctly overlap due to their proximity (nearly 45 km). In the southern part of the sample, the east-west configuration of the frames suggests the relative barrier of other stations (Fig. 1e). Valladolid and Segovia also overlap but in lower proportion.

Figure 3 shows the absolute barriers to the topographic configuration in two cases—Segovia and Valladolid—at their southern limit and northern limits, respectively, partially in the northeast-southwest alignment in the case of Zaragoza. The limits between Toledo and Ciudad Real and the southern edge in Puertollano are less distinct but are visible (likely due to the tunnel effect.

Topographical constraints are relevant when theoretically defining catchment areas; however, the spatial frames derived from the surveys show the limits in this case.

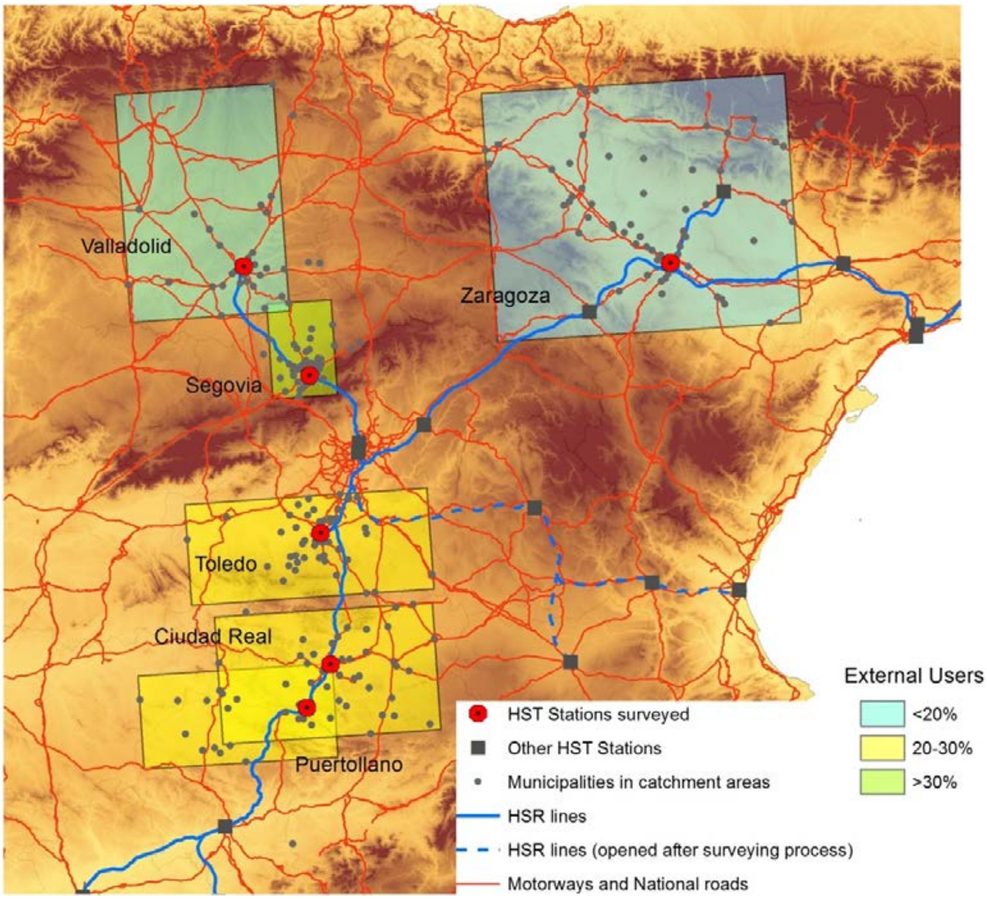



*Figure 3. Extension of catchment areas and external use. Source: CNIG, own elaboration.*

### *5.1 Profile of stations according to distance and ridership*

Regression analyses using distance decay functions produce uneven results for the correlation of ridership according to distance (Table 4). As demonstrated by Tables 2 and 3, the role of distance in the configuration of demand is significant with reduced statistical adjustment for the entire sample. The heterogeneity of the situations indicate that a specific regression for each station may provide additional insights.

**Table 4. Coefficient $R^2$ of different regressions using log-logistic and power decay functions (dependant variable: users, independent variable: distance)**

| | **Log-logistic decay** | | **Power decay** | |
|---|---|---|---|---|
| | Total | < 30 min. | Total | < 30 min. |
| Zaragoza | 0.0978 | 0.0257 | **0.2183** | 0.0636 |
| Valladolid | 0.3724 | 0.3968 | **0.5036** | 0.6357 |
| Segovia | 0.4169 | = | **0.7069** | = |
| Toledo | 0.7389 | 0.8348 | **0.7863** | 0.7923 |
| Ciudad Real | **0.5035** | 0.5964 | 0.382 | 0.3507 |
| Puertollano | **0.7507** | 0.582 | 0.5438 | 0.2771 |

The decline in demand according to distance differentiates both distance decay functions. The majority of the stations show a significant decrease in ridership with distance, which indicates enhanced performance with the power decay function. The remaining two stations (Ciudad Real and Puertollano) yield better adjustment with the log-logistic decay function, which reveals that their catchment areas experience a smoother decay in demand in the proximity of the station.

The adjustments are reasonable in general terms but exhibit noticeable differences. Zaragoza does not fit in this analysis according to Table 1, which indicates that its main demand is located beyond the third distance threshold of 75 km. Valladolid and Ciudad Real also show little adjustment—barely above 0.5 in the best performance—which requires the need to employ other factors for a better understanding.

Given that HSR services are scarce in the territory, especially in the case studies, we assumed that some distant cases may distort the results of the regressions. However, the relationship between ridership and distance is coherent given that reducing the sample to closer areas does not substantially improve performance (<30 min column). Only Valladolid accounts for the better performance in the threshold of 30 minutes.

Performance diminishes in two cases: Zaragoza and Puertollano. The explanation of the small adjustment in the first case is beyond this reasoning but the adjustment of Puertollano is much worse in the threshold compared with the entire sample. This finding is probably caused by the overlap between the catchment area of Puertollano and the catchment area of Ciudad Real, which distorts the similar demand in Puertollano.

### *5.2 Shaping HSR catchment areas*

Representing the results of surveys using maps, including background information, enables deepening of the spatial configuration and a contextual approach to the problem. Due to the size of the resulting maps, the maps have been placed in the appendices, where they can be easily consulted; a brief summary is included in Table 5).

As the scope of analysis includes regional extensions, contextual factors such as topography will have a considerable effect in some cases (Segovia and Zaragoza, Figs. 5 and 7, respectively). However, the main factor that affects the shape of the catchment areas along the entire sample of stations is the distribution of other HSR stations. In this case, the barrier effect can be absolute (between Toledo and Ciudad Real, Figs. 8 and 9, respectively) or relative, as in the case of Ciudad Real and Puertollano (Fig. 10), whose respective catchment areas overlap.

The effect caused by transport networks is diverse. HSR stations with conventional rail services show a profile of intermodality that may lead to situations in which regional trains feed HSR trains and create a tunnel effect inside the catchment area along the conventional rail line (as in the case of Zaragoza, Fig. 5 and Valladolid, Fig. 6). In these cases, the conventional rail serves as a secondary network of the HSR.

Roads can create a similar situation when connections are complementary and roads and HSR do not compete. This feeding role by motorways appears in some cases—in local configurations around Zaragoza or in the case of Toledo (Fig. 8). A different effect appears by competition between modes when roads and the HSR link similar nodes and/or follow similar directions. This situation occurs in the eastbound direction in the Toledo, Ciudad Real and Puertollano areas. In these two latter cases, a motorway that connects both cities enables their respective areas to overlap and share a common space of influence, which included places that contain passengers travelling through both stations.

Regarding the extensive range of results and interpretations, factors are dependent on specific contextual configurations, which highlights the relevance of the urban network. These results suggest an in-depth analysis for each case with the objective of creating robust connections between spatial configuration and HSR ridership.

Assessing the results of the proximity shown in Table 5, the size and shape for each case can be compared. First, the primarily concentrated catchment areas appear in Segovia, Toledo and

Valladolid, where the majority of the users (80% of external use) originate in municipalities that are located less than 13 min away by car. Conversely, more than 70 minutes of travel time is required in Zaragoza to encompass 80% of external use. Some municipalities that are located far from the HSR station benefit from the satisfactory connections with Zaragoza, either by conventional rail or private car. However, this finding must be carefully considered, as it yields the lowest regional use, which demonstrates the prominence of the central city on a regional scope. Ciudad Real and Puertollano are placed in an intermediate situation.

**Table 5. Summary of results**

| | **Distance** | | | **Shape** | |
|---|---|---|---|---|---|
| | *Dprox** | *Dmax*** | *Decay adjustment* | *Barriers* | *Modulators* |
| **Zaragoza (Fig. 5)** | 73,6 | 93,6 | Power | Other HSR stations | Feeders: motorway, conventional rail |
| **Valladolid (Fig. 6)** | 12,6 | 87,7 | Power | Other HSR stations | Terminal station<br>Feeder: conventional rail |
| **Segovia (Fig. 7)** | 7,6 | 33 | Power | Topographic barrier<br>Other HSR station | |
| **Toledo (Fig. 8)** | 12,2 | 60,8 | Power | Other HSR stations<br>Road alternative | Corridor effect<br>Tunnel effect |
| **Ciudad Real (Fig. 9)** | 25,6 | 97,7 | Log-logistic | Other HSR stations<br>Road alternative | Tunnel effect |
| **Puertollano (Fig. 10)** | 57,7 | 111 | Log-logistic | Other HSR stations<br>Road alternative | |

**Dprox*: Travel time to HSR station, which encompasses 80% of regional use (minutes)
***Dmax:* Maximum travel time obtained from surveys (minutes)

Depicting the ridership's decay functions with an equivalent time threshold enables the comparison between the sizes of the catchment areas, and its relation with distance explains the different identified situations (Fig 4).

In general terms, demand is unequally distributed, in terms of both quantity and distance covered. Catchment areas with very different extensions are compared; they range from small catchment areas, in the case of Segovia (slightly higher than 30 min of travel time), to larger catchment areas, such as Zaragoza or Puertollano (90-100 min of maximum travel time). The demand is generally large until approximately 15 min of travel time, with a subsequent sharp decrease.

The case of Zaragoza stands out; it shows the lowest adjustment, and its distribution of demand according to the distance seems to include different patterns. Fig 5 suggests the influence of conventional rail feeding the HSR station.

Other cases, such as Puertollano and Ciudad Real, present a low level of adjustment, as no symmetry is observed in the shape of their catchment areas. In Ciudad Real, the western part of the catchment extends its influence to 100 min of travel time, whereas the presence of the alternative station of Puertollano in the south, the motorway A4 in the east and the tunnel effect in the north reduce the extension of the catchment area to 30 min in these directions.

The best adjustment occurs in Toledo, which presents the smallest catchment area without distorting elements, with the exception of the metropolitan area of Madrid. Below the limit of 30 min of travel time, the correlation with both functions increases as it approximates to an ideal case.

Barriers are relevant factors that determine the size of the catchment areas, whereas modulators are relevant in the subsequent configuration with a more distributive impact in the relation between distance and demand and the adjustment of ridership decay functions.

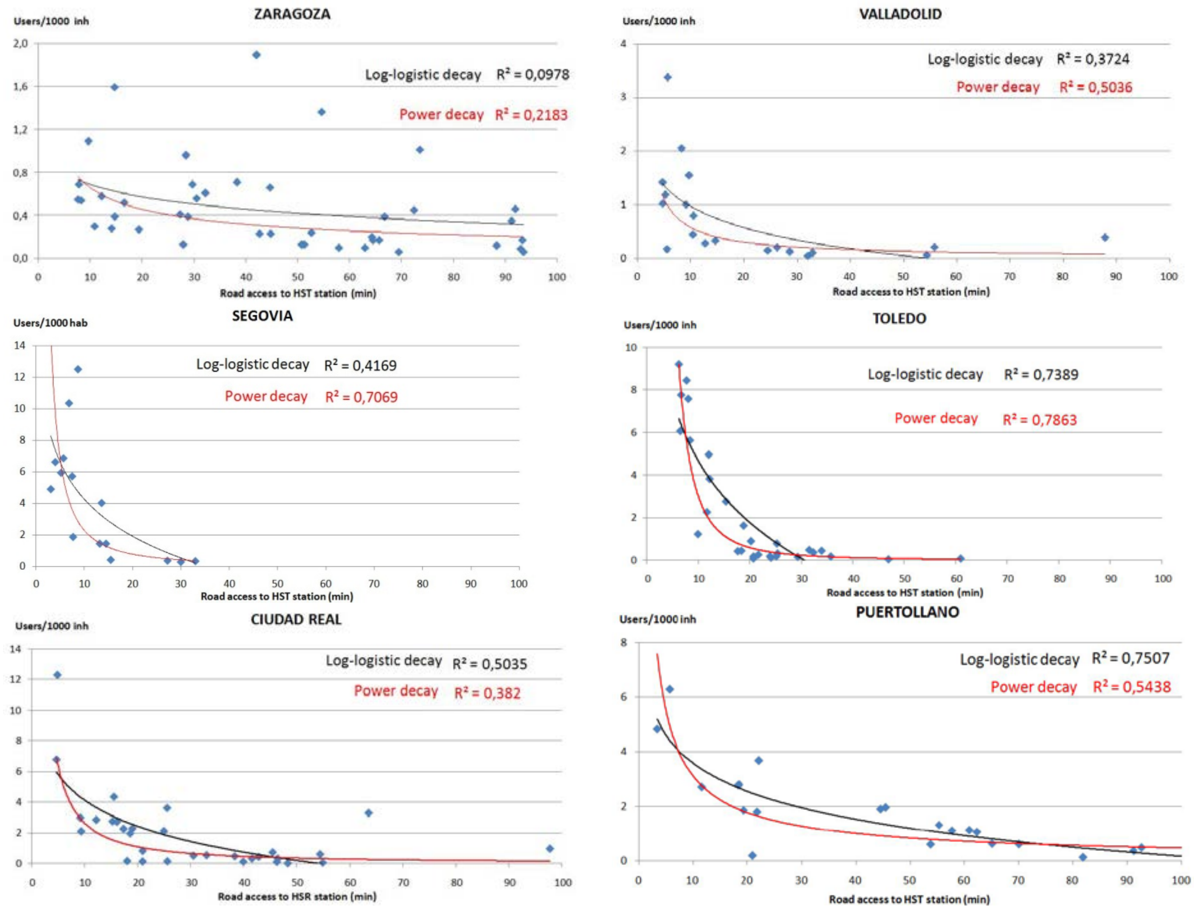



*Figure 4. Ridership's decay functions for HSR stations*

## 6. Conclusions

This study highlights the relevance of the spatial configuration and context when analysing the HSR stations catchment areas. HSR is an anchored transport mode that is intended to connect medium- and long-distance stations with catchment areas that generally involve an extensive range of territory; their spatial influence may be affected by very different factors. A comprehensive analysis of the regional influence of the stations will boost the usefulness of the HSR and its feasibility.

Due to the nature of the HSR system, it cannot be constricted to a predictive model. As expected, distance is the most consistent variable when conducting a bivariate analysis of station external users. The main results show a better adjustment of the relation between distance and the external use of HSR stations in medium and small cities. Conversely, larger cities in the analysis distort the effect of distance as the level of services generates more attraction, whereas the share of external users is lower due to higher local demand.

However, the empirical analysis demonstrates that the structure and shape of catchment areas may be significantly affected by other elements, which are assessed in this paper via a spatial analysis of the HSR area of influence and its configuration. For instance, the proximity between two HSR stations can generate overlap in the areas of influence that condition their configuration (the cases of Ciudad Real and Puertollano). In addition, the presence of other transport networks may generate two contradictory effects: they can offer an alternative for travel, diminish the use of an HSR station and limit the extension of their catchment area, or they can cooperate with the HSR service and feed the station. In the latter case, a conventional railway that feeds an HSR station will produce isolated points of demand in the territory, which are located in each station, and distort the correlation between users and distance, as in the case of Zaragoza. This finding sparks an interesting debate about intermodality and modal coordination. Unfortunately, the available data do not enable an investigation of these factors and new data and surveys; all stations would help to move forward in such rationales.

These factors have different consequences in the catchment area configuration depending on the context and the characteristic of the station, which hinders a systematic analysis by modelling variables. Therefore, the spatial analysis and its interpretation may offer a better understanding of the regional effect of HSR stations and their influencing factors.

This study creates an important opportunity to improve the usefulness of HSR by introducing transport policy measures that facilitate coordination. Exploring these factors and its relation with HSR demand would be an interesting study in relation to policy goals, both at the national level and the European level, as a reduction in HSR development is proposed. In this context, HSR must be examined beyond the station for better optimization of investments and to justify forthcoming funding efforts. Depending on a regional influence and the use of these long-distance services must implemented in reports and planning documents.

Another interesting consideration is the direction for future studies. Once the relevance of different factors has been proven, the addition of variables to contrast with ridership will produce interesting results and enable a qualitative analysis of the resultant structures. In addition, the focus on different factors that configure the profile of the stations should enhance the analysis.

## Acknowledgment

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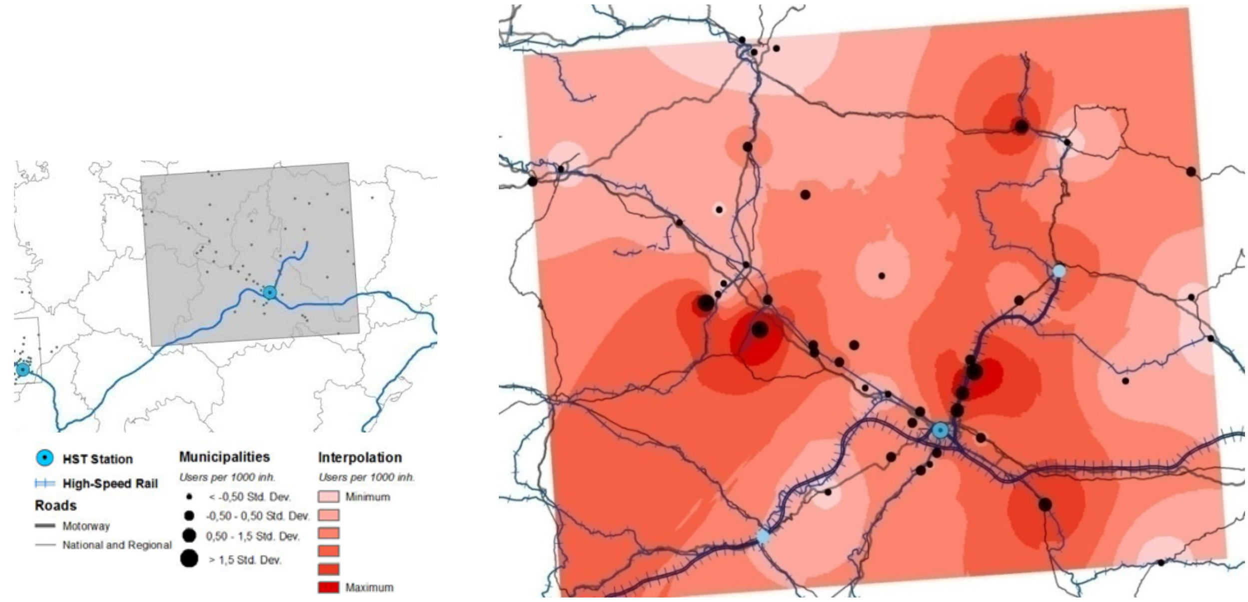
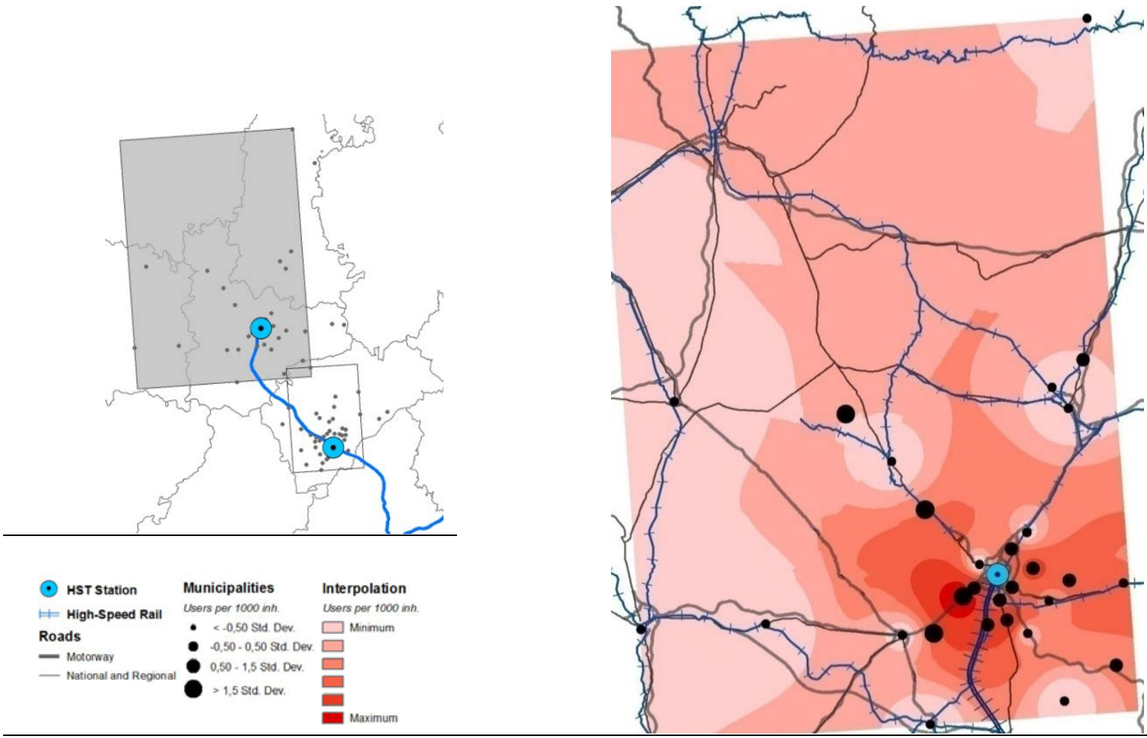
# Appendix A: Catchment areas of HSR stations




**Comments**

HSR stations in close proximity limit the influence towards the southwest (Calatayud) and east (Lleida).
Conventional rail serves as a feeder, which creates a tunnel effect inside the catchment area.
Accesses to the city generate the corridor effect.
In addition to distance, the distribution of the population and urban network configurations may serve a crucial role.

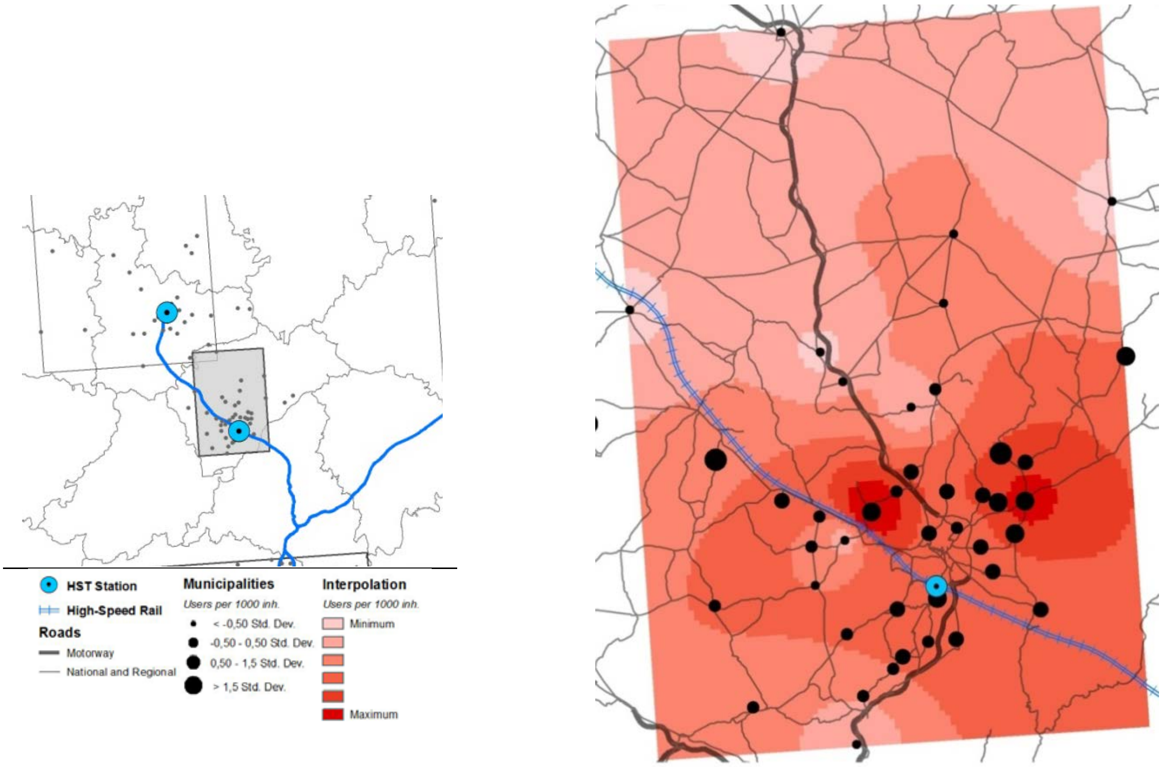
*Figure 5. Zaragoza's catchment area*




**Comments**

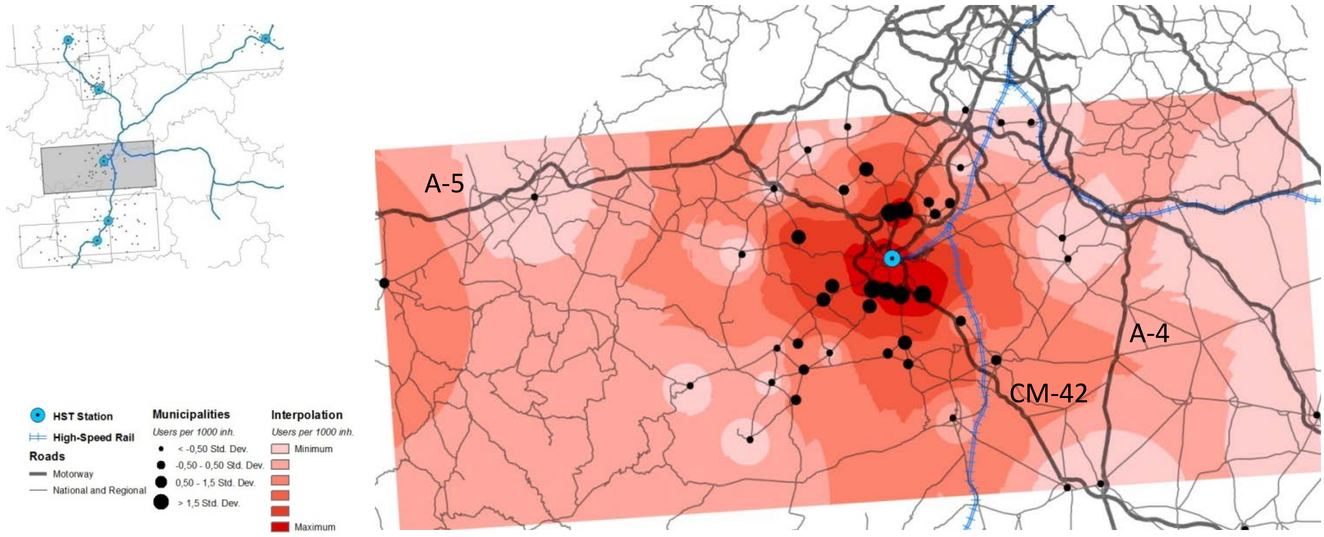
Other station limits influence towards the south (Segovia)
Due to its terminal positioning, its area spread opposite the HSR line
Conventional rail feeds the HSR station

*Figure 6. Valladolid's catchment area*



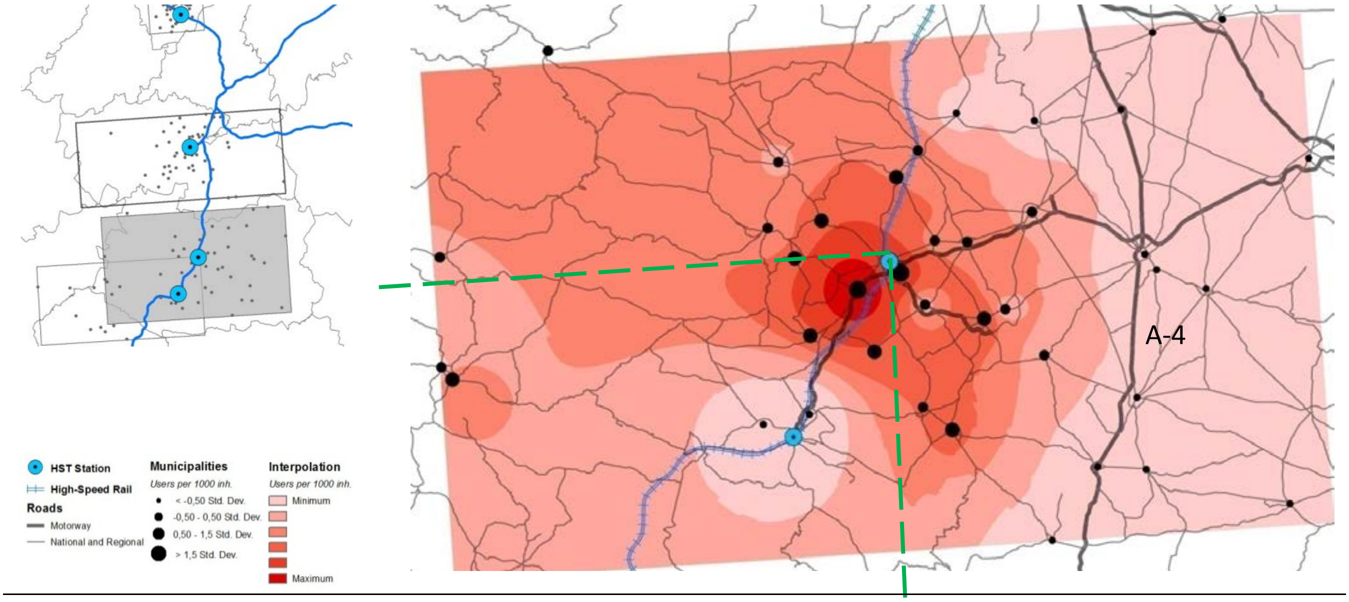

**Comments**
Strong topographic limitation to the south, separates from Madrid
Limitation of northern HSR station (Valladolid)

*Figure 7. Segovia's catchment area*




**Comments**
Limitation of HSR network southwards and proximity to Madrid (North) (barriers).
Competition with motorway (A4) reduces extension towards the east (barrier)
Motorways (A5 and CM42) allows feeds the station from distant locations (corridor effect)

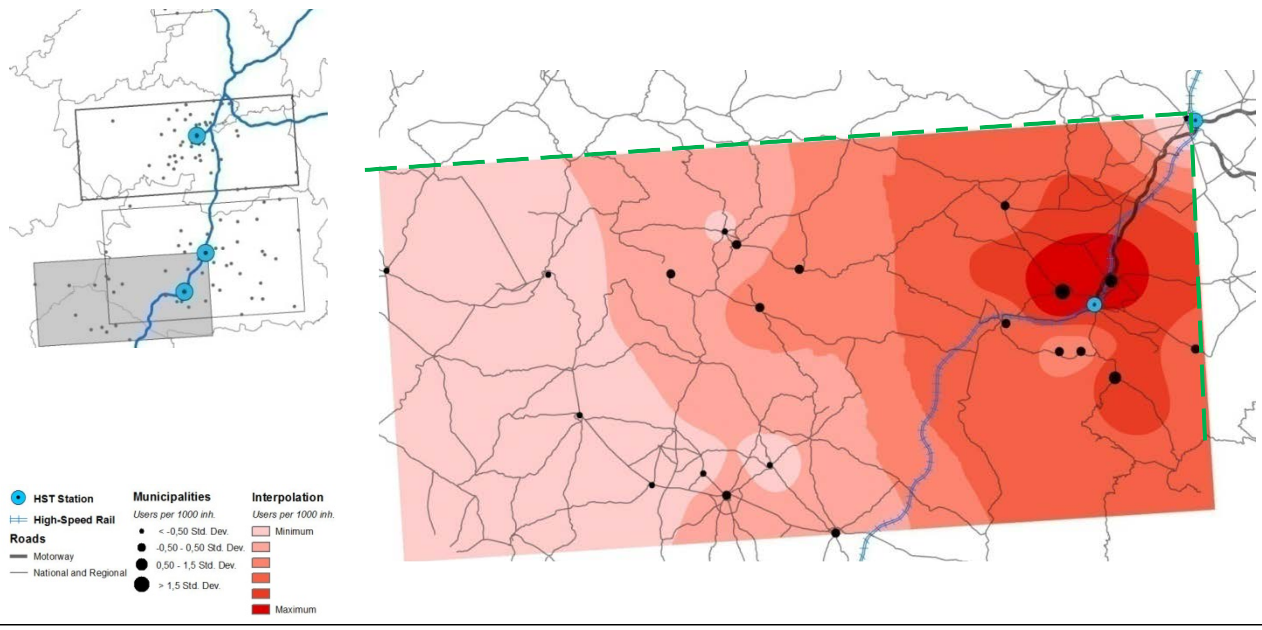
*Figure 8. Toledo's catchment area*




**Comments**

Its influence is limited by HSR stations: Toledo (North) and Puertollano (South) (barriers)
Motorway (A4) compete against HSR as both lead to the same destination (Madrid)

*Figure 9. Ciudad Real's catchment area*




**Comments**

Strong influence of motorway (A4) to the east as a relative (or absolute) barrier
Area is highly overlapped by Ciudad Real's catchment area

*Figure 10. Puertollano's catchment area*