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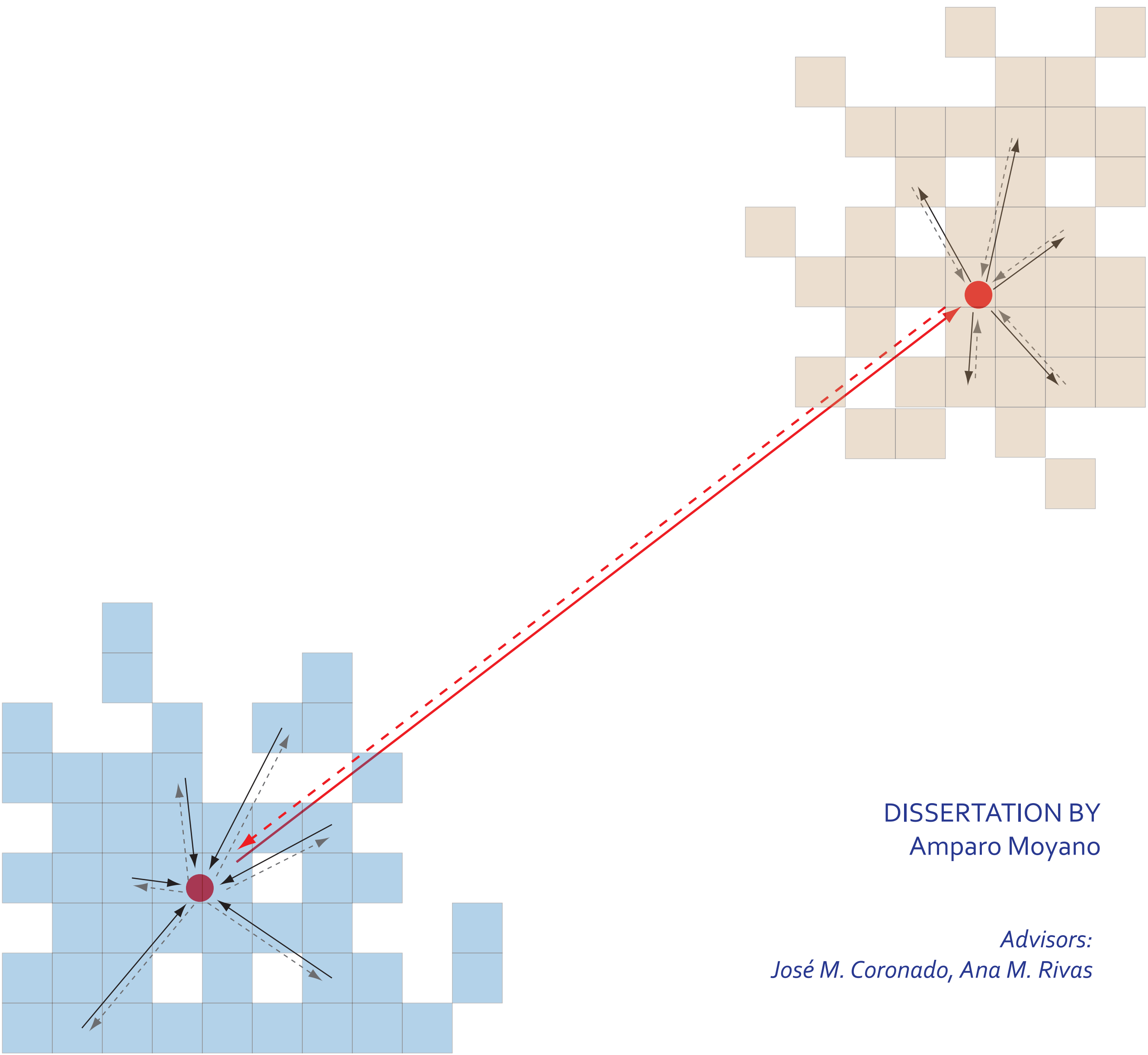
Efficiency of high-speed rail same-day trips for different purposes

Characterising the supply of services in the Spanish high-speed rail system



DISSERTATION BY
Amparo Moyano

Advisors:
José M. Coronado, Ana M. Rivas

UNIVERSIDAD DE CASTILLA-LA MANCHA

E.T.S.I CAMINOS, CANALES Y PUERTOS

Efficiency of high-speed rail same-day trips for different purposes: characterising the supply of services in the Spanish high-speed rail system

La Alta Velocidad Ferroviaria en España:
Caracterización de la oferta y análisis de su utilidad para distintos propósitos de viaje

DISSERTATION BY

Amparo Moyano Enríquez de Salamanca

Advisors:

Dr. José María Coronado Tordesillas

Dr. Ana María Rivas Álvarez

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Summary

The development of high-speed rail systems in recent decades, transitioning from single lines to a complex mode of transportation that encompasses many lines and cities and involves many kinds of services, requires a global assessment to understand the real utility of HSR for each city.

Since the beginning, the literature and stakeholders have focused on the infrastructure itself. HSR systems were conceived to connect large metropolitan areas over distances of around 400-600 km. However, as this infrastructure generates impacts on the regions in between, it challenges how smaller cities en-route are still going to be serviced by rail. In many cases, local/regional authorities have actually applied pressure to secure specific HSR infrastructures that were originally designed primarily to serve bigger cities. Subject to the balance of power, technical feasibility, costs and financial contributions of local/regional authorities, HSR acquired a social and political compromise through which it served smaller cities on the lines. The local authorities of these smaller intermediate cities believe an HSR station in their locality is an iconic element needed for surviving the national competition between cities and an opportunity for urban and regional development. Being included in the HSR map generates important expectations for urban projects, based mainly (and sometimes excessively) on the 'image effect' of HSR in terms of modernity, accessibility and connectivity. Indeed, local and regional authorities often do their best to secure specific rail infrastructures to accommodate HSR services. Nevertheless, in their euphoria they usually forget to consider HSR operations. Yet it is the services supplied (routes, frequencies and timetables) that ultimately determine the utility of HSR for cities, and the real possibility of being connected to other cities.

This focus on infrastructure has also been reflected in the scientific literature on the subject, in which scholars have mainly examined the socioeconomic impacts generated by the systems and improvements in accessibility provided by HSR. Such impacts are generally centred on the reduction of travel times generated and the benefits this improvement provides in terms of accessibility, mobility and socioeconomic development. However, **at a time when medium- and long-distance accessibility is considered a key element of the attractiveness of cities and regions, it is necessary to think beyond infrastructures to also consider services**. Improving long-distance/high-speed accessibility is not enough to induce economic development if adequate HSR services are not also implemented.

In addition, in the context of HSR expansion, the quality of the operating services is just as important as securing an HSR infrastructure. The new panorama of HSR development, with its many possibilities for connections and services provided for the

cities involved, highlights the need for a whole reassessment of HSR systems from a service-related perspective.

Importantly, this **dissertation focuses on the services and opportunities they provide for Spanish HSR cities** in terms of accessibility and mobility choices. The aim of the dissertation is to c**haracterise the supply of services of the different HSR connections** found in HSR systems and to **analyse their efficiency and utility for different same-day trip purposes**. This will help us understand and identify the differences between cities in terms of possibilities for travelling in the current HSR map. This dissertation presents three main contributions and helps to answer key questions about the utility of HSR services for cities.

1) First, this dissertation highlights that the **'HSR brand' should not be considered the same for all the cities included in HSR networks**. The evolution of HSR networks and services is opening up a new panorama in which the quality of the services determines different types of connections, highlighting the fact that an **HSR system could play different roles in terms of connectivity and mobility choices**. Among all the types identified, it is possible to recognise not only the 'early stage' HSR connections, which are those links between large cities located approximately 350–600 km apart, with high frequencies and speeds oriented to compete with air transport, but also other types, to which little consideration was given during the conception of the initial HSR system. The latter connections generally appear due to the development of the network (new lines and intermediate stops) and the bypasses connecting different lines. They offer a new perspective on the HSR service and establish a multirole network that can cover a wider range of possibilities from which travellers may benefit.

2) Second, this new scenario highlights **the need to assess HSR systems from a different perspective based on the need to incorporate the characteristics of the supplied services into the accessibility analyses** of the means of transport that are limited to fixed timetables, such as HSR systems. The main contribution of this dissertation is an efficiency analysis of the HSR system for same-day trips in the Spanish HSR network. Traditional accessibility analysis, usually location-based approaches that consider travel time as the main friction in network analyses, reveal the potential of network configurations but generally overestimate the outcomes, as they assume that all nodes in a network are equally well served in terms of frequencies and costs. However, in this dissertation, the **efficiency measure proposed – the available time at a destination that can be gained with a given monetary investment – is a new approach to assessing the accessibility of transport networks.** Therefore, this dissertation focuses on an analysis of the efficiency of HSR networks as a whole for different trip purposes, such as tourism, business and commuting, identifying and

analysing the influence of the 'network effects' (different services, bypasses, transfers, etc.) in mobility choices.

3) Finally, this efficiency approach should not be understood without including **the stations' integration in urban transport systems**. HSR trips must be considered, including the influence of all the links in the whole transport chain, because the **influence of access and egress times to/from HSR stations and their spatiotemporal variations are determinant in door-to-door HSR trips.**

Resumen

El desarrollo de la Alta Velocidad (AV) ferroviaria en España en las últimas décadas ha supuesto pasar de líneas y corredores aislados a un modo de transporte complejo, con muchas líneas, un gran número de ciudades conectadas y muchos tipos diferentes de servicios. Por ello, se hace necesario un análisis global para evaluar y comprender la utilidad real de la Alta Velocidad para cada una de las ciudades de la red.

Desde los inicios, se ha prestado una mayor atención a la infraestructura en sí misma. Los sistemas de AV se concibieron para conectar grandes áreas metropolitanas distantes alrededor de 400-600 km. Sin embargo, dado que esta infraestructura genera impactos en los territorios y regiones intermedias, pronto ciudades más pequeñas situadas en estas regiones comenzaron a demandar también servicios de Alta Velocidad. En muchos casos, las autoridades locales/regionales presionaron para asegurar la implantación de estaciones de AV en sus municipios y así, poder dar cabida a los servicios de AV que, en principio, estaban pensados para las grandes ciudades. En este contexto, y teniendo en cuenta tanto la viabilidad técnica, los costes de la infraestructura y la financiación de las mismas por autoridades locales, la infraestructura de AV adquirió un compromiso social y político a través del cual comenzó a dar servicio a las ciudades más pequeñas situadas en posiciones intermedias de los corredores principales. Las estaciones de AV eran percibidas por estas ciudades como elementos icónicos indispensables para sobrevivir en la competencia nacional entre ciudades y, además, como una oportunidad única para favorecer el desarrollo urbano y regional. El hecho de estar incluidas en el mapa de la Alta Velocidad genera grandes expectativas para el desarrollo de importantes proyectos urbanos, basados principalmente (y a veces excesivamente) en el "efecto de imagen" de la Alta Velocidad en términos de modernidad, accesibilidad y conectividad. Esta euforia por conseguir la infraestructura de AV hace que, generalmente, se olviden de los servicios (rutas, frecuencias y horarios) que, sin embargo, son los que finalmente determinan la utilidad de la AV para las ciudades y la posibilidad real de conectarse a otras ciudades de la red.

Este enfoque basado en la infraestructura también se ha puesto de manifiesto en la literatura científica sobre el tema. La mayoría de los estudios se han centrado principalmente en los impactos socioeconómicos y las mejoras en accesibilidad proporcionadas por la Alta Velocidad. En general, se centran en la reducción de los tiempos de viaje y los beneficios potenciales que ofrece esta infraestructura en términos de accesibilidad, movilidad y desarrollo socioeconómico. Sin embargo, en un momento en que **la accesibilidad de media y larga distancia se considera un elemento clave para el atractivo de las ciudades, es necesario pensar más allá de las infraestructuras y considerar también los servicios.** En este nuevo panorama, en el que existen muchas posibilidades de conexiones y ciudades involucradas, se pone de manifiesto la necesidad

de una evaluación y análisis completos de los sistemas de AV desde una perspectiva relacionada con los servicios.

Precisamente, **esta tesis doctoral presenta un enfoque basado en los servicios y las oportunidades que estos brindan a las ciudades AVE españolas en términos de accesibilidad y opciones de movilidad.** El objetivo de esta tesis es **caracterizar la oferta de servicios de AV** para las diferentes conexiones existentes y **analizar su eficiencia y utilidad para diferentes tipos de viaje en el día**. Esta investigación permitirá comprender e identificar las diferencias entre ciudades según sus posibilidades de viaje. En concreto, esta tesis doctoral presenta tres contribuciones principales y permite responder a una serie de preguntas clave sobre la utilidad de los servicios de AV para las ciudades en la red española.

1) En primer lugar, esta investigación pone de manifiesto que **la "marca AVE" no debe considerarse igual para todas las ciudades incluidas en las redes de AV. Según la calidad de los servicios, pueden identificarse distintos tipos de conexiones de Alta Velocidad que abren un amplio abanico de opciones de movilidad**. Entre los tipos de enlaces identificados se encuentran, no sólo las conexiones AV iniciales, que son aquellas entre grandes ciudades separadas aproximadamente a 350 - 600 km de distancia, con altas frecuencias y velocidades orientadas a competir con el transporte aéreo, sino también otros tipos mucho menos esperados en la concepción inicial del sistema de AV. Muchos de estos nuevos enlaces aparecen generalmente gracias al desarrollo de la red (nuevas líneas y paradas intermedias) y a los bypass que permiten conectar líneas y corredores diferentes. Todas estas conexiones ofrecen una nueva perspectiva del servicio AVE y ponen de manifiesto los múltiples roles que puede desempeñar hoy en día la AV, abarcando un rango mucho más amplio de posibilidades de viaje de las cuales los usuarios puedan beneficiarse.

2) Segundo, en este nuevo escenario **se hace necesario un análisis desde una perspectiva diferente, basada en la necesidad de incorporar las características de los servicios en los análisis de accesibilidad de aquellos medios de transporte limitados a horarios fijos, como en el caso de la AV**. La principal contribución de esta tesis doctoral es el análisis de la eficiencia de la Alta Velocidad española para diferentes propósitos de viaje (turismo, negocios y commuting), identificando y analizando la influencia de los 'efectos de red' (desvíos, transbordos, etc.) en las opciones de movilidad. En los estudios de accesibilidad tradicionales, generalmente los enfoques están basados en la ubicación de las ciudades en la red y consideran el tiempo de viaje como el principal factor de análisis. Estos estudios revelan el potencial de las redes pero generalmente sobreestiman los resultados, ya que suponen que todos los nodos en una red están igualmente bien servidos en términos de frecuencias, horarios y costes. Sin embargo, en esta tesis, **la medida de eficiencia propuesta - el tiempo disponible en**

destino que puede obtenerse en función del coste - es un nuevo enfoque para evaluar la accesibilidad de este tipo de redes transporte.

3) Finalmente, este enfoque de eficiencia no puede entenderse sin considerar **la integración de las estaciones en los sistemas de transporte urbano**. Los viajes de AV deben evaluarse incluyendo todos los eslabones de la cadena de transporte, pues **la influencia de los tiempos de acceso y dispersión hacia/desde las estaciones de AV y sus variaciones espaciotemporales son determinantes en los viajes puerta a puerta**.

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PART I: INTRODUCTION

Chapter 1

General approach and main objective of the thesis

1. INTRODUCTION

High-speed rail (HSR) has become a popular mode of transportation in several countries, including China, Japan, Spain, France, Germany and Italy. Furthermore, high-speed lines (HSLs) are under construction in some other countries too (including the US and Saudi Arabia) or have at least been proposed in many others (for instance, Australia, India and Mexico). The aim of the first high-speed lines in Europe – the Paris-Lyon line in France and the Madrid–Sevilla line in Spain – was to discharge conventional lines servicing the main corridors in different countries. This new transport mode offered a fast, comfortable and prestigious option for travelling between the main cities. It quickly appeared that, based on the attractive travel times, HSR could indeed compete with airlines mainly for business purposes, securing higher market shares and contributing to a decrease in their absolute level of use (see Givoni and Dobruszkes, 2013, for a review). The imperative to save time and the need to offset the costs of infrastructure made HSR prioritise fast connections between large markets, which thus reinforced the dominance and centrality of the main metropolitan cities on a national scale (Albalate and Bel, 2012; Givoni, 2006; Vickerman et al., 1999)[1]. Since the beginning, the temptation to bypass

[1] Notwithstanding political choices moving away from main markets. For instance, Spain decided to build the HSL between Madrid and Seville before the Madrid-Barcelona HSL, which is a larger market and offered further extensions to France.

intermediate, smaller cities was thus strong, especially when the travel time between metropolises was critical in relation to air services (Vickerman, 2015).

Several authors have shown that, technically speaking, bypassing smaller cities can be a deliberate decision, even though the HSL runs alongside them, or because of new HSLs located far away from cities previously served by the traditional railway (Ureña et al., 2009). For instance, the historical Paris–Lyons axis went via Dijon, and accounted for 508 km. The more direct HSL made it possible to save 81 km. Although Dijon is still served by high-speed trains through a branch connecting it with the traditional railway, the city has lost its key position on France's densest route (Troin, 1995). Conversely, HSL may involve longer routes (which are, nevertheless, faster journeys) that also bypass cities. In Belgium, for instance, Mons has lost Paris–Brussels services and Charleroi, Mons and Namur have lost Paris-Cologne services after the opening of the Paris-Brussels-Cologne/Amsterdam HSR. Other examples of cities that have lost rail services include border stations where trains used to make customary stops or to change their engines. All these phenomena have been identified in the literature as the "tunnel effect" (Plassard, 1991), which produces a discontinuous, polarized and hierarchic territory where only the main cities profit from the benefits of the new infrastructure (Gutiérrez et al., 2006; López et al., 2008; Vickerman et al., 1999).

However, in contrast to air transportation, where the flexibility to fit supply and demand is higher because connections are city-to-city, HSR runs through the territory and generates impacts on the in-between regions. This implies that, in time, HSR acquired a social and political compromise for servicing smaller intermediate cities, guaranteeing that smaller communities would remain accessible and (or) that their long-distance accessibility would improve. In fact, in most cases, HSR projects mean debates on servicing intermediate cities, whose leaders have often done their best to ask for (and to some extent secure) HSR stations. Besides new central business districts (CBDs), large concert halls, stadiums and museums, preferably hosted in iconic buildings, HSR stations became a key example of a facility regarded as necessary to survive national and international competition between cities (Chen and Hall, 2012; Garmendia et al., 2011; Preston and Wall, 2008). The resulting infrastructures express the result of a compromise between the will of second- or third-tier cities to be served and railways that aimed to offer the fastest services between bigger cities (Facchinetti-Mannone and Richer, 2011; Troin, 2010). In some cases when HSR lines started operating, stopping at intermediate stations generated an imbalance in the demand for long-distance, high-speed trains, as was the case of the first Spanish HSR line between Madrid and Sevilla (this case will be explained in detail in Chapter 2). This fact was the origin of the regional HSR services in Spain in 1992. Soon, due to the success of this new formula, regional HSR services were extended to other connections and networks.

Currently, the growth and expansion of HSR networks with bypassing connections allowing direct links between cities located in different lines and the compromise of servicing the intermediate territory have generated an advanced and complex mode of transportation. Nowadays, HSR systems have evolved to encompass many cities with very diverse profiles, and pass from those initial connections between main metropolitan areas to a large spectrum of different links that multiply the opportunities for travelling by HSR.

In addition, HSR operators are currently exploring other kinds of mobility and interesting markets in which they should compete. Although the initial concept of HSR was primarily oriented toward business purposes, rail operators in highly developed HSR networks such as France and Spain are reorienting their services to other markets in an attempt to attract travellers who would otherwise use alternative transport modes. New commercial policies are focused on increasing the occupancy of all the trains by offering more economical ticket prices (the dynamic ticket price system offers discounts of up to 70%) or introducing new services to expand traditional long-distance HSR services to off-peak hours and/or stop at secondary stations. In Spain, for instance, since HSR's launch in 2013, these policies have generated a 23% increase in the number of passengers and around a 12% increase in the trains' occupancies (RENFE, 2014).

This variety of cities involved and the connections and different kinds of services call for an in-depth analysis of HSR systems as a whole, especially to evaluate the opportunities for users in terms of enhanced mobility resulting from the growth of this infrastructure.

2. GENERAL CONTEXT OF THE THESIS: LITERATURE REVIEW

In the literature on the subject, HSR systems have been widely examined from different perspectives. Since their implementation, scholars have focused on: 1) transport effects, evaluating changes on accessibility and mobility patterns; 2) socioeconomic implications, assessing HSR impacts for different activities; 3) HSR stations' integration, analysing the effects of stations' location on local mobility and on urban development in their surroundings (Figure 1.1). Although there are many other approaches, these three main perspectives of HSR studies are of interest in this dissertation.

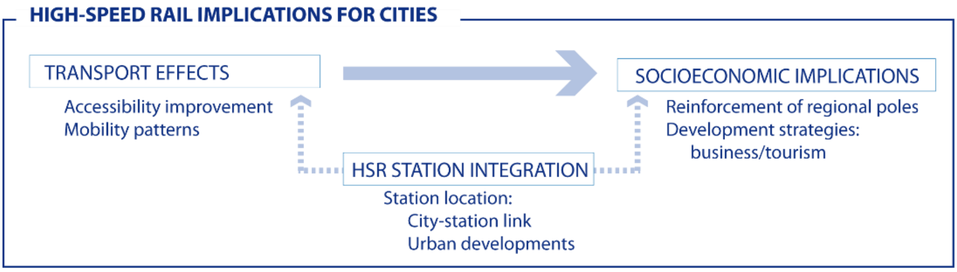


Figure 1.1: High-speed rail implications for cities: processes and effects

2.1 High-speed rail transport effects: accessibility and mobility patterns

Accessibility is a key analytical concept related to the assessment of transport networks, and has become a hot topic in the field of transport and spatial interactions. It can be addressed using multiple approaches and conceptualisations. Accessibility is usually defined as a potential, reflecting the ease with which certain movements can occur under different conditions. We can define three main elements of an accessibility analysis (Halden, 2011): 1) the active subjects (who are accessing the resources of interest), 2) the passive subjects or locations (where they are being accessed), and 3) how access is achieved. The last named is a more complex element involving the means of movement (network, infrastructure, conditions, etc.). To these three elements or factors (or even questions), Geurs and van Wee (2004) added a temporal component. The specific relative share among these factors; namely, which of these contributes more or less to a particular accessibility measure is a matter of purpose and objective. In other words, it is a matter of conceptualisation.

Since its first implementation, HSR has been analysed in transport geography from the perspective of accessibility provided to cities in the network. In general, literature on the subject assesses accessibility improvements by using different indicators, most of which are based on the perspective of the cities' location in the network, considering the measure of travel time as the main impedance. These studies have been built on the concept of the 'shrinkage' of space HSR systems provide in relation to the remarkable reduction in travel times they enable (Spiekermann and Wegener, 1996). This perspective is very useful for understanding changes in accessibility generated by the new infrastructure in the cities it serves (Cao et al., 2013; Chang and Lee, 2008), assessing different scenarios of network development (Bruinsma and Rietveld, 1993; Jiao et al., 2014; Monzón et al., 2013; Ortega et al., 2014). The perspective is especially useful for assessing the potential access given by the HSR system. In addition, some of these analyses tend to assume that the influence of an HSR system on accessibility extends far beyond each station because these indicators are applied to extensive surfaces, which could be regarded as an overestimation of accessibility in spatial terms (Martínez Sánchez-Mateos and Givoni, 2012). With the implementation of HSR, we can assume it will facilitate the movement of people in and out of a place. However, accessibility, understood as the interaction between land use and the transport network, only increases in combination with the services and operations in place (Boisjoly and El-Geneidy, 2017). In this debate, transport planning needs to focus on accessibility as a way of understanding the actual impacts of transport in spatial systems in a wider perspective.

On the other hand, accessibility improvements provided by HSR induce changes in modal share and new transport demands. These changes are called the 'transport' effects of HSR (Givoni, 2006) and are based directly on space/time relations. Several research studies on the assessment of high-demand transportation corridors have demonstrated the variations in modal shares that have been produced by the opening of new HSR lines. These studies have centred mainly on the competition between air and rail transportation (Dobruszkes, 2011; Martín et al., 2014; Román et al., 2007). Many authors have stated that HSR can compete significantly with air transport, provided the travel time is three hours or less. Based on data covering 161 city-pairs in Europe, Dobruszkes et al. (2014) found that the impact of HSR travel time on the provision of air services decreases quickly between 120 and 150 minutes. This air and HSR competition remains today in the main European HSR connections: the Paris–London or Madrid – Barcelona links are some of the most relevant examples. In some of these links, HSR has secured a higher market share based on attractive travel times (Dobruszkes et al., 2014; Givoni and Dobruszkes, 2013). In addition, HSR is currently not only an alternative to air travel but also to road transportation. The development of HSR networks, through the involvement of many different cities and the introduction of different types of services, makes it possible for HSR to also compete in the short- and medium-distance travel market.

Literature on the topic has identified different ranges of travel times for which HSR can compete against other transportation modes, and found a limit of 2 hours of travel time for road transportation and 2.5-3 hours for air transportation (Ureña et al., 2009). These short- and medium-distance HSR connections, generally between smaller intermediate cities and a main metropolis, have also displayed variations in modal shares and mobility patterns, experiencing a significant decrease in private vehicle demand in favour of HSR services (Garmendia et al., 2011). In addition, the modal share of a specific route may be conditioned by certain characteristics of the travel, such as the final destination (arriving at or leaving from the destination city), trip length, use of luggage and temporal restraints in terms of travel and arrival times for certain trip purposes (Ureña et al., 2012, 2009). Some other studies have analysed the effects of socioeconomic characteristics on modal choice and their variations across different trip purposes, such as business, tourism and commuting (Limtanakool et al., 2006); and distances and lengths (Scheiner, 2010).

The different characteristics of each trip purpose for travelling (temporal restraints, time available needed at the destination, value of time to the traveller, etc.) open the debate about the adaptability of traditional accessibility measures in the analysis of complex long-distance networks such as HSR, which are conditioned by specific services and schedules. In HSR networks, having an HSR station and fast connections does not imply achieving a good quality of services' supply.

2.2 Socio-economic implications of high-speed rail

As mentioned in the previous section, accessibility improvements facilitate changes in mobility patterns, characterising passengers and inter-city relationships in terms of socio-economic activities. Therefore, the decision to service certain cities is anything but neutral at a time when traditional spatial planning has moved largely to entrepreneurial approaches to regional development. Harvey (1989) showed how much 'managerial practices (...), which focused primarily on the local provision of services, facilities and benefits to urban populations during the welfare state era have been replaced by 'urban entrepreneurialism', which aims to 'foster and encourage local development and employment growth'. This post-Fordist accumulation regime involves competition between urban or regional public authorities at both national and international levels to attract (or to keep) firms, tourists and wealthy people. Fast transportation modes play a key role in such a context: they make places more accessible on a larger scale than slower means of transportation, and this accessibility may contribute to making places more attractive, provided other factors of development are present too (Albalate and Fageda, 2016; Bazin-Benoit et al., 2016; Chen and Hall, 2013; Feliu, 2012; Jean-Paul et al., 2013; Loukaitou-Sideris et al., 2013; Willigers and Van Wee, 2011).

Most of the studies on HSR are oriented mainly towards these socio-economic impacts. Many studies have focused considerable attention on business trips by HSR, which initially was built mainly for business purposes between the main metropolitan areas in a bid to compete with air transport services, as mentioned in the previous section. In addition, the need to balance the costs of the rail infrastructure made HSR prioritise connections between large markets, reinforcing labour relationships between the main metropolitan areas on a national scale (Givoni, 2006; Vickerman et al., 1999). However, the development of HSR networks and the introduction of different kinds of services, such as regional HSR, favour other kinds of labour relationships between cities at different scales. Shorter HSR services, within one-hour travel time from the main city, offer new travel opportunities, with important effects on residence-workplace location, reinforced travel-to-work mobility and, in general, regional integration (Chen and Hall, 2012; Garmendia et al., 2012b; Mohíno et al., 2017). Also, recent studies on commuting mobility reveal that HSR is a key variable for assessing the growth of labour contracts and for understanding the dynamics of labour markets (Guirao et al., 2017).

In addition, leisure/tourism mobility is an interesting market for high-speed rail systems. The main rail operators in Europe have been exploring and reorienting their services to the tourism market with new commercial policies aimed at attracting travellers who would otherwise use alternative modes of transport. The launch of OuiGo in France (Delaplace and Dobruszkes, 2015) or AV City in Spain, combined with the introduction of more economical ticket fares, are some of the examples of this change in commercial policies. Evidently, these new HSR products are increasing HSR demand but there is no clear evidence in the literature of the positive effects of HSR on tourism development (Albalate and Fageda, 2016; Guirao and Campa, 2016), unless there is a strong local promotion of the tourist destination that may accompany increased accessibility (Delaplace et al., 2016; Masson and Petiot, 2009; Mimeur et al., 2013). However, the situation changes when analysing tourism-related same-day visits to other cities in the network from main national and international tourist destinations, such as Paris or Madrid. In this case, HSR has a significant effect on tourists' destination choice (Pagliara et al., 2017, 2015).

Most of these studies have focused on impacts of HSR in certain cities and on an analysis of the effects of HSR infrastructure on different kinds of mobility patterns. Nevertheless, in this new context of HSR expansion, the quality of the operating services is just as important as securing an HSR infrastructure. The opportunities for travelling opened by HSR, which will determine the success of different economic activities, are linked directly to the characteristics and suitability of the services supplied for specific travel purposes.

2.3 High-speed rail stations' integration: regional and local perspectives

The socio-economic effects of HSR for cities are also related to the location of the station in the city it serves. As Bertolini and Spit (1998) note, a train station performs two roles: first, stations are nodal points in the transport path, and second, they are city landmarks. In this sense, the historic role of conventional train stations as gates of the city, which has been overshadowed by the expansion of freeways and airports, is strengthened again by HSR stations. Studies that address access to train stations highlight the importance of the city-station link in the door-to-door railway trip, and identify the quality of access to the station as a key factor that can influence the choice of using the train for travelling (Givoni and Rietveld, 2007; Keijer and Rietveld, 2000a; Rietveld, 2000), instead of a bus or private car. Therefore, this role of city gate must be accompanied by an adequate integration of the station into the city. Nevertheless, the development of HSR networks encompassing many cities of diverse sizes and territorial characteristics is generating different situations. Nowadays, not only large metropolitan areas but also many small and medium-sized cities are served by an HSR infrastructure with different configurations and station locations.

In general, large metropolitan areas benefit from HSR central stations, which generally reuse existing railway stations, and therefore offer considerable accessibility to the city through all the available modes of transportation. Scholars suggest that a central station location produces greater positive effects in urban development and dynamics than other locations. A central location could exploit pre-existing complementary developments (Loukaitou-Sideris et al., 2012) and provide a catalyst for additional development (Bertolini et al., 2012). However, achieving agreement among the political, economic and social stakeholders is not always possible. On the other hand, as mentioned in the introduction of this chapter, for smaller cities, acquiring a station is usually the main concern for local and regional authorities, regardless of the way in which a station integrates into the city (Bellet et al., 2012), although the access quality to these new HSR stations will be determined by their location. Indeed, these intermediate cities usually secure a peripheral station located on the HSL but out of the city supposedly served, making the connections to/from the city centre with other public transportation difficult. There are peripheral stations located somewhere in the countryside 'near' the city served (Figure 1.2A). The urban projects undertaken around these first peripheral stations were unsuccessful in most cases because of the lack of activity in their surroundings and an excessive confidence in the 'image effect' provided by the HSR system (Garmendia et al., 2012a; Ureña et al., 2012). Currently, some peripheral stations have become major transport nodes with improved connections to other modes of transport, especially with traditional railway stations that maintain regional services and some HSR services (Facchinetti-Mannone and Richer, 2011). However, in most of the cases, the connections between the HSR station and the city supposedly served are very difficult. A more favourable station location for smaller cities is represented by an edge HSR station (Figure 1.2B). The edge station is located near the limits of the urban space. It is potentially better integrated with the city, notably in terms of access by public transport. However, this edge location is not always possible due to infrastructural restraints and the focus on the directness of the main HSR line. Another case is an HSR station serving some cities located in the intermediate area, acquiring a regional role (Figure 1.2C).

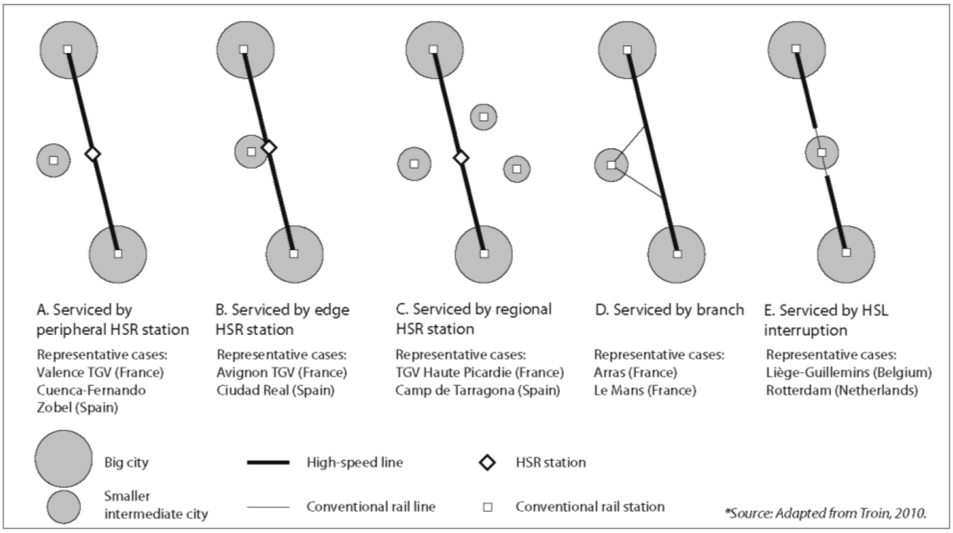


Figure 1.2: Classifying the location of intermediate HSR stations (Moyano and Dobruszkes, 2017)

Instead of a peripheral station, intermediate cities are sometimes served, thanks to a complementary branch of conventional railway, allowing high-speed trains to reach the incumbent central station (Figure 1.2D). This scheme is generally limited in terms of the number of services that turn off the main HSR line to get to the intermediate city. The last possible configuration can be found mainly in big or medium-sized cities such as Rotterdam (The Netherlands) or Liège and Brussels (Belgium), where the HSL is interrupted in order to reach central stations through a conventional railway (Figure 1.2E), which obviously costs much less than building an HSL through or under the existing built environment.

The role of HSR stations with their different configurations and locations can be analysed from different approaches. From the regional perspective, the potential use of HSR stations, which relates mainly to the station's location and its position along the network, can help on the definition of stations' catchment areas. 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 terminals, which emphasizes the convenience of categorising them according to different factors (Zemp et al., 2011). Other studies have confirmed 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 aspects (Ewing and Cervero, 2010), such as socioeconomic and transportation-related features (Givoni and Rietveld, 2014). A more extensive scope of these considerations is identifying 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). Therefore, the relationship between context and station is crucial in understanding the functionality of the latter.

Apart from this spatial perspective, many studies have focused on access to stations and assessing the integration of main railway stations in urban and metropolitan transport systems. The research on access to stations has focused on the analysis of different variables affecting local accessibility, such as distance or access time (Givoni and Rietveld, 2007; Rietveld, 2000) and other variables related to station supply (Reusser et al., 2008). Other examples are centred on the analysis of Transit-Oriented Developments (TODs) as urban design models for areas around stations. Recent studies have evaluated the node-place model (Bertolini et al., 2012; Lyu et al., 2016), considering the integration of land use and transport as key features of TODs. However, in HSR accessibility studies, scholars have paid scant attention to the local and regional integration of HSR stations, even when HSR accessibility depends not only on station-to-station travel time, but also on access and egress times to/from HSR stations. In fact, the influence of the first and last mile can be a determinant in door-to-door HSR trips (Monzón et al., 2016).

3. MAIN OBJECTIVE AND RESEARCH QUESTIONS

The new panorama of HSR development, with its many possibilities of connections, services and cities involved highlights the need for a comprehensive assessment of HSR systems from a service-related perspective. The aim of this dissertation is to c**haracterise the supply of services in the different HSR connections** currently found in HSR systems and to **analyse their efficiency and utility for different same-day trip purposes**, which helps us understand and identify the differences between cities in terms of the possibilities for travelling in the actual HSR map.

Methodologically, this study focuses specifically on accessibility analysis traditionally applied to transport networks and widely addressed in the literature on the subject. The work carried out in this dissertation proposes a different approach for the analysis of transport systems, based on the concept of 'Time Geography' (Hägerstrand, 1970) and 'contactability' (Törnqvist, 1970) and focuses on the needs and restrictions of individuals travelling by HSR for different purposes. It proposes a useful tool for transport planning in the analysis of the potentialities provided by HSR from individuals' perspective. The Spanish HSR system is selected as a case study in this thesis. It is considered as a relevant case with its highly developed network (more than 3,100 km, six main lines and 31 stations) and wide range of different services leading to a very heterogeneous situation in terms of the quality of the connections between cities.

In order to achieve the main aim of this thesis, the following research questions (RQ) have been addressed (Figure 1.3):

RQ1_ Are all HSR links similar? Is the 'HSR brand' the same for all the cities? Has HSR become a transport mode with many different roles in relation to the services supplied?

The growth of HSR networks and the variability of the supply of services suggest that the Spanish HSR system is experiencing a change of conception in relation to its role as a transport mode. In this new panorama with its high number of connections in which the initial links between large metropolitan areas are only a part of a very complex mode of transportation, it is essential to characterise the supply of services and **identify the different types of HSR links** found in highly developed HSR systems.

RQ2_ How efficient is the HSR system as a transport mode for different same-day trip purposes? How can this efficiency of HSR connections between cities be measured? Which service-related factors influence the efficiency of HSR same-day trips the most?

As mentioned in the introduction to this chapter, in most cases local or regional authorities have negotiated transport infrastructures but have neglected HSR services. Assuming HSR services can benefit cities' economy under given conditions, services arguably matter much more than facilities. It has been found that impacts are subject to the actual spatial and temporal design of the new rail services (routes, stops and frequencies). Since scholars have paid scant attention to this gap between infrastructures and services, this dissertation proposes **an analysis of the efficiency of HSR connections for different activities**. Considering actual timetables and associated costs and restrictions imposed by different kinds of trips (business, commuting or tourism), a **schedule-based measure of efficiency** is developed with the aim of assessing actual opportunities for both travellers and cities serviced by HSR.

RQ3_ To what extent does the efficiency of the services supplied in each HSR connection allow for the attainment of the maximum potential accessibility provided by the HSR infrastructure?

Location-based accessibility measures, which are the most commonly used indicators in transport network analysis, focus on the cities' location in the network, and generally consider 'travel time' as the main impedance. Nevertheless, in transport infrastructures limited to specific schedules, such as HSR, these measures overestimate the accessibility improvements provided by the infrastructure, as they consider that there will always be a fast train available at the right time to start the journey. On the contrary, the efficiency measure proposed in this dissertation tries to highlight the importance of considering services, schedules and costs (in both time and money) in accessibility analysis. The **comparison between efficiency and location-based accessibility** for every city in the Spanish network will allow for an analysis on **how the efficiency of the services' supply meets the potentialities provided by the infrastructure**.

RQ4_ What is the influence of access and egress times to/from HSR stations in the efficiency of HSR connections? Is this influence affected by temporal and/or spatial dimensions?

As mentioned in Section 2.3, an HSR station's integration in an urban and interurban context is determinant on HSR trips, as the city-station connection is currently an important link for travellers in the whole transport chain. **The station's location and its level of intermodality** will influence first, the quality of this station-city connection and second, the catchment area of the station itself. Therefore, HSR stations' integration and the influence of access and egress times could be a determinant in the efficiency of door-to-door high-speed rail trips. This dissertation analyses the **importance of access and egress times to/from HSR stations**, and considers **spatiotemporal variations of travel times** for different urban transport modes.

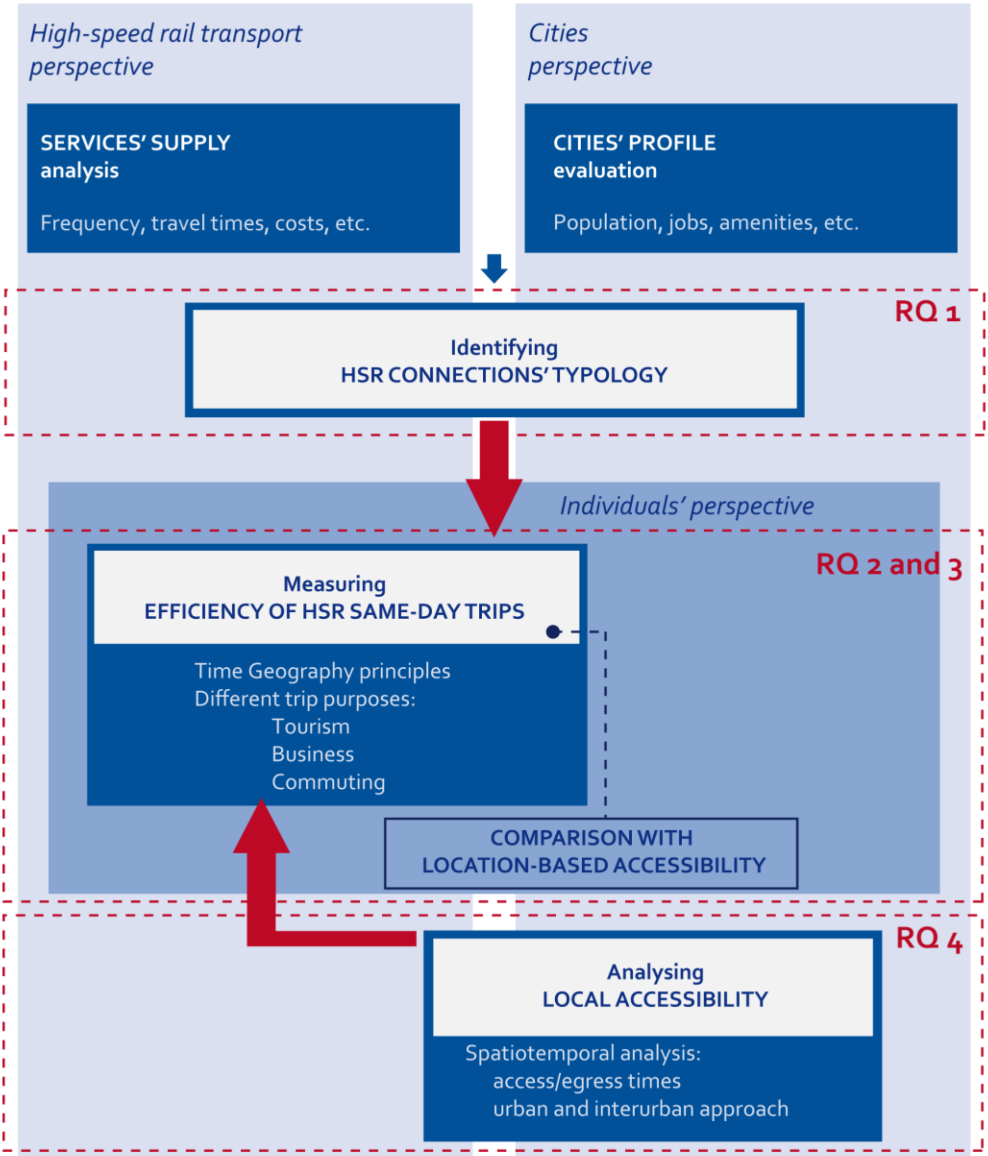


Figure 1.3: Concept map of the main empirical analysis of the thesis

Chapter 2

Thesis organisation and framework

1. STRUCTURE OF THE DOCUMENT

This thesis is organised in three main parts supported by different papers and scientific contributions already published or in the process of publication in relevant scientific journals related to the transport planning fields (Figure 2.1). The first part is a general introduction explaining the context of the dissertation, the main research questions and the structure of the document. The second part includes the main empirical contributions and analysis carried out in the dissertation, giving answers to the research questions exposed. Finally, the third part contains the main conclusions and future lines of research.

Apart from the main body of the dissertation, some related contributions to each chapter have been added at the end of the document as supplementary material (Supp.).

PART I. Introduction

This part of the dissertation includes two chapters:

First, *Chapter 1* presents the general approach of the thesis and its objectives, setting the basis that supports the whole research and specifying the main research questions addressed in this dissertation. The paper Moyano A. and Dobruszkes, F. (2017) 'Mind the services! The risk of HSR cities to be bypassed by HSR services, *Case Studies on Transport Policy, 5(4), 537-548* (Supp. 1.1) highlights the relevance of the services, and not only the HSR infrastructure, in the analysis of the impacts of HSR for cities. Cities make the most of securing an HSR station because they consider that being included in the HSR system will provide a better city image and will favour the development of different activities and urban projects. Nevertheless, ultimately, these opportunities will be linked largely to the exploitation of the infrastructure and, in this aspect, cities have generally nothing to say about the services finally provided. This consideration about the importance of the services in the real utility of HSR for cities and their citizens will define the main line of this dissertation.

Second, *Chapter 2* explains the organisation of the thesis and establishes the framework of this research defining the case study.

PART II. Empirical analyses

This second part is the core of the dissertation, and is divided into three chapters that deal with the main empirical contributions of the research.

Chapter 3 focuses on a general analysis of the Spanish network from the services' supply perspective. It is based on the paper Moyano A. and Coronado J.M. (2017) Typology of HSR city-to-city links, ICE – Transport, *in press* (Supp.3.1), which is centred on the different types of connections found in the whole HSR system. This chapter addresses the hypotheses linked to the research question RQ1, analysing the characteristics of all the HSR city-to-city connections in the Spanish network and establishing a typology of HSR links depending on different territorial and service-related variables.

Chapter 4 is the central section of the dissertation and is related to the research questions RQ2 and RQ3, which refer to the efficiency analysis of HSR connections for different travel purposes.

The first part of the empirical contributions of this chapter is focused on RQ2 and combines two different papers. First, Moyano A., Rivas A. and Coronado J.M. 'Business and tourism high-speed rail same-day trips: factors influencing the efficiency of high-speed rail links for Spanish cities', *European Planning Studies*, Accepted for publication (Supp.4.1) and second, Moyano A. (2016) 'High-speed rail commuting: efficiency analysis of the Spanish HSR links' *Transportation Research Procedia*, 18, 212-219 (Supp.4.2), which proposes an assessment of the efficiency of Spanish HSR services for same-day trips oriented towards business, tourism and commuting purposes. The second part is mainly focused on RQ3 and presents the paper Moyano A., Martínez H.S.

and Coronado J.M. (2018) 'From network to services: a comparative accessibility analysis of the Spanish high-speed rail system', *Transport Policy*, 63, 51-60 (Supp.4.3). It focuses on the comparison between the efficiency indicator proposed in this dissertation and the potential measure commonly used in accessibility analysis, as a way of assessing the sensitivity of the new indicator, and understanding its potentialities for network analysis.

Related to this chapter, previous research has been published. This includes the papers Coronado J.M., Garmendia, M., Moyano, A. and Ureña, J.M. (2013) 'Assessing Spanish HSR network utility for same-day tourism', *RTS - Recherche, Transport et Securité*, 29(3), 161-175 (Supp.4.4) and Moyano A., Coronado J.M. and Garmendia M. (2016) 'How to choose the most efficient transport mode for weekend tourism journeys in Spain: An HSR and private vehicle comparison', *The Open Transportation Journal*, 10, 84-96 (Supp.4.5). These contributions served as references for the starting point of the dissertation and the preliminary steps of the efficiency measure proposed. Their content applied to tourism trips for both same-day visits and weekend journeys.

Chapter 5 is centred on an analysis of access and egress times to/from high-speed rail stations. This chapter is directly related to RQ4 and is based mainly on the contribution Moyano, A., Moya-Gómez, B. and Gutiérrez, J. 'Access and egress times to high-speed rail stations: a spatiotemporal accessibility analysis', *Journal of Transport Geography*, Accepted with major revisions (Supp.5.1). This contribution is centred first on the influence of local accessibility in the whole high-speed rail trip as a determinant factor in the evaluation of the efficiency of HSR connections, and second, on the spatiotemporal variations of access and egress times to HSR stations, especially in large metropolitan areas.

Although it is not the approach carried out in Chapter 5 of this dissertation, the station's local integration can be analysed from different perspectives. The contributions of Moyano A., Coronado J.M., Ruiz R. and Romero V. 'Station Avenue: high-speed rail's missing link. Assessing pedestrian city-station routes for edge stations in Spanish small cities', *Journal of Housing and the Built Environment*, Accepted with major revisions (Supp. 5.2), and the study by Martínez H.S, Moyano, A., Coronado J.M. and Garmendia M. (2016) 'Catchment areas of high-speed rail stations: a model based on spatial analysis using ridership surveys' *European Journal of Transport and Infrastructure Research*, 16(2), 364-384 (Supp. 5.3), are also related to this topic. They assess the integration of the station in the city it serves and its catchment area at different scales. The former focuses on the quality of pedestrian links between stations and city centres as a way of understanding the integration of the station in the urban environment on a local scale, and the latter analyses the ridership of HSR stations from a regional perspective.

PART III. Conclusions

The third part of the dissertation contains only *Chapter 6*, which focuses on the main conclusions of the thesis and presents some aspects and ideas for further research.

References

This section includes all the references cited in the dissertation.

Supplementary material

The last part of the dissertation encompasses the main and related contributions of the dissertation in their current format and structure. Only those main contributions already published, which have been edited and adapted in the main body of the document, are included, as well as all the related research mentioned above, which are not included in the main structure of the dissertation.

** Note for the reader: this dissertation is based on different papers and scientific contributions already published or in the process of publication, and focuses on the same case study, the Spanish HSR network. Because of that, some overlaps might be found throughout the document, although the author has rewritten and combined some of the contributions where required, trying to avoid most repetitions.*

STRUCTURE OF THE THESIS

Main contributions	Related contributions
PART I. INTRODUCTION	
Chapter 1 _ General approach and main objective	***Paper _*** Moyano A., Dobruszkes, F. (2017) 'Mind the services! High-speed rail cities bypassed by high-speed rail services', *Case Studies on Transport Policy,* 5 (4), 537-548.
Chapter 2 _ Thesis organisation and framework	
PART II. EMPIRICAL ANALYSIS	
Chapter 3 _ High-speed rail city-to-city links' typology ***Paper _*** Moyano A., Coronado J.M. (2017) 'Typologies of high-speed rail city-to-city links', *ICE - Transport, In press.*	
Chapter 4 _ High-speed rail efficiency analysis for same-day trips ***Paper _*** Moyano A., Rivas, A., Coronado J.M. 'Business and tourism high-speed rail same-day trips: factors influencing the efficiency of high-speed rail links for Spanish cities', *European Planning Studies,* Accepted for publication. ***Paper _*** Moyano A. (2016) 'High-speed rail commuting: Efficiency analysis of the Spanish HSR Links', *Transportation Research Procedia*, 18, 212–219. ***Paper _*** Moyano A., Martínez, H.S., Coronado J.M. (2018) 'From network to services: A comparative accessibility analysis of the Spanish high-speed rail system', *Transport Policy,* 63, 51 - 60.	***Paper _*** Coronado J.M. et al. (2013) 'Assessing Spanish HSR network utility for same-day tourism',RTS,29 (3), 161-175. ***Paper _*** Moyano A. et al (2016) 'How to choose the most efficient transport mode for weekend tourism journeys in Spain: An HSR and Private Vehicle Comparison', *The Open Transportation Journal,*10, 84-96.
Chapter 5 _ Access and egress times to high-speed rail stations ***Paper _*** Moyano A., Moya-Gómez, B., Gutiérrez, J. 'Access and egress times to high-speed rail stations: a dynamic accessibility analysis', *Journal of Transport Geography,* Accepted with major revision.	***Paper _*** Moyano A., Coronado J.M., Ruiz, R., Romero, V. 'Station Avenue: High-Speed Rail's missing link', *Journal of Housing and the Built Environment*, Accepted with major revision. ***Paper _*** Martínez, H.S. et al (2016) 'Catchment areas of High-Speed Rail stations: a model based on spatial analysis using ridership surveys', *European Journal of Transportation and Infrastructure Research*, 16 (2), 364-384.
PART II. CONCLUSIONS	
Chapter 6 _ Discussion and conclusions	

Figure 2.1: Schema of the structure of the dissertation.

2. DEFINITION OF THE CASE STUDY

2.1 Spanish HSR network: actual configuration and services

This thesis is focused on the Spanish HSR network as a relevant case study. At the end of the year 2015, the network encompassed 31 stations and comprised more than 3,100 km, divided into five main corridors (with different branches) ending in Madrid (Fig. 2.2).

This research includes all HSR lines existing in the Spanish network in October 2015 (date of data collection) in addition to the Mediterranean line that connects Barcelona, Tarragona, Valencia and Alicante. This is an upgraded line that offers a more convenient choice for passengers than travelling through Madrid. Only the Galician corridor, including Coruña, Santiago and Ourense, is excluded in this research, as this HSR line has not yet been connected to the entire network.

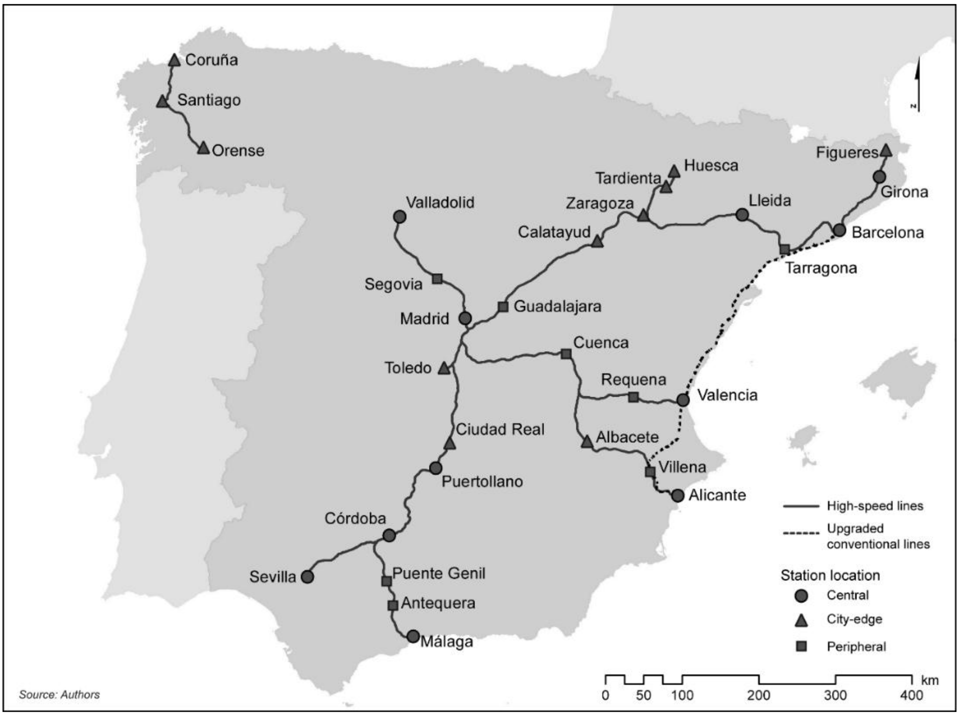


Figure 2.2: High-speed rail lines in Spain at the end of 2015

In addition, the existence of bypasses in Madrid between the South (Seville and Malaga) and North-East lines (Barcelona) and between the South and East lines (Valencia) allow direct train connections between these cities that do not stop at Madrid. By contrast, the Madrid-Valladolid line is penalised because transferring from this line to other lines in the network requires changing between the Chamartín and Atocha stations in Madrid.

The actual configuration of the Spanish HSR system is the result of 25 years of network development, oriented to both infrastructure and services. In Spain, the implementation of the HSR system started with the development of the Madrid – Sevilla line in 1992 (Figure 2.3). This line put into operation HSR services connecting Madrid, Ciudad Real, Puertollano, Córdoba and Sevilla, trying to release the conventional railway connection to the south of the country. After that, it was nine years until the next HSR project was implemented: the Madrid – Barcelona connection, the main air transport corridor in Spain. It started with the construction of the stretch Madrid – Lleida in 2003 and finished in 2008, connecting to Barcelona. During this period from 2003 to 2008, other HSR corridors were also developed: Madrid – Toledo in 2005 or Madrid – Valladolid in 2007. Until then, the Spanish network had been growing with the addition of single lines connecting Madrid to large cities located in the periphery of the country, following a radiocentric scheme (Figure 2.2).

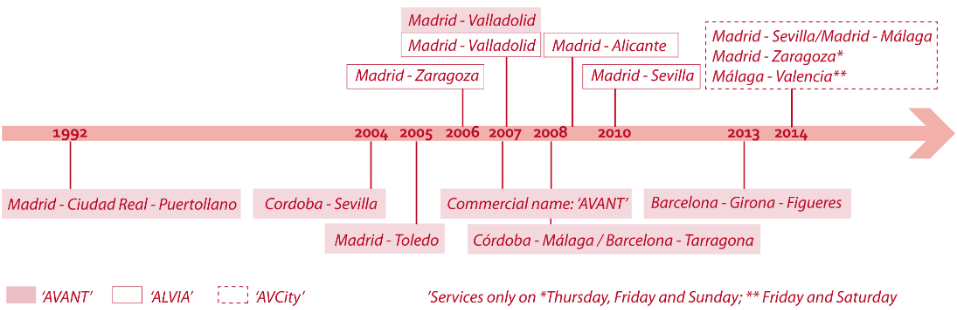
Nevertheless, the integration of the different lines constituting a whole network started in 2009 with the creation of the bypasses in Madrid connecting the South (Seville and Malaga) and North-East lines (Barcelona), and then, in 2012, connecting the South and East lines (Valencia). These bypasses allow direct train connections between these cities without stopping at Madrid, which improves the connectivity among cities located in different lines. In 2013 the Madrid – Barcelona line was continued to the French border, also servicing the stations of Girona and Figueres, and integrating the Spanish HSR system in Europe.

Figure 2.3: Timeline of the HSR system development in Spain

The development of the Spanish HSR system was not oriented only to the construction of new infrastructure, but also to the supply of different kinds of services and fares. In this sense, it has to be highlighted that it was decided to build the HSR network in Spain using UIC track gauge (international gauge of 1,435 mm, as in the rest of Europe), as opposed to the Spanish conventional railway, whose infrastructure adopted the Iberian gauge (1,668 mm). This circumstance will condition the integration between HSR and conventional railways, avoiding the need for HSR services to run through conventional lines, and vice versa.

In this context, the HSR system started with a unique type of service, the AVE (Alta Velocidad Española) service, conceived for long-distance and high-quality connections. However, after several months of operation of the first HSL Madrid – Sevilla, the high demand between intermediate cities – Ciudad Real and Puertollano – and Madrid unbalanced the long-distance connection to Sevilla. This fact was the origin of the regional HSR services, Ciudad Real/Puertollano – Madrid in October 1992, which offered an alternative to long-distance services for medium-distance commuting purposes (Figure 2.4). This regional HSR service (initially commercially named 'AVE Lanzadera', and later 'AVANT') was implemented in several links connecting Madrid to small closed cities such as Toledo or Segovia or Barcelona to Tarragona, Girona and Figueres.

Apart from that, trying to solve the problem of gauge incompatibility, the Spanish railway operator RENFE, implemented the ALVIA services in 2006, which were able to change the gauge during the same trip. Finally, in 2014, RENFE presented a new low-cost HSR service, AV City, to complete the long-distance supply in certain connections, reducing fares to attract other kinds of users.



*Source: Author
Information from www.ferropedia.es

Figure 2.4: Timeline of new HSR services complementing long-distance AVE services in Spain

Nowadays, the Spanish HSR supply currently includes four types of service:

- AVE, which is the classical high-performance, long-distance HSR service
- AVANT, known as the regional HSR service, which has a lower quality of rolling stock and speeds but presents more competitive fares because it is generally oriented to commuting purposes
- ALVIA, which is a long-distance service slower than the AVE and has the ability to change the gauge for running both on HSR (international gauge) and

conventional lines (Iberian gauge) during the same trip.

- AV City, which is a HSR service oriented to complete the 'AVE' supply in certain city-pair links, normally in the valley hours, by offering more competitive fares and using slower trains that stop at most stations.

In summary, the scenario included in this dissertation as the case study includes all these services and the network configuration shown in Figure 2.2. However, the Spanish HSR system is constantly evolving. For instance, a new, low-cost HSR service called EVA will be implemented soon in the connection Madrid – Barcelona. It will be running in 2019 and will stop at a peripheral station in El Prat (Barcelona), close to the airport. This is only an example that HSR is a changing transport system, which tries to integrate and adapt the infrastructure and services to attract different kinds of users.

2.2 Spanish HSR cities

The Spanish territorial configuration and population distribution follows a central-periphery model, where the highest volumes of population and economic activities are located in Madrid, as the capital of the country, and cities on the periphery of the country, such as Barcelona, Valencia, Sevilla or Málaga. In comparison, the centre of the country is highly depopulated, and only Zaragoza or even Valladolid or Cordoba count with higher volumes of inhabitants. Therefore, there is a noticeable imbalance between inland regions and the coastline of Spain in terms of population and activity distribution.

Since the beginning of the HSR system in Spain, the strategy for this infrastructure was to reach all the provincial capital cities in the country. In this territorial system, the main HSR corridors are oriented to connect Madrid with cities on the coastline, benefiting in-between cities included in these corridors. At the end of 2015, the HSR system encompassed 30 cities, including the Galician corridor. However, the latter is not included in the analyses developed in this dissertation because this corridor has not yet been integrated with the rest of the network. The characteristics of the cities included in the research are shown in Table 2.1:

Table 2.1. Description of Spanish HSR cities included in the analysis

	Population (inhab.)*	Capital status	Profile of the city
ALBACETE	171,030	Province	Commercial and industrial city. Economic capital of the region of Castilla La Mancha.
ALICANTE	328,100	Province	Touristic (mainly sun and beach) and services-oriented city.
ANTEQUERA	41,590	-	Regional logistics centre.
BARCELONA	1,601,935	Region	Main metropolitan area, with very high relevance for tourism (urban/cultural and sun and beach), business activities, conferences, fairs, etc.
CALATAYUD	20,615	-	Small municipality of the Province of Zaragoza.
CIUDAD REAL	74,865	Province	Services-oriented city, the economic centre of the province. Hunting tourism.
CÓRDOBA	327,205	Province	Urban/cultural touristic city of national and international relevance. City declared a World Heritage Site by the UNESCO.
CUENCA	55,780	Province	Urban and cultural touristic city, declared a World Heritage Site by the UNESCO.
FIGUERES	44,200	-	Urban and cultural touristic city and node of communications between Spain and France.
GIRONA	95,665	Province	Urban/cultural touristic city of national relevance.
GUADALAJARA	83,700	Province	Provincial economic centre.
HUESCA	51,170	Province	Economic centre of the province. Nature tourism.
LLEIDA	136,670	Province	Services-oriented city; economic centre of the province. Relevant inherited assets in the city.
MADRID	3,186,595	**Country**	Main metropolitan area, with very high relevance for tourism (urban/cultural), business activities, conferences, fairs, etc.
MÁLAGA	559,680	Province	Urban/cultural touristic city of national and international relevance. Node of communications in the south of Spain.
PUENTE GENIL	30,115	-	Very small city with some relevant inherited assets.
PUERTOLLANO	51,745	-	Industrial city, focused mainly on petrochemicals.
REQUENA	21,105	-	Small city with a mainly agricultural and wine-making economy.
SEGOVIA	54,520	Province	Urban/cultural touristic city of national and international relevance. City declared a World Heritage Site by the UNESCO.
SEVILLA	696,315	Region	Metropolitan area, with high relevance for tourism (urban/cultural), business activities, conferences, fairs, etc.
TARDIENTA	985	-	Very small agricultural town
TARRAGONA	133,025	Province	Urban/cultural and sun and beach touristic city of national and international relevance. City declared a World Heritage Site by the UNESCO.
TOLEDO	83,070	Region	Urban/cultural touristic city of national and international relevance. City declared a World Heritage Site by the UNESCO.
VALENCIA	790,755	Region	Metropolitan area, with high relevance for tourism (urban/cultural and sun and beach), business activities, conferences, fairs, etc.
VALLADOLID	309,930	Region	Services-oriented city, the economic centre of the region of Castilla y León. Relevant inherited assets in the city.
VILLENA	34,480	Region	Industrial centre in the province of Alicante.
ZARAGOZA	672,955	Region	Main city with high relevance for tourism (urban/cultural), business activities, conferences, fairs, etc. Important logistics and communications node.

**Population data provided by the Spanish National Institute of Statistics (INE) in 2017. Refers to the whole municipality of every HSR city in the network.*

PART II: EMPIRICAL ANALYSIS

Chapter 3

High-speed rail city-to-city links' typology

OUTLINE OF THE CHAPTER

The development of high-speed rail (HSR) networks is leading to a very complex situation in terms of network configuration and the variety of services. This new panorama presents very different feasible connections between city-pairs, multiplying the possibilities of travelling (see PART I: Introduction for more details).

This chapter is centred on the **research question RQ 1** and evaluates the characteristics of all city-pairs served by high-speed rail in Spain through a clustering analysis, with the goal of deriving an **HSR city-pair link typology**. This assessment offers a new perspective on the HSR network as a multirole system encompassing eight types of links with very different characteristics. Identifying these types of HSR links will be a useful transport-planning tool for emerging HSR networks to anticipate the different kinds of links they will encompass and for future HSR cities to foresee the possibility of benefiting from one or another type of link and adapting their policies and strategies according to their potential services.

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It has been slightly edited to fit the format of this dissertation.

1. INTRODUCTION

Since their inception, high-speed rail (HSR) lines in Europe have been implemented to connect large cities separated by distances of between 400 km and 600 km, in order to compete with air transportation (Givoni, 2006). This modal competition started a debate about the economic profitability of the HSR system and led to many studies on the cost-benefit analysis of the HSR infrastructure. These studies have focused on the main corridors in different countries and assessed their implications in terms of cost-benefit balance (Albalate and Bel, 2012; de Rus and Román, 2006). However, in contrast to air transportation, where the flexibility to fit supply and demand is higher because connections are city-to-city, HSR runs through the territory and generates impacts in between regions. This fact meant that, in time, HSR acquired a social and political compromise through which it served smaller cities on the lines (Le Creusot, Mâcon; Ciudad Real, Puertollano). The growth of the HSR networks in these countries, with their particular structure and topology as branching networks (Martín-Cañizares et al., 2015) originating in Paris or Madrid, has made direct connections possible between the main peripheral cities located along different HSR lines, without stopping at the capitals of these countries. Currently, these bypassing connections and the compromise of serving the intermediate territory have made it possible to establish many secondary interregional links between intermediate small and medium-sized cities, multiplying the number of direct connections feasible through the HSR network (Figure 3.1).

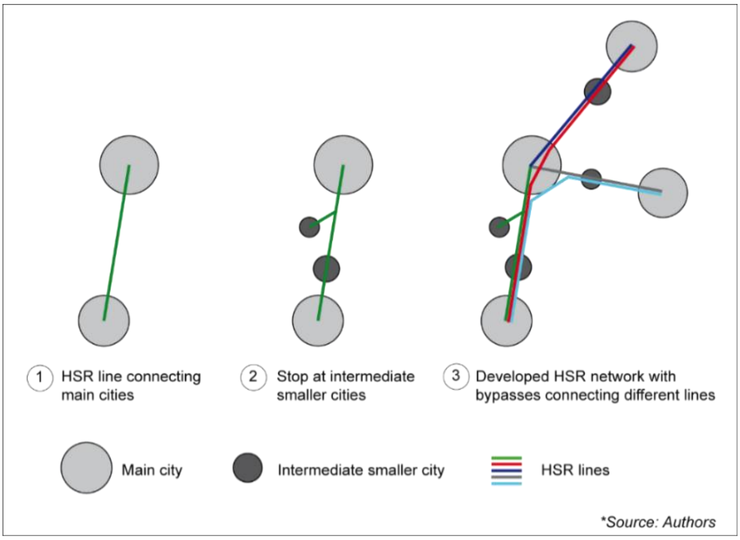


Figure 3.1: HSR network evolution

This new panorama presents many connections in which HSR does not compete with air transport because it links small cities without airports or runs very short distances. There are also very long-distance connections (Málaga-Barcelona, 1,133 km; Lille-Marseille, 967 km), in which HSR has longer travel times than an airplane; nevertheless, competition remains. Furthermore, these new services have a place in the HSR system because travellers can embark on, or disembarked from, the same train at several stations; therefore, different trips can be undertaken with a specific train service. This behaviour is obviously not possible on a plane.

Currently, the variety of connections and services supplied is changing the conception of the HSR system, which has passed from those initial connections between the main metropolitan areas to a large spectrum of different links that are generally overshadowed in the cost-benefit analysis as they generate different effects from mere economic profitability. The main aim of this chapter is to identify the different types of HSR links that can be found in highly developed HSR systems in order to evaluate the multiple roles they play in this new HSR panorama. It is a panorama in which the initial connections between large metropolitan areas are only one part of a very complex mode of transportation. The method proposes a clustering analysis to systematically assess the entire HSR network, focusing on the attributes of each link. It is applied to the Spanish HSR system as a representative case study of a highly developed HSR network that encompasses many cities, more than 3,100 km of lines and a wide variety of services.

2. BACKGROUND

2.1 Assessing the quality of high-speed rail connections

Many studies in the literature on HSR focus on the classification of HSR cities and connections, both from qualitative and quantitative approaches. Some studies focus on the qualitative analysis of these HSR cities, classifying them according to their territorial situation and connections to a large metropolitan area (Ureña et al., 2012) and normally addressing travel time as the main factor of analysis. Travel time can be a determinant to understand the different activities that can be performed through the HSR network, such as commuting (<1.5 h), travel for business purposes (>2.5 h) or leisure trips (> 3 h) (Chen and Hall, 2011; Garmendia et al., 2011). It can also be used to establish different temporal intervals in which a certain HSR connection may compete with other transportation modes (Givoni and Dobruszkes, 2013; Ureña et al., 2009).

However, for similar travel times, all connections are not comparable; in addition, they do not imply the same territorial effects. In this sense, the literature has given extensive coverage to quantitative analysis centred on accessibility measures (Geurs and van Wee, 2004; Gutiérrez, 2001). These studies have been applied to analyse the HSR system using different types of indicators depending on the aim of the study. Many of them are based on the important reduction of travel times provided by the new infrastructure to evaluate accessibility changes in the territory served by HSR (Monzón et al., 2013; Ortega et al., 2012). Others have focused mainly on the number of opportunities available from a given temporal or cost constraint (Gutiérrez, 2001; Páez et al., 2012). Also, certain studies have considered the characteristics of the services supplied to assess the 'contactability' of same-day business trips on a European level (L'Hostis and Leysens, 2012) or to analyse HSR utility for tourism trips through the Spanish network (Coronado et al., 2013; Moyano et al., 2016). These studies consider that the utility of the services depends not only on the travel time but also on other factors such as ticket costs, number of trains per day or convenient timetables. In summary, although they consider the characteristics of the services supplied in each connection, accessibility analyses are centred on the cities connected (or different origins and destinations) and the changes they experience when a new infrastructure arrives.

However, there are no examples in the literature on HSR that focus on the quality of services, analysing the 'vectors' connecting different HSR cities. In this research, the main focus is on the characteristics of the links and their comparison, which will allow us to identify the differences in the quality of services supplied by rail operators in the HSR system. This study will serve as a basis for a better understanding of the multiple roles the HSR system currently plays and the different mobility options it provides.

2.2 Cluster analysis in transportation studies

Because the development of HSR networks has led to a large number of connections (i.e., 274 in Spain), it has become necessary to classify these systematically and objectively. In this case, cluster analysis would probably be most appropriate. Cluster analysis is a statistical technique that aims to identify natural groupings of items in a database. Grouping is performed on the basis of similarities or distances (dissimilarities), with items as similar as possible within a group and very dissimilar among groups (Johnson and Wichern, 1992; Peña, 2002).

Although cluster analysis is not common in the transportation literature, there are certain examples in different fields. Most analyses are found in an urban and metropolitan context within the framework of travel behaviour assessments or traffic studies. The classifications relate to the effect of land use and transportation alternatives (Levine et al., 2005) or lifestyle characteristics (Hildebrand, 2003) that influence people's travel behaviour. Cluster analysis has also been useful in traffic studies to predict traffic and control it (Stutz and Runkler, 2002), to assess automobile congestion (Dornbush and Joshi, 2007) or detect road points with a statistically high level of accidents (Sabel et al., 2005).

Focusing on major infrastructures such as air and rail, clustering assessments are mainly centred on terminals. The most extended analyses focus on the identification of different types of airports, generally clustering them according to such characteristics as their dimensions, the number of flights and the number and location of their destinations (Malighetti et al., 2009). This previous classification is occasionally used to examine the application of benchmarking policies (Sarkis and Talluri, 2004) and to adopt strategies for managing demand and allocating scarce airport capacity (Rodríguez-Déniz et al., 2013). Other analyses concerning airports relate to their passengers, classifying them according to their choice of transport to reach the terminal (Psaraki and Abacoumkin, 2002) or their different characteristics when using low-cost airlines (Martinez-Garcia and Royo-Vela, 2010). Cluster analysis is used less commonly with regard to railway stations, with the focus generally oriented to the intermodality and access to the station (Tapiador et al., 2009a). Thus, the influence of the intermodal transportation system and the land use context around the railway stations allows for a classification that will facilitate strategy implementation and urban planning (Reusser et al., 2008; Zemp et al., 2011).

3. OBJECTIVE AND METHODOLOGY

This study evaluates the characteristics of all city-pairs served by high-speed rail in Spain, with the goal of deriving an HSR city-pair link typology that helps us understand the multiple roles HSR connections currently play and the extent to which secondary connections are representative in the system.

As of September 2015, the Spanish HSR network has comprised five main lines and encompassed 30 cities, including the Galician corridor. There are 274 direct connections among all the HSR cities; many of these are feasible due to bypassing connections among the South, East and Northeast lines, which allow travelling without changing at Madrid (Figure 3.2).

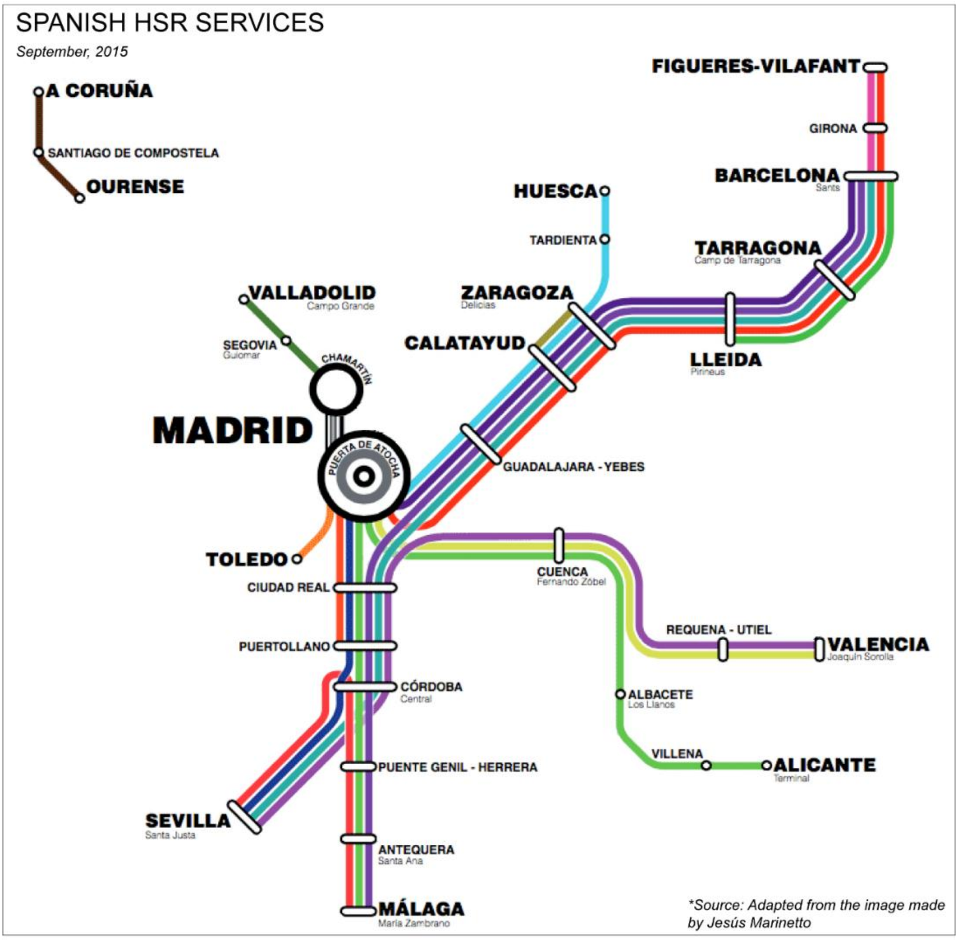


Figure 3.2: Spanish HSR services in September 2015

In the analysis, a k-means cluster has been used to analyse the 274 HSR direct connections existing in the Spanish network. The k-means method is a non-hierarchical clustering technique that uses the Euclidean distance between items to establish groupings. Its objective is to minimise the distance among items in the same group and maximise distances among groups (Peña, 2002). This statistical method allows for the classification of HSR connections (items in the database) in a highly heterogeneous and complex network. The method is justified precisely because of this network's complexity, where the quality of the HSR connections, which is characterised by different variables, must be objectively analysed to capture its variations in the network.

In this case, the HSR links are characterised by different territorial and service-related variables:

a) Territorial variables

- *Population (P)* is provided by data from the Spanish National Institute of Statistics (INE). In the cluster analysis conducted in this study, the population is divided into P_{max} and P_{min}, which represent the maximal and minimal population values of each HSR link, without distinguishing between origin and destination, to unify groups that have symmetric pairs of links in the same cluster, as long as they present similar service-related values.
- *Rail distance (Dr)* is the distance between two cities following the railway route in each case.

b) Service-related variables

- *Frequencies (F)* refers to the number of services per day between a certain origin and destination. In the assessment, all the trains that run on HSR lines are included.
- *Commercial Speed (Vc)* is the speed obtained from the quotient between the rail distance noted above and the travel time, which is provided by the Spanish rail operator ('RENFE') website (www.renfe.es). The weighted average travel time of all the different kinds of services provided in a certain HSR link is used.
- *Commercial Cost (Cc)* is the cost per km obtained from the quotient between the ticket cost and the rail distance. Methodologically, ticket cost refers to the standard tourist ticket offered by RENFE, without discounts or promotions. The weighted average ticket cost of all the different kinds of services provided in a certain HSR link is used.

Before computing the k-mean cluster, and given the differences in units and ranges of variation, the variables are normalised to homogenise the Euclidean distances calculated through the k-means cluster method; therefore, all the variables in the clustering have the same influence. Once the variables have been selected and homogenised, the k-means cluster can be computed. In this method, a predefinition of the number of clusters is a requisite that may be an obstacle for certain analyses, particularly when there are no previous expectations of the number of final groups into which specific data will be divided. Therefore, there are certain statistical processes that help predefine the number of clusters. One of the most extended is the Variance Ratio Criterion (VRC), which will be applied in this study (3.1). Calinski and Harabasz (1974) defined this criterion and it has worked well in many situations. This criterion is also easily computed through statistical software because it is represented by the F-value of a one-way ANOVA. Once the VRC is calculated for the different number of clusters, the w_k value for each one must be computed (3.2):

$$VRC_k = (SS_B / (k-1)) / (SS_W / (n-k)) \quad (3.1)$$

$$W_k = (VRC_{k+1} – VRC_k) – (VRC_k – VRC_{k-1}) \quad (3.2)$$

where *n* is the number of objects in the database, *k* is the number of clusters, SS_B is the sum of the squares between the segments and SS_W is the sum of the squares within the segments.

The number of clusters established in the assessment will be that which minimises the W_k value (Mooi and Sarstedt, 2011).

4. RESULTS

4.1 Differences among HSR connections

A systematic analysis of the variables that characterise all the services (*P1*, *P2*, *Dr*, *F*, *Vc*, *Cc*) shows that noticeable differences exist in the Spanish network. The original connection, the Madrid-Sevilla case, shows these values (3,273,049 inhabitants, 704,198 inhabitants, 471 km, 20 trains per day, 185.4 km/h, 0.155 €/km), which will be used as a reference in the analysis of the main results.

In the Spanish HSR network, the population (*P*) ranges between more than three million inhabitants in Madrid and 985 inhabitants in Tardienta, with 592,000 as the mean value. However, 20% of the cities have a population higher than 500,000 inhabitants. In addition, the rail distances (*Dr*) are very different, ranging from 20 km between Tardienta and Huesca to more than 1,100 km between Barcelona and Malaga. As shown in Figure 3.3, more than a third of the total number of links are under 250 km, and around 25% of the present rail distances are between 250 and 500 km, resulting in a wide spectrum of types of HSR links.

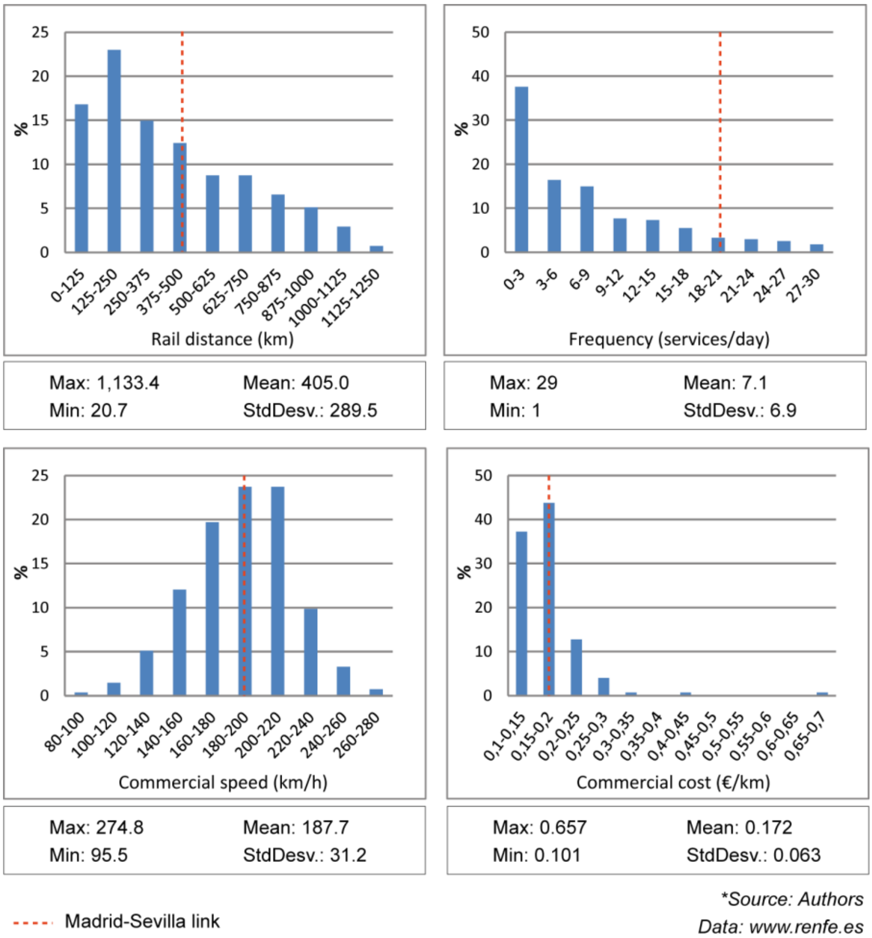


Figure 3.3: Histograms of different HSR links' factors

These differences among territorial variables also affect the quality and conditions of the services supplied. For instance, distances are directly related to travel times, and the number of daily services (*F*) is significantly influenced by the size of the cities connected. The Madrid-Barcelona connection presents the maximal value (29 trains) followed by the Madrid-Cordoba (27 trains) connection in which, in addition to the influence of the size, Cordoba benefits from its position in the network at a point of divergence between two lines (Madrid-Seville and Madrid-Malaga). Conversely, the connections in which the number of services is very low correspond generally to those connections that include very small cities (Madrid-Huesca, with one train per day) and/or in which there is a large distance between them (Barcelona-Puertollano). Concerning commercial speeds (*Vc*), the maximal value of 274 km/h is found in the Ciudad Real-Cuenca connection. In this case, the rail distance is sufficiently large to allow trains to operate at higher speeds;

furthermore, there are no intermediate stops, due to the bypass between the South and East lines. The Huesca-Tardienta connection has the lowest commercial speed of 95 km/h, due to the proximity between the two cities. In general terms, nearly two thirds of the total connections have a commercial speed of 180-200 km/h. Commercial costs (*Cc*) oscillate mainly between the 0.10 and 0.20 €/km interval, in which nearly 80% of the connections are included.

These variations and dissimilarities among the connections' characteristics will allow for the identification of different types of HSR links that will elucidate the multiple roles of the Spanish HSR system.

4.2 Identifying HSR links' types

The cluster analysis is carried out establishing eight groups, as is suggested by using the VRC analysis (Table 3.1). These clusters represent all the cases that currently exist in the Spanish HSR network. In Figure 3.4, the links closest to the centre of the cluster are drawn in the maps, and the values for this centre are shown.

Table 3.1: VRC_k and W_k values for different number of clusters

N cluster k	6	7	8	9	10	11	12
VRC_k	770.25	731.76	781.89	622.74	690.62	672.37	664.92
W_k	-112.97	88.62	**-209.29**	227.05	-86.14	10.80	23.75

Cluster 1: This refers to the **'early stage' HSR links,** that is, those between **large cities approximately 400 km apart** and with high frequencies. In Spain, this type of link is found between Madrid and other main cities (most of which are located at the end of the HSR lines), such as Sevilla, Malaga, Valencia or Valladolid. The most representative link (closest to the cluster's centre) is Madrid-Sevilla, which, as previously mentioned, was the first HSR connection launched in the country.

Cluster 2: This comprises solely the **Madrid-Barcelona connection** (inbound and outbound), and represents a particular case of Cluster 1. This cluster is an extreme case and the most favourable of the entire network; it has many trains per day, high commercial speeds, and the costs per km are close to the mean. As in Cluster 1, this type of service connecting large metropolitan areas more than 400 km apart is the one oriented mainly to compete against air transport.

Cluster 3: These are links between medium-size/large cities and a small one at short distances (approximately 100 km) located on the same line with a high number of daily trains. This cluster encompasses first, HSR links between two nearby cities that benefit from various long-distance trains serving different lines (Zaragoza-Lleida or Cordoba-Ciudad Real) (refer to Figure 3.2), and second, HSR links between small cities and large metropolitan areas, in which the combination of long-distance and regional services (AVANT) can be found (Barcelona-Tarragona or Madrid-Segovia). Speeds are low because of the short distances.

Cluster 4: In this case, the cluster encompasses **connections between a large metropolitan area (Madrid) and small distant cities**. The cluster presents medium frequencies because certain trains connecting Madrid to other important cities on the line stop at these small cities. Generally, this type of link also has a low cost per km and similar speeds to Cluster 1. The most characteristic cases are Madrid-Antequera or Madrid-Tarragona. The quality of the service is similar to Cluster 1, the 'early stage' HSR; therefore, the distance between the centres of these two clusters is reduced (Table 3.2). However, in these cases, no air competition is expected because of the small size of the cities (most have no airport infrastructure).

Cluster 5: This is the **link between medium-sized/large cities located on different lines**; therefore, there are long distances between them. The trains do not stop in Madrid because they use bypasses, so travel demand is reduced and the daily services are very low. The long distances allow high commercial speeds, and the low costs per km are applied to avoid excessively high ticket fares. The most representative cases are Zaragoza-Malaga or Valencia-Sevilla.

Clusters 6 and 7: These correspond to **links between two medium-sized or small cities**. The distance between both clusters is small (Table 3.2); therefore, they are very similar. Cluster 6 includes most of the cases in which both cities are on the same line, whereas Cluster 7 encompasses most of the cases in which cities are on different lines. As occurred in Cluster 3 in relation to Cluster 5, Cluster 6 has lower speeds, higher frequencies and higher prices than Cluster 7 (this is also verifiable by the distances between clusters; refer to Table 3.2). The most characteristic links are Ciudad Real-Antequera (Cluster 6) and Ciudad Real-Tarragona (Cluster 7).

Cluster 8: This corresponds to the **Huesca-Tardienta link**. This cluster is also an extreme case and is the most unfavourable of the network. The cluster counts only one train per day. In addition, its quality is very deficient because the commercial speed is really low and the cost per km is the highest in the network.

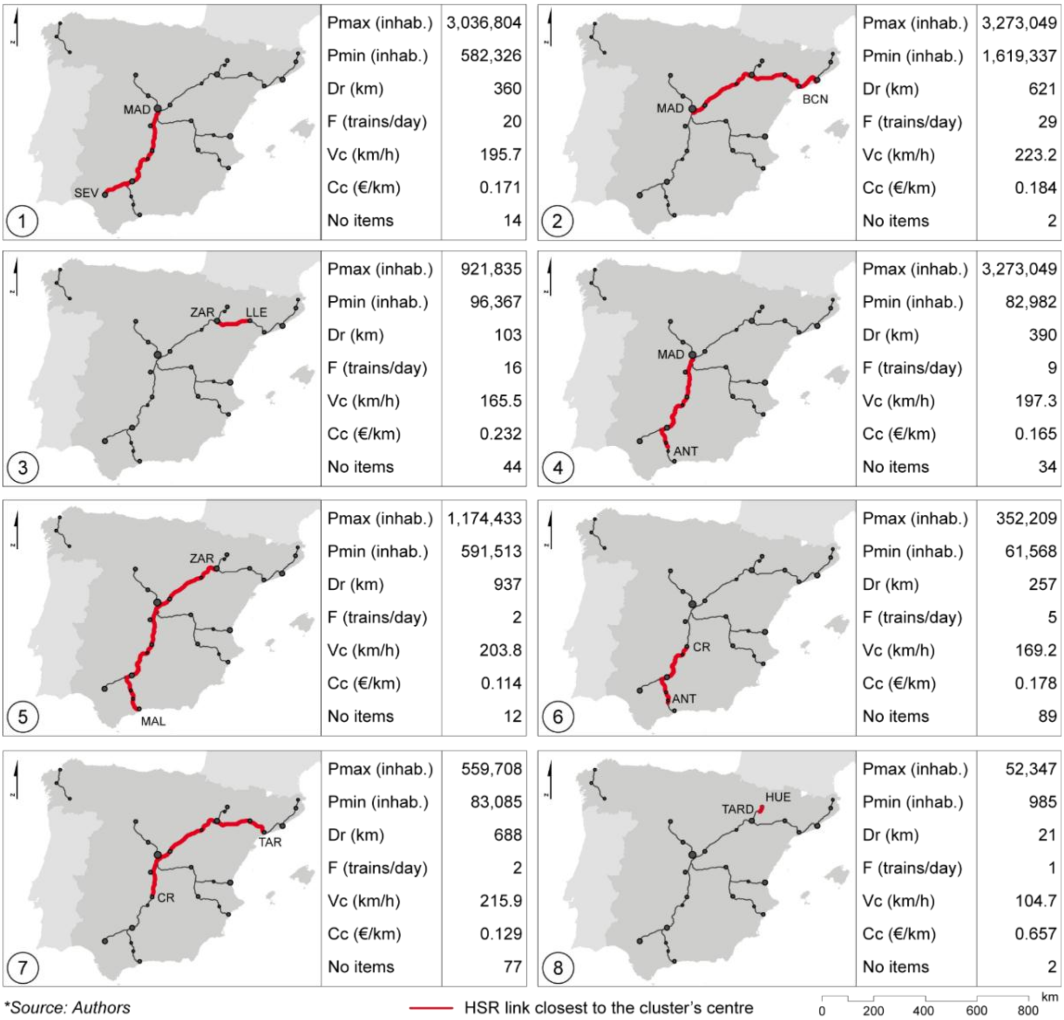


Figure 3.4: Clustering of HSR links' types

Table 3.2: Distances between clusters' centres

Cluster	1	2	3	4	5	6	7	8
1	0.000	5.133	3.370	2.803	3.751	4.107	4.318	9.485
2	5.133	0.000	8.026	7.749	6.591	8.658	8.463	12.415
3	3.370	8.026	0.000	2.869	4.763	1.996	3.674	7.361
4	2.803	7.749	2.869	0.000	3.755	2.789	2.861	8.938
5	3.751	6.591	4.763	3.755	0.000	3.801	2.604	10.097
6	4.107	8.658	1.996	2.789	3.801	0.000	2.290	7.898
7	4.318	8.463	3.674	2.861	2.604	2.290	0.000	9.365
8	9.485	12.415	7.361	8.938	10.097	7.898	9.365	0.000

Once the cluster analysis has been performed, a deeper analysis of cluster variables is carried out. For instance, the *Vc-Dr* dispersion graph (Figure 3.5a) shows that the 'early stage' HSR links (Clusters 1 and 2) are in the centre of the graph; these are characterised by commercial speeds of over 180 km/h and distances of between 350 and 600 km. This observation appears to be mixed with Cluster 4, which is similar in terms of speed and distance, but very different in the size of the smaller city in the connection, and therefore differs in the provision of daily services, as can be observed in Figure 3.5b.

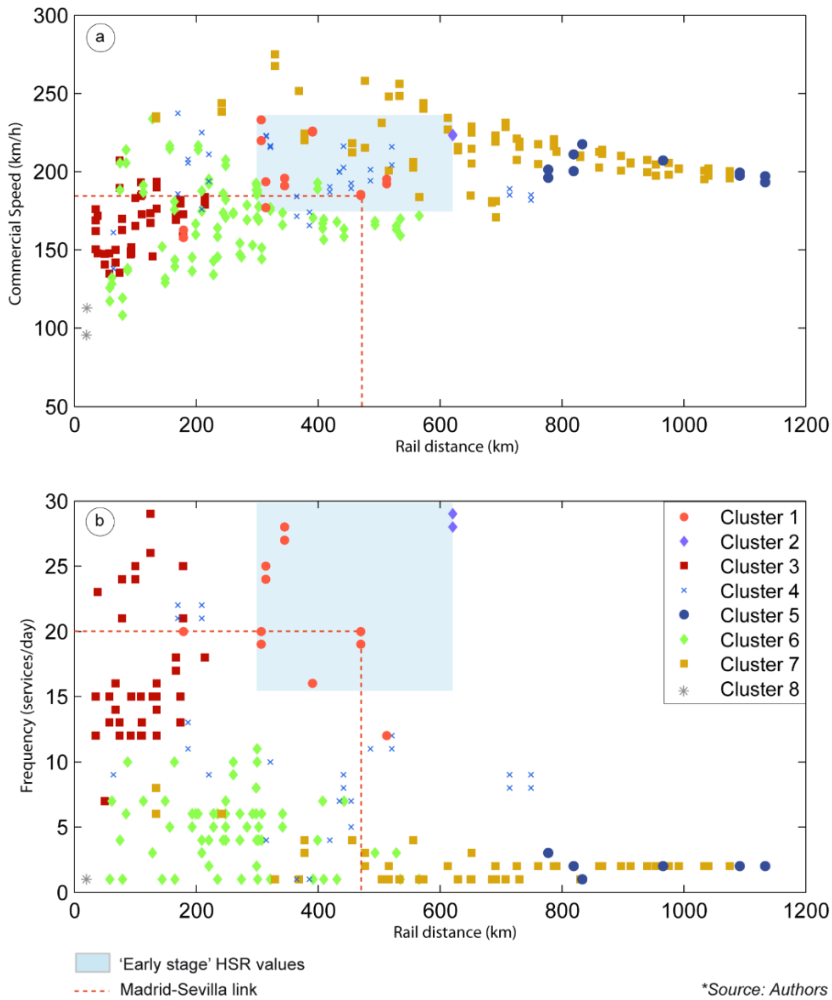


Figure 3.5: Vc-Dr (a) and F-Dr (b) dispersion graph

The other clusters appear well grouped in terms of distance and speed either above or below the 'early stage' ones. In the first case, the long-distance connections made possible by the Madrid bypasses create these groups (Clusters 5 and 7); in the second case, the intermediate stops in small and medium cities generate two more groups: Cluster 3, in which frequent regional high-speed trains are relevant (AVANTs), and Cluster 6, in which the links between same-line intermediate cities extend the HSR network effects.

These graphs also show how different the services running under the high-speed brand are. Speed and frequency variations among HSR connections have an important influence on their quality and utility, particularly when the costs per km are similar. For example, for the same rail distance, approximately 300 km, the speed oscillates from 150 to nearly 280 km/h (Figure 3.5a). These oscillations are due mainly to the number of intermediate stops and the characteristics of the routes: points of reduced speed such as tunnels and non-stopping stations. In certain cases, i.e., the Huesca-Tardienta link (Cluster 8), the commercial policy of the Spanish Rail Company (RENFE) is to dissuade the use of HSR services charging the highest cost per km in the network, 0.66 €/km (tripling the cost of services offering similar quality). In contrast, very long distance connections present the lowest costs per km, offering more reasonable ticket prices to attract passengers. In terms of frequencies (Figure 3.5b), Cluster 3 is the sole cluster that achieves a level of services similar to the 'early stage' links; in this case, this is because short distances and ticket costs promote higher travel demand that must be covered by more frequent trains (regional HSR). The other clusters involve a high number of links, but in most cases present low frequencies, which could be a sign of their marginal role in terms of demand.

Once the cluster analysis has been carried out, it is relevant to identify the relative importance of each group in terms of the number of links, the population involved and ridership (Figure 3.6).

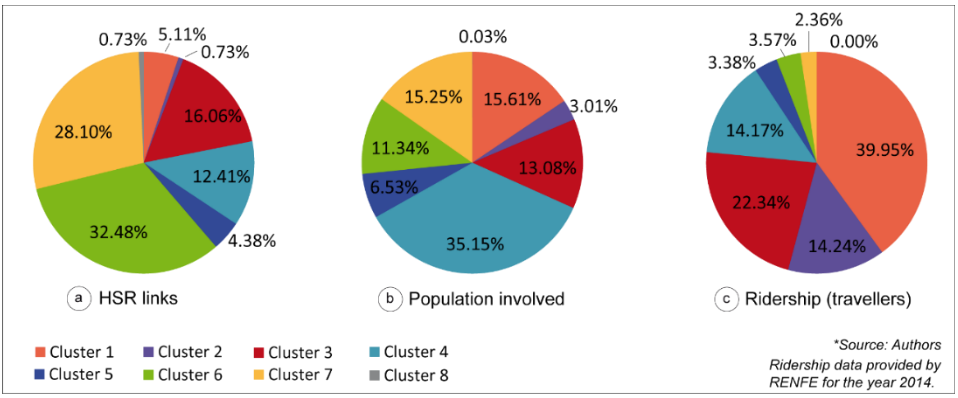


Figure 3.6: Distribution (%) among clusters of all the Spanish HSR links

First, the 'early stage' HSR links (Clusters 1 and 2) are only 6% of the total number of connections; logically, when the population is considered, their share grows to 18% because these types of links were implemented to cover the main city-pairs connections. This is confirmed by the share of ridership (around 55% of the total HSR ridership).Conversely, Clusters 5, 6 and 7 are highly represented in the number of links (around 65% of them) but decrease in relevance when considering the population involved (33%), and finally, they are marginally represented in total ridership (only 10%). However, these HSR links open new opportunities in terms of connectivity, which can be very relevant for certain cities, offering in some cases the sole transportation alternative, at least a same-day feasible alternative, in the city-pair involved. Finally, Clusters 3 and 4 show a more balanced representation when considering the number of links, the population involved and ridership. Cluster 3 links, the regional HSR, benefit from good quality services and are generally oriented to daily commuting, reaching a relevant share in terms of ridership (22%). Cluster 4 increases their representation when considering the population involved, rising from 12% to 35% of sharing, because these HSR links generally include a large metropolitan area (Madrid) in the two cities connected. In terms of ridership, this cluster achieves a share (14%) similar to that of Cluster 2, the Madrid-Barcelona link, which has the highest demand in the network. The type of links also makes it possible to connect many small cities to Madrid, allowing them to reach the wide business, commercial and administrative facilities located in the country's capital.

In summary, HSR offers a wide spectrum of different links that fulfil different roles. From an infrastructure perspective, the 'early stage' links cover most of the HSR ridership, although Clusters 3 and 4 are also representative. However, there are many other kinds of connections (Clusters 5, 6 and 7) that, although they are marginally represented in total ridership, perform a more social role improving opportunities for travellers because they increase the possibilities of travelling, allowing same-day trips between many city-pairs that were unfeasible before the advent of the HSR network.

5. DISCUSSION AND CONCLUSIONS OF THE CHAPTER

This study elucidates the multiple roles the HSR system may perform as a transportation mode nowadays, highlighting the fact that **not all the links branded as high-speed fit into the same profile** because there is a wide range of variations. Apart from the 'early stage' HSR connections, there are also other types that were not envisioned when the initial HSR system was developed; these offer a wider range of travel options that can benefit travellers. In terms of ridership, this study shows that the 'early stage' connections are those that present a higher share, as expected; however, there are other types of links that also rise to a representative volume of travellers that must be taken into account in transport planning. On the other hand, many of those less expected links, although less representative in terms of ridership, offer an important improvement in terms of connectivity, mainly for small cities in the network. **All these aspects confirm the hypothesis proposed in the research question RQ1**, which asked about differences between HSR links in terms of services' characteristics and the multiple roles performed by HSR systems nowadays.

Methodologically, this research presents a new focus to be considered in relation to high-speed rail studies as it is centred on the links, on the 'vector' that characterises the quality of the services supplied in each connection. Apart from the service-related variables included in the methods, there are other aspects, such as station location and intermodal accessibility to/from the station, which could also influence the quality of a specific HSR service and should be analysed individually in each connection. However, **this link-oriented approach may serve as a general basis for a better understanding of HSR connections and the services they provide**. In addition, the application of the methods to the Spanish network shows a general view about the main types of HSR links that can be found in other cases, although other networks' analyses could highlight their own singularities. Precisely, for further research, applying this approach to other networks could offer a wider spectrum of connections, which would allow for a comparison of different network structures and different ways of developing the HSR system.

The approach carried out in this chapter may be a useful tool in transport planning in order to anticipate how new HSR systems may be developed in terms of types of future city-to-city links. The HSR links' typology obtained in this study may help transport planners to estimate which kinds of services and frequencies should be planned when a new HSR city is included in the network, facilitating the implementation of new HSR connections. In addition, potential HSR cities would know a priori the different possibilities of connections that could serve it, according to their own characteristics, position in the network, and the entity of nearby cities. Therefore, this approach could serve to establish a benchmark for future HSR cities, helping them to adapt its policies and strategies according to its potential services.

Chapter 4

High-speed rail efficiency analysis for same-day trips

OUTLINE OF THE CHAPTER

Since the opening of the first HSR, several studies have been undertaken to evaluate the accessibility HSR provides. Generally, the measures used in these studies consider the characteristics of the new transport system (speed, layout, stops, etc.) that are related mainly to the infrastructure itself. However, many studies on HSR have also highlighted the importance of providing services (timetables, frequencies and fares). A high-performance infrastructure such as HSR may not reach its full potential in terms of accessibility unless adequate services are provided. Considering this service approach, this chapter is centred on the main methodological basis of this dissertation and focuses on two main objectives, trying to answer **research questions 2 and 3**:

1) An analysis of the efficiency of HSR connections with regard to business and tourism same-day trips, which allows quantifying the opportunities provided by the whole HSR network in terms of mobility choices for each city. This first aim is explained in **Section 4**, and is complemented by an efficiency analysis of commuting trips in **Section 5**, as a particular case of business journeys.
2) A comparative accessibility analysis between the efficiency measure as a schedule-based approach and a location-based accessibility indicator. Comparing these two measures helps us evaluate the extent to which the services provided in each city allow the HSR network to reach its full potential accessibility. This second aim is developed in **Section 6** of this chapter.

1. INTRODUCTION

Since the launch of the first high-speed rail (HSR) line in Europe in the 1980s, HSR has become an increasingly complex mode of transport. On the one hand, the HSR system has passed from the initial single lines connecting the main metropolitan areas to whole HSR networks involving many cities and multiplying the possible connections between them. On the other hand, the new variety of HSR services and changes in commercial policies, offering more economical ticket prices to attract users, is opening up a new panorama in which the HSR system plays different roles in providing mobility opportunities for travellers (Moyano and Coronado, 2017). These opportunities are also available to HSR cities, and may increase their visibility, improve their image and extend their potential markets for different activities, such as business, commuting and tourism.

Literature on the socioeconomic and mobility effects of HSR has widely analysed the influence of this infrastructure on business activities. As was mentioned in *Part I: Introduction* of this dissertation, from the start, HSR prioritised connections between large markets, reinforcing labour relationships between the main metropolitan areas (Givoni, 2006; Vickerman et al., 1999). However, the implementation of regional HSR services favours other kinds of labour relationships between cities, with important effects on residence-workplace location (Chen and Hall, 2012; Garmendia et al., 2012b). In fact, the literature recently identified HSR as a key variable for assessing the growth of labour contracts and for understanding the dynamics of labour markets (Guirao et al., 2017). In addition, the main rail operators in Europe have been exploring new commercial policies aimed at attracting travellers who would otherwise use alternative transport modes, especially for non-mandatory purposes (leisure, tourism, etc.). Examples are found in France and Spain, with the introduction of low-cost HSR services (Delaplace and Dobruszkes, 2015), combined with the introduction of dynamic pricing systems that allow users to find more economical ticket fares in some cases. However, the literature offers no clear evidence of the positive effects of HSR on local tourism development (Albalate and Fageda, 2016; Guirao and Campa, 2016), unless there is a strong local promotion of the tourist destination (Delaplace et al., 2016, 2014; Masson and Petiot, 2009). However, an analysis of tourism-related, same-day visits to other cities in the network from the main national and international tourist destinations shows that HSR has a significant effect on tourists' choice of destination (Pagliara et al., 2017, 2015).

Most of these studies have focused on the impacts of HSR in certain cities, analysing HSR impacts on mobility and opportunities for socioeconomic development, thanks to the arrival of this new infrastructure. Nevertheless, in this new context of HSR expansion, the quality of the operating services is just as important as securing an HSR infrastructure. The opportunities for travelling opened by HSR are linked directly to the characteristics and suitability of the services supplied for specific travel purposes. However, most studies in the literature on transport geography analysis have been based on the remarkable reduction in travel times they enable, from the perspective of cities' location in the network (Spiekermann and Wegener, 1996) (Bruinsma and Rietveld, 1993; Monzón et al., 2013). This location-based perspective is very useful for understanding changes in accessibility generated by a new infrastructure. However, nowadays, having a faster train does not always imply having a good connection. The possibilities open to travellers using the HSR system, and the requirements they face must be considered because, from the users' point of view, aspects such as frequency, fares, adequate schedules and, especially, the useful time required at the destination may become more relevant than the reduction in travel times provided by HSR.

This chapter presents two main objectives. First, analysing the efficiency of HSR connections with regard to business, tourism and commuting same-day trips in Spanish cities. This first main aim is not to measure the effects but to quantify the opportunities provided by the whole HSR network in terms of mobility choices for each city, and to assess the extent to which different transport-related factors influence the efficiency of each HSR connection. Second, analysing and comparing HSR accessibility by reflecting on the difference between how a location can potentially be connected and how this connection is actually achieved by the services provided. This second analysis evaluates the differences between accessibility measures, especially with regard to the extent to which the real opportunities the services supplied by the HSR system encompass the potential opportunities the infrastructure offers.

This approach is applied to the cities included in the Spanish HSR, which is a relevant case study as the network is highly developed (more than 3,100 km, six main lines and 31 stations) and there is a wide range of different services leading to a very heterogeneous situation in terms of the quality of the connections between cities (Moyano and Coronado, 2017). At present, it is not sufficient just to have an HSR station; it is also necessary to achieve a certain quality of operating services (Moyano and Dobruszkes, 2017), which will drive the potential contribution and, in general, the real utility of HSR to a city and its citizens.

2. ACCESSIBILITY MEASURES IN TRANSPORT NETWORKS

Accessibility is a key analytical concept related to the assessment of transport networks. It has become a hot topic in the field of transport especially with regard to spatial interactions that can be addressed using multiple approaches and conceptualisations.

Accessibility is usually defined as a potential, reflecting the ease with which certain movements can occur under different conditions.

2.1 The location-based approach: networks

Indicators based on location focus on places and different access between them in a given transport system. Accessibility measures were commonly calculated based on potential expressions that struck a balance between the attractiveness of accessing a destination and the inconvenience (friction) imposed by the distance of that destination from the traveller's origin. Different indicators are used depending on the specific aim of the study (Bruinsma and Rietveld, 1998; Geurs and van Wee, 2004; Gutiérrez, 2001; Schürmann et al., 1997).

Travel cost measures refer to the degree of connection between two places. They represent the accumulated or weighted cost of travel from a fixed origin to other destinations in the network or a pre-defined set thereof. Such measures are particularly useful when assessing changes in accessibility resulting from new infrastructures or when comparing different scenarios. Spiekermman and Wegener (1996) represented the 'shrinkage' of space in relation to the reduction of travel times between pairs of cities with regard to changes in accessibility in Trans-European networks using what they called time-space maps. In these maps, the distances between cities are proportional not to the physical separation, as in topographical maps, but to the travel times between them. Another type of location-based measure is a *potential accessibility indicator*, in which accessibility is regarded as being proportional to a mass (typically, a population-based or economic index) and decreases with increasing distance, which is generally represented by travel time. Such indexes are usually called gravity-based measures and have appeared in the literature with various functional forms, including power-law, Gaussian and negative exponential functions (Bruinsma and Rietveld, 1993; Spiekermann and Wegener, 2006), and they are applied to assess the changes in accessibility (López et al., 2008; Monzón et al., 2013; Ortega et al., 2012) and to analyse the economic effects and spillovers (Condeço-Melhorado et al., 2011; Gutiérrez et al., 2010; López et al., 2009) caused by the establishment of a new infrastructure. Finally, *daily accessibility measures*, also known as contour or cumulative-opportunity measures, represent the number of opportunities that can be reached within the constraints of a given travel time, cost or distance (Gutiérrez, 2001; Páez et al., 2012; Spiekermann and Wegener, 1996). All these location-based indicators ultimately compare the potential of different locations in the areas to which they are applied, thereby evaluating the spatial accessibility conditions provided by a given transport network.

2.2 The schedule-based approach: services

In recent decades, accessibility studies have been returning to the concept of 'time geography' (Hägerstrand, 1970) as a person-based approach to assessing transport networks, which means that the focus is placed on who is accessing the resources provided by the network. In time-space approaches, each individual describes a path, graphically represented by a 'daily prism' and a 'Potential Path Area (PPA)', which is defined by the constraints imposed by certain patterns of human activity (Miller, 1991; Neutens et al., 2010). This idea of *activity pattern* is also used in travel behaviour modelling and activity-based accessibility measures, which forecast people's travel during a whole day's schedule of multiple activities and trips (Bowman and Ben-Akiva, 2001). These activity-based measures incorporate the impact of trip chaining, the full set of activities pursued in a day, and the scheduling of these activities (Dong et al., 2006). Scholars have demonstrated the usefulness of these approaches for evaluating individuals' accessibility to the environment (Fransen et al., 2018; Kwan, 2004; Schwanen and Dijst, 2003). However, difficulties arise when we need to combine this individual-based approach with network analysis because such a combined analysis needs more complex computations (Tong et al., 2015) and sometimes requires a priori hypotheses concerning traveller profiles. For this reason, in spatial analyses, location-based approaches are much more widely applied.

Several studies have combined both approaches in some manner by including elements that consider various aspects related to both locations and individuals. In schedule-based transportation systems such as transit, rail or air transport, access is limited to fixed timetables and, therefore, the level of service will change throughout the day, depending on the frequencies that will play an important role. On the one hand, the adaptability of the services' timetables to the travellers' needs, that is, the relation between the schedule-based and desired departure times will be a key element in the choice of transport mode (Cascetta et al., 2011). On the other hand, the differences in travel time in schedule-based systems depending on the time of day will have a high influence on accessibility. Many studies have introduced concepts drawn from the space-time approach in the traditional location-based formulations, such as weighted travel times (Shaw et al., 2014) or contour measures. The latter studies are developing continuous accessibility calculations which allow identifying the accessibility variations in different time windows (Farber and Fu, 2017; Fransen et al., 2015; Xu et al., 2015). These continuous measures are normally applied to transit systems, in an urban scale, and focus on identifying the time-dependent accessibility levels to certain facilities such as jobs or educational centres (Boisjoly and El-Geneidy, 2016; Owen and Levinson, 2015), supermarkets (Farber et al., 2014; Widener et al., 2017, 2015), health care services (Langford et al., 2016), etc. Even more, recent schedule-based approaches include aspects of social equity, analysing accessibility not only by travel time variations but also by transit costs (El-Geneidy et al., 2016). In general, all these approaches are a very useful tool for analysing schedule-based transportation systems and highlight the importance of the services supplied in accessibility analysis.

When considering long-distance networks, such as rail and air systems, on a national or even international scale, travellers usually buy their tickets in advance and organise their trip by choosing a specific service, as frequencies are not as high as they are in transit systems. In these cases, the accessibility analyses conducted in the literature are generally conditioned by the travellers' needs according to different travel purposes. The first examples are oriented to business trips and are based on the concept of '*contactability*', which refers to the number of 'potential contacts' a business traveller can reach from a certain point of origin in a network (Törnqvist, 1970). This approach begins to introduce certain hypotheses regarding individuals' daily activities and their needs for the purpose of establishing an adequate time budget at a destination. Using the time available at a destination and considering all transport modes, Erlandsson (1979) analysed accessibility in the European system of cities and calculated the number of people potentially reachable from a point (outbound potential contacts), and the number of people who can reach a point under the same conditions (inbound potential contacts). Despite being a powerful tool, time available at destination has not been used regularly in the analysis of transport networks. Gutiérrez (1991) used this methodology in assessing accessibility to public transport in the villages north of the Madrid metropolitan area. After establishing the minimum or maximum departure and arrival times, commutes or leisure travels to Madrid were determined in order to obtain a combined accessibility indicator. Building on these considerations, as part of the European ESPON project, a similar indicator of the number of cities contactable by air and rail transport at the European level was computed, establishing certain hypotheses regarding the trip chain (required time budget, access time to each station, departure and arrival times, etc.) for both business (L'Hostis and Leysens, 2012) and commuting (L'Hostis and Baptiste, 2006) purposes. Although they are formulated as location-based measures, these indicators are actually introducing a new way to understand a network's operation from an individual perspective. These indicators of 'contactability' result in dummy variables as they assess whether access to a certain destination is possible or not, following the pre-established conditions.

In this dissertation a similar way of analysis is carried out, addressing the efficiency of HSR services in Spain, considering the time available at a destination and the associated travel costs for different travel purposes (Moyano, 2016; Moyano et al., 2016); and also comparing the usefulness of HSR services with the potential accessibility afforded by the infrastructure itself (Moyano et al., 2018).

3. METHODOLOGY

3.1 Efficiency measure: parameters and restrictions

The methodology proposed in this dissertation allows a two-step approach. First, this systematic assessment is based on an analysis of the efficiency of all the HSR connections, considering different travel requirements regarding tourism, business or commuting same-day trips. Second, these efficiencies of each HSR connection allow us to calculate a global measure of efficiency for every HSR city in the network, which enables us to compare the utility of HSR for same-day trips among cities and identify the cities that benefit most from the opportunities HSR provides for each travel purpose.

Methodologically, the 'efficiency' indicator is based on the useful time available at the destination (T_u) and the associated costs (C_{total}). It represents the efficiency of the money invested to gain time available at a destination and follows the expression (4.1):

$$E_{ij} = \frac{T_{u\,ij}}{C_{total\,ij}} \tag{4.1}$$

This efficiency measure is optimised through a computation algorithm considering actual HSR timetables and ticket cost information provided by the Spanish rail operator, Renfe[1]. The efficiency indicator for every city-to-city connection depends on the choice of outbound and inbound high-speed trains for a return journey and, therefore, takes into account the requirements and restrictions related to different users' needs, depending on their travel purpose. First, the days chosen for travelling were Saturday for tourism trips, and Wednesday for business trips. In the first case, Saturday is the best day for travelling because it is not a workday for many employees, and tourist amenities (museums, expositions, etc.) are open for visitors. For business trips, Wednesday was considered the most representative working day because it is not influenced by the services' variations on weekends, as happens on Fridays and Mondays, for instance. Second, the time available at the destination (4.2)(4.3) depends on the arrival and departure times of the selected outbound and inbound trains (a_1, d_2), the access/egress times in the destination city ($t_{a\,dest}$) and the different useful time at the destination needed (T_{obj}) for each travel purpose. Tourists attempt to maximise their time at a destination so their costs are profitable, whereas business travellers only require that the time at a destination fits the maximum meeting duration to the extent possible, minimizing waiting times.

[1] The data were collected at the end of 2015.

Finally, the associated costs (4.4) include both ticket (C_{ticket}) and travel time costs (C_{time}). For the ticket cost, the return fare offered by RENFE, which includes a discount of 20%, was considered. Travel time costs depend on travel and waiting times and the value of time (vt) of the traveller for each travel purpose.

$$T_u = g\,(a_1, d_2) = \begin{cases} T_u^* & if\ T_u^* < T_{obj} \\ T_{obj} & if\ T_u^* \geq T_{obj} \end{cases} \quad (4.2)$$

$$T_u^* = (d_2 - a_1) - (2 \cdot t_{a\,dest} + t_{security}) \quad (4.3)$$

$$C_{total} = C_{ticket}\,(c_{o1},\ c_{o2}) + C_{time}\,(d_1, a_1, d_2, a_2) \quad (4.4)$$

$$C_{ticket} = 0.80 \cdot (c_{o1} + \ c_{o2}) + 2 \cdot (c_{a\,orig} + c_{a\,dest}) \quad (4.5)$$

$$C_{time} = vot_1 \cdot t_{travel} + vot_2 \cdot [2 \cdot (t_{a\,orig} + t_{a\,dest})] + vot_3 \cdot t_{wait} \quad (4.6)$$

Where:

T_{obj}: objective useful time

d_1, a_1 : departure and arrival times of train 1 (outbound)

d_2, a_2: departure and arrival times of train 2 (inbound, return train)

$c_{o1},\ c_{o2}$: ticket cost of trains 1 and 2, respectively

$c_{a\,orig}$: Egress and access cost from/to the station in the city of origin

$c_{a\,dest}$: Egress and access cost from/to the station in the destination city

$t_{a\,orig}$: Egress and access times from/to the station in the city of origin

$t_{a\,dest}$: Egress and access times from/to the station in the destination city

$t_{security}$: Security time before train's departure, 10 min

t_{wait}: Waiting time in the destination city, $t_{wait} = T_u^* - T_{obj}$

vot_i : Value of time for 1) travel time; 2) access and egress times and 3) waiting times

As mentioned earlier, the choice of the outward and return trains depends on users' preferences. In this chapter, the different parameters and restrictions used in the calculation are shown in Table 4.1:

Table 4.1: Parameters and restrictions used in the efficiency calculation

	Tourism trip	Business trip	Commuting trip
Parameters	T_{obj}: max vot_1: 7.03 €/h vot_2: 10.00 €/h vot_3: 10.77 €/h $t_{a\,dest/orig}$: PT travel time $c_{a\,dest/orig}$: PT travel cost	T_{obj}: 6 h vot_1: 23.34 €/h vot_2: 28.33 €/h vot_3: 73.68 €/h $t_{a\,dest/orig}$: taxi travel time $c_{a\,dest/orig}$: taxi travel cost	T_{obj}: 8.5 h vot_1: 10.35 €/h vot_2: 10.00 €/h vot_3: 10.77 €/h [2] $t_{a\,dest/orig}$: PT travel time [3] $c_{a\,dest/orig}$: taxi travel cost [4]
Restrictions	$a_1 + t_{a\,dest} \geq$ 10:00 h $d_1 - t_{a\,orig} \geq$ 7:00 h	$a_1 + t_{a\,dest} \geq$ 8:30 h $d_1 - t_{a\,orig} \geq$ 5:00 h	$a_1 + t_{a\,dest} \leq$ 9:30 h $d_1 - t_{a\,orig} \geq$ 5:00 h $T_{obj} \geq$ 8.5 h [5]

PT: public transport

[2] The research conducted by Román et al. (2014) provides different **values of time (VOT)** for the various components of total travel time (access and egress, waiting and in-vehicle times) for HSR travelers in the Madrid – Barcelona corridor. In our case, the values selected for the different trip purposes are those obtained in the multinomial logit model, considering that for business trips the enterprises pay for the ticket, and for tourism and commuting, travelers pay for their own ticket.

[3] **Access and egress times** used in the calculations are the weighted average travel times of both private vehicle (taxi) and public transport, using Google's API and the population of the Eurostat 1kmx1km grid as the mass factor. Access and egress times analysis is carried out in detail for the case of large metropolitan areas, Madrid and Barcelona, where the influence of these local travel times can be determinant in the whole HSR trip. This in-deep analysis is developed in the Chapter 5 of this dissertation.

[4] **Access and egress costs** included in the measure correspond to the ticket cost in the case of public transport, rounded to €2. In the case of taxi, the equivalent cost is computed considering the weighted average distance and the cost per km established for each city in the network (Facua, 2015). The distance is obtained using Google's API information and the population of the Eurostat 1kmx1km grid as the mass factor.

[5] The **arrival to the final destination** ($a_1 + t_{a\,dest}$) is different depending on the trip purpose: tourists are not interested in being at the final destination before 10:00 hours because the main amenities (museums, monuments, shops, etc.) usually open at that time. Business travellers could be at the final destination at 8.30 hours, when the workday is started, and commuters must be at work before 9.30 hours (considering certain flexibility in their working schedules). The **departure time to the station** ($d_1 - t_{a\,orig}$) should not be before 7:00 hours for tourists, as they normally would not like to get up very early for a leisure trip, while business and commuting travellers assume they must be able to take the first train in the morning. In addition, for commuting trips, T_{obj} must be higher than 8.5 h, because the labour schedule consists of 7.5 daily working hours (37.5 hours per week) and one hour for lunch, which is 8.5 hours of total time available at the destination.

With all these parameters and restrictions, the global value of efficiency 'E_G' (4.7) and the weighted average efficiency measure 'Ew' (4.8) for all the cities in the network are obtained:

$$E_{G\,j} = \sum_i E_{\,ij} \qquad (4.7)$$

$$E_{w\,j} = \frac{\sum_i E_{\,ij} \cdot M_{\,i}}{\sum_i M_{\,i}} \qquad (4.8)$$

Where:

$E_{\,ij}$ is the efficiency measure for each city-to-city link in the network.

$M_{\,i}$ is the mass factor related to the importance of each city. It will be different depending on the travel purpose.

These global values of efficiency allow for assessing the performance of each city for different travel purposes and for comparing cities in the network. While the 'E_G' measure is calculated as the linear sum value for a certain city, the 'Ew' indicator is the weighted average measure that takes into consideration the relevance of the cities connecting to a certain destination. This relevance is represented by different mass factors depending on the travel purpose: the total population[6] in the case of tourism and the number of high-skilled jobs in the case of business [7] (Table 4.2).

Trips taken for commuting purposes can be influenced by certain characteristics and constraints that differ from those inherent in trips taken for tourism and business purposes (see Table 4.1). In addition, for commuting trips, only several connections will be accessible due to the strict temporal requirements governing working schedules and time available at destinations. For that reason, the computation of global values of efficiency is not carried out because, in this case, these indicators lose reliability in comparison with the city-to-city efficiency analysis (see Section 5 of this chapter).

[6] Population data obtained from the Spanish National Institute of Statistics (INE) by the year 2017.

[7] The number of high-skilled jobs is obtained from the Spanish Census Data 2011 (CNO – 11).

Table 4.2: Population (P) and High-skilled jobs (HSJ) in the HSR cites analysed

City	Population (P) (inhab.)	(% of total)	High-skilled Jobs (HSJ) (workers)	(% of total)
Figueres	44,200	(0.46%)	4,950	(0.26%)
Girona	95,665	(0.99%)	18,820	(0.99%)
Barcelona	1,601,935	(16.59%)	374,450	(19.62%)
Tarragona	133,025	(1.38%)	23,960	(1.26%)
Lleida	136,670	(1.42%)	20,450	(1.07%)
Huesca	51,170	(0.53%)	7,795	(0.41%)
Tardienta	985	(0.01%)	80	(0.00%)
Zaragoza	672,955	(6.97%)	112,905	(5.91%)
Calatayud	20,615	(0.21%)	2,615	(0.14%)
Guadalajara	83,700	(0.87%)	13,915	(0.73%)
Madrid	3,186,595	(33.00%)	719,685	(37.70%)
Segovia	54,520	(0.56%)	7,885	(0.41%)
Valladolid	309,930	(3.21%)	51,180	(2.68%)
Cuenca	55,780	(0.58%)	9,150	(0.48%)
Requena	21,105	(0.22%)	2,480	(0.13%)
Valencia	790,755	(8.19%)	150,410	(7.88%)
Albacete	171,030	(1.77%)	28,375	(1.49%)
Villena	34,480	(0.36%)	3,200	(0.17%)
Alicante/Alacant	328,100	(3.40%)	53,550	(2.81%)
Toledo	83,070	(0.86%)	16,670	(0.87%)
Ciudad Real	74,865	(0.78%)	15,570	(0.82%)
Puertollano	51,745	(0.54%)	6,190	(0.32%)
Córdoba	327,205	(3.39%)	51,955	(2.72%)
Sevilla	696,315	(7.21%)	125,300	(6.56%)
Puente Genil	30,115	(0.31%)	2,935	(0.15%)
Antequera	41,590	(0.43%)	4,665	(0.24%)
Málaga	559,680	(5.80%)	79,750	(4.18%)

3.2 Calculation procedure: outbound and inbound trains' selection

The computation of the efficiency measure is conditioned by the characteristics of both outbound and inbound HSR trains between cities: schedules, ticket prices, day of the week etc. This information is provided by the Spanish rail operator RENFE. Working with all this data requires a computer application to automate the computations. First, all necessary data were collected in October 2015, and then a computer algorithm was programmed to select the most convenient outbound and inbound trains of each connection. This selection is made guaranteeing the most efficient connection in terms of time available at destination and costs, given the parameters and restrictions established in Table 4.1 for each trip purpose (Figure 4.1).

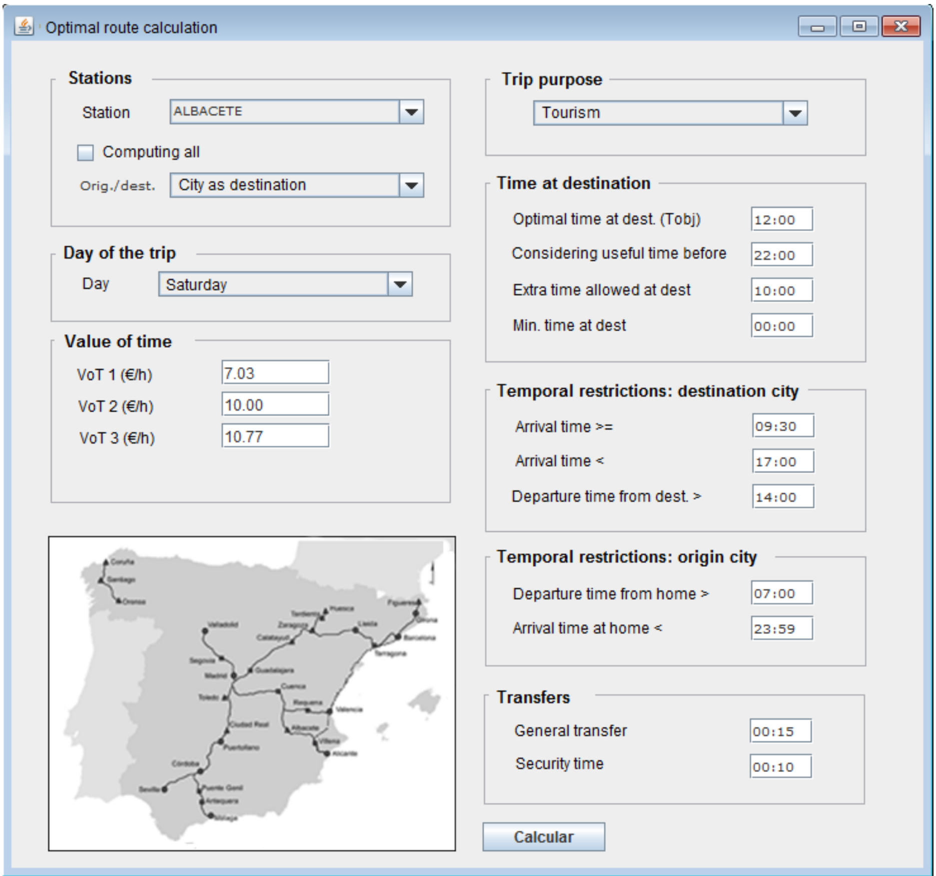


Figure 4.1: HTML pop-up window provided by the algorithm

Currently there are more than 270 direct connections among HSR cities in the Spanish network (Moyano and Coronado, 2017). However, the algorithm also takes into account the possibility of changing at intermediate stations in order to cover all the situations offered to travellers: first, to make possible non-direct connections between cities in the network, and second, to find more efficient connections. In those cases where a change between trains is needed, at least 15 minutes of difference between arrival and departure times is required when the change is to be made at the same station, and at least 45 minutes is required when the change is made between Chamartín and Atocha stations in Madrid.

4. EFFICIENCY OF HIGH-SPEED RAIL SAME-DAY TRIPS: BUSINESS AND TOURISM

This section is based on the paper:

Moyano A., Rivas A. and Coronado J.M. 'Business and tourism high-speed rail same-day trips: factors influencing the efficiency of high-speed rail links for Spanish cities', *European Planning Studies*, Accepted for publication

It has been edited and adapted to fit the structure of this dissertation.

INTRODUCTION

In this section of Chapter 4, an analysis of the efficiency of high-speed rail connections with regard to business and tourism same-day trips is carried out. The aim is not to measure the effects but to quantify the opportunities provided by the whole HSR network in terms of mobility choices for each city and to assess the extent to which different transport-related factors are influencing the efficiency of each HSR connection. This analysis of the efficiency of HSR connections and its sensitivity to different factors and travel purposes is a useful tool for transport planning, especially for cities, because they may do their best to achieve service quality improvements or even adapt their strategies to different activities.

METHODOLOGICAL HYPOTHESES ADOPTED IN THIS SECTION

I) Efficiency measure

This section deals with a systematic study of all of the Spanish HSR connections. Methodologically, the 'efficiency' measure of the actual HSR services explained in section 3 of this Chapter is applied in this section for tourism and business purposes. The objective in this section is to assess first, the opportunities provided by the HSR system for same-day trips to each city in the network and second, the potential improvement of this efficiency in relation to the optimal scenario and its sensitivity to different transport-related factors.

II) Optimal efficiency calculation: sensitivity analysis to transport-related factors

The calculation of optimal efficiency is carried out considering different scenarios in which the different variables included in the indicator achieve their best performance: the optimal values of ticket costs, an ideal adaptation of the HSR services to the travellers' needs and supposing there is no access/egress friction in the destination city (the final destination of the trip is the station itself). Precisely, the scenarios considered are:

- *Scenario 1: Ticket cost.* In this case, the ticket cost considered in the calculation of efficiency is calculated using the lowest cost per km in the network, 0.10 €/km, and the real rail distance between the cities connected.
- *Scenario 2: HSR service timetables*. This scenario supposes an ideal adaptation of the HSR services for each travel purpose, achieving the maximal useful time at the destination in the case of tourism trips and six hours for business, but maintaining the friction introduced by in-vehicle and access travel times for each city and the associated costs of the trip. Also, in this scenario, the penalty introduced by transfers between trains disappears.
- *Scenario 3: Access/egress times*. In this case, access and egress times, which influence both the useful time at the destination and the associated costs (in time and monetary terms), is reduced to zero in the destination city, considering that the end of the trip is the station itself. However, the friction introduced by access/egress times in the origin city is maintained, as it is related to the population's spatial distribution in the home-end of the trip.
- *Scenario 4: Optimal efficiency*. This scenario encompasses the optimisation of the three variables considered above.

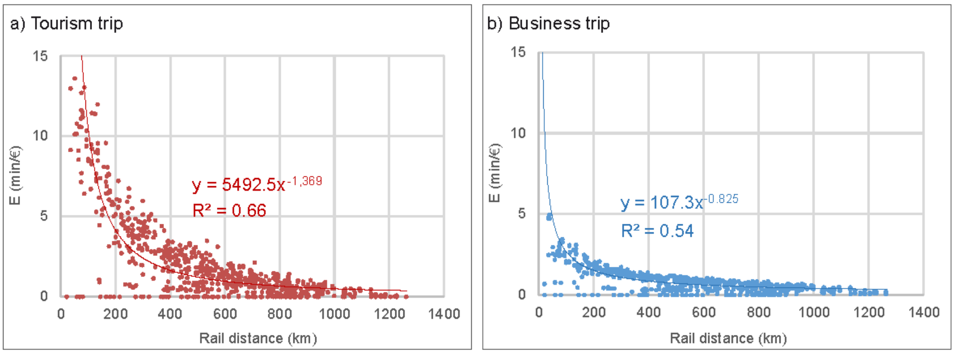
The latter scenario of optimal efficiency allows for an understanding of the actual performance of each city and connection in relation to their best possible situation. Also, the other derivative scenarios, considering only the optimisation of one of the variables mentioned above, are interesting for assessing the different influence of these variables, depending on the city analysed.

EFFICIENCY ANALYSIS OF SPANISH HSR CITIES: BUSINESS AND TOURISM SAME-DAY TRIPS

The efficiency measures (E) for all the city-to-city connections in the Spanish network are represented in Figure 4.2, in relation to the rail distance between the cities connected in each case. Focusing on the trends both for tourism and business trips, the graphs show the adjustment of the efficiencies to a potential expression ($y = b \cdot x^{-\alpha}$):

in the case of tourism, the ajustment is higher (R^2 = 0.66) than for business trips (R^2 = 0.54). For tourism (Fig. 4.2a), the dispersion of the graph is due mainly to access/egress times in the destination city and to the different ticket fares, which do not keep the same cost per km for all the connections in the network. In the case of business (Fig. 4.2b), the actual efficiency graph is more scattered because, apart from the above-mentioned factors influencing the dispersion for tourism, in this case waiting times represent an important penalty that is not related to the rail distance. The relationship between efficiency and rail distance shown in these figures is one of the main insights of this study. Apart from the differences between business and tourism purposes, both graphs show certain scattering (shown by the R^2 adjustments), which allow for the detection of differences between connections: there are HSR links with the same value of efficiency but a very different rail distance (sometimes more than 200 km). These differences between efficiency and rail distances supposes a relevant contribution of this efficiency approach with regard to traditional accessibility studies, highlighting that not only travel times but also quality of services (timetables, costs, etc.) are key in the analysis of HSR same-day trips.

In addition, the negative potential expressions for tourism and business give some other insights. The values of the constant 'b' are very different, surpassing 5,000 for tourism and only 100 for business. This is related to the absolute values of the indicator which is able to reach much higher figures for tourism trips than for business. In the former travel purpose, the aim of maximising the time available at a destination and the lower values of time (vt) for tourists (see Table 4.1) allow for the achievement of higher effiencies, especially for shorter trips, while for business, efficiency is limited due to the maximum of six hours at the destination established as T_{obj}. Another insight is the influence of distance in both same-day trips, which is related to the alpha parameter of the potential expression. For tourism, the distance decay is more pronounced than for business ($\propto = 1.369$ and $\propto = 0.825$, respectively), because in this second case the influence of distance on the efficiency measure is not as relevant as it is for tourism. For business, achieving six hours at a destination is easier, even for long-distance links, which is why the effect of distance is less marked. Therefore, in Figure 4.2b, for rail distances greater than 250-300 km, the differences in the efficiency values are very reduced. Finally, it has to be said that, in both cases, there are some destinations that are not reachable in a single day trip due to inconvenient HSR services or to very long travel times, and that is why there are some zero efficiency points in the graphs.



Source: Authors

Figure 4.2: Actual city-pair efficiency for tourism (a) and business (b) same-day trips

In addition to general trends, a global value of the efficiency measure (E_G) is obtained for every city in the network, both for tourism and business trips. Figure 4.3 shows first the normalised values of this global indicator (the diameter of the rings is proportional to this measure) and then the comparison between the global efficiency for tourism (Et_G) and business (Eb_G) in each city (the thickness of the ring represents the difference between these values). In general, cities placed in central positions in the network achieve a higher efficiency than peripheral ones, although the efficiency measure allows for the detection of relevant differences among cities a priori in a similar territorial situation. For instance, Toledo, Segovia and Guadalajara have a similar situation close to Madrid; however, even when Toledo is located in a dead end high-speed line only connecting directly to Madrid, and Segovia is located in an unconnected line that needs to transfer between stations in Madrid to reach the rest of the cities in the network, both of them present a higher efficiency than Guadalajara, thanks to the better services supplied in terms of frequencies and ticket costs. It is also remarkable the situation of Huesca, which is only served by one HSR train connecting to Madrid in the morning and coming back in the evening, making impossible to visit the city in a same-day trip (the value of E_G is zero).

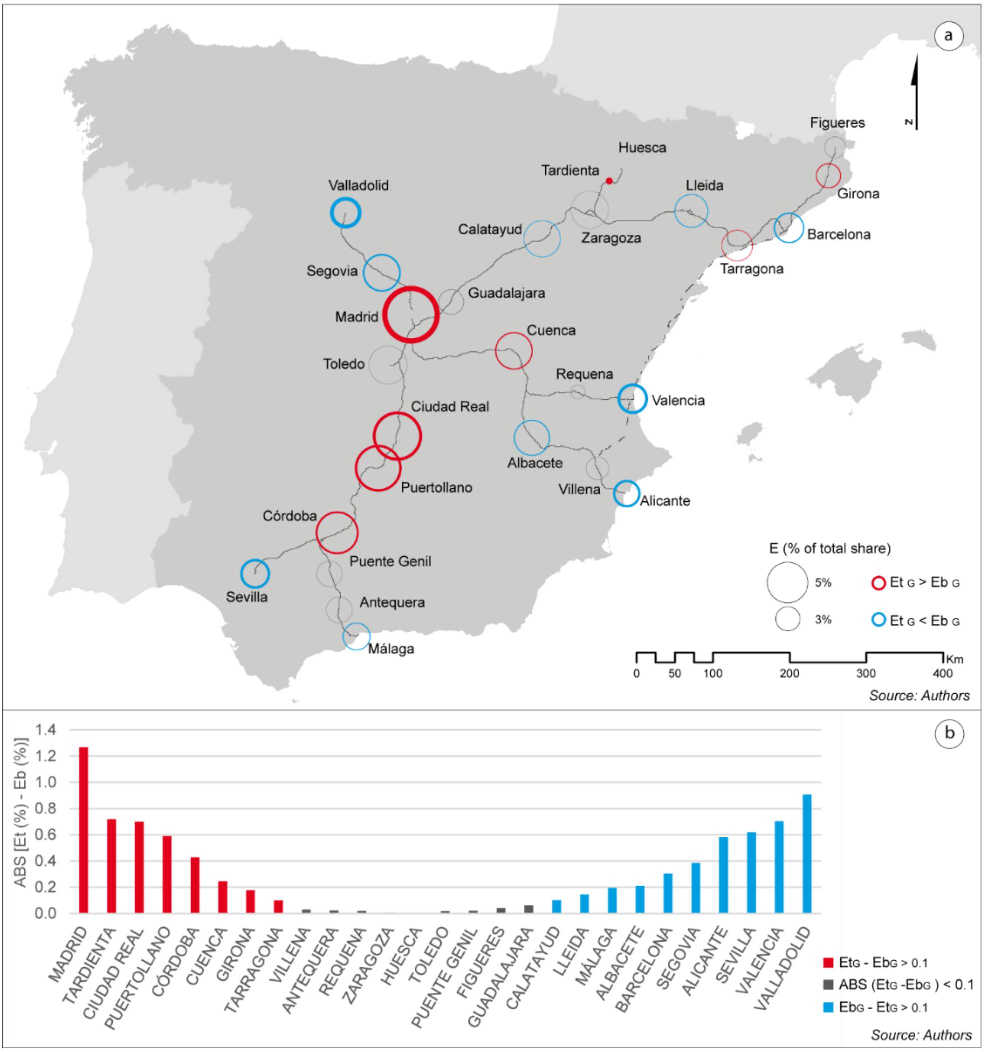


Figure 4.3: Comparison of tourism and business trips' global efficiencies (E_G)

Analysing the balance between tourism and business efficiencies for each city, we can also detect some interesting patterns: peripheral HSR cities such as Sevilla, Valencia and Barcelona, generally present better business efficiency, because, as mentioned earlier, travellers present more difficulties in getting enough useful time at these destinations for tourism trips due to their location at the end of the lines. Nevertheless, central locations usually have more opportunities to receive travellers gaining enough time available, thanks to the shorter distances linking to other cities in the network, thus increasing their efficiency for tourism trips.

This tendency is increased when considering weighted average efficiencies 'Ew' (Figure 4.4). Cities with efficient connections to large metropolitan areas favour tourism trips as they can receive a large number of travellers enjoying high efficient same-day HSR links. For instance, in Toledo and Segovia, even when their 'E_G' is better for business trips, the efficient connection to Madrid that counts with the highest volume of population (see Table 4.2) is determinant in the 'Ew' analysis, making tourism trips more favourable.

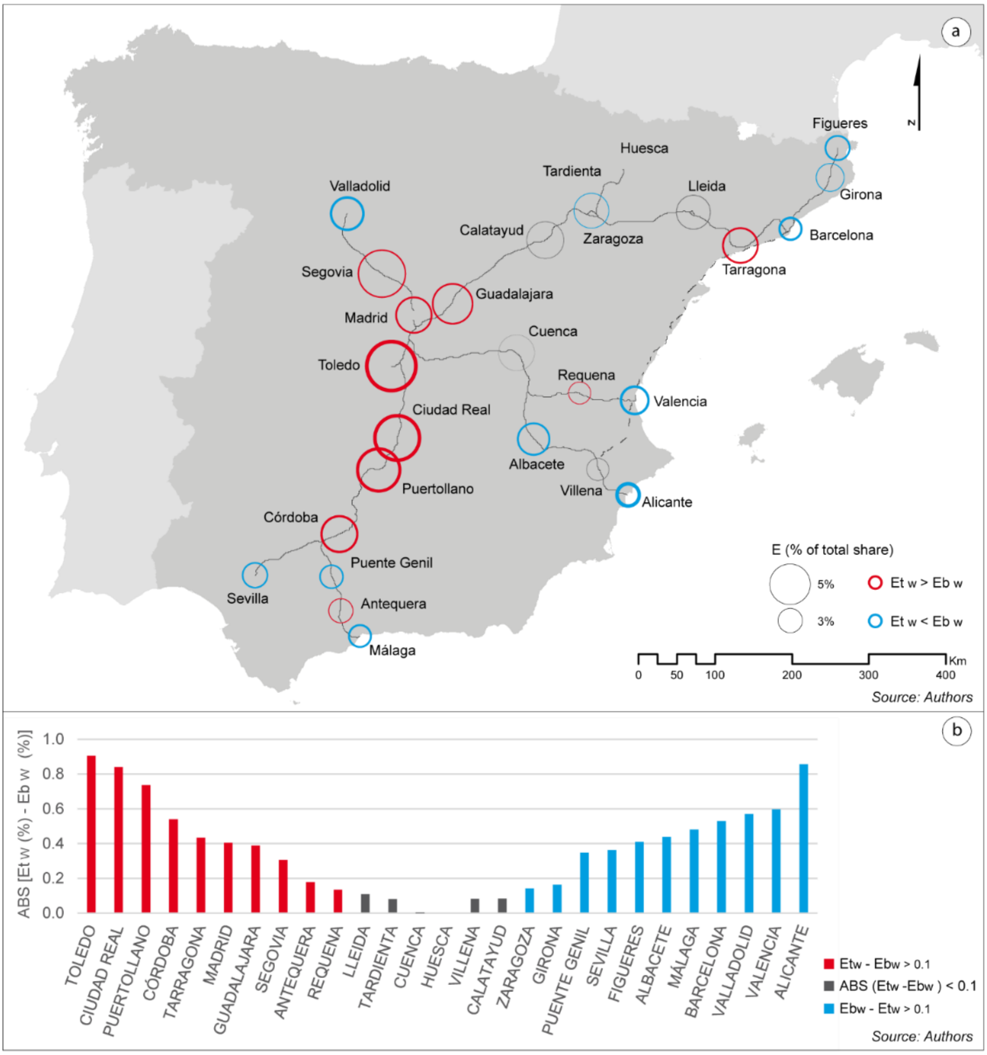


Figure 4.4: Comparison of tourism and business trips' weighted average efficiencies (E_W)

Although the share of the HSR connection to Madrid is a determinant in the global efficiency both for tourism and business, it represents a higher difference in the case of tourism, because in the case of business, other potential origins can also offer an efficient connection to these cities, diminishing the relevance of Madrid in the total share. In the case of Barcelona, smaller nearby cities, such as Tarragona, Girona or Figueres, show a difference in performance: while Tarragona is served by frequent and economic regional HSR trains connecting to Barcelona which favours tourism trips, Girona and Figureres do not present such as level of daily services which, added to their location at the end of the line, diminish their opportunities for travellers, mainly from Barcelona, to spend more time at these destinations.

Apart from these differences, peripheral settings generally strengthen their business weighted average efficiency. Business connections benefit from the very early HSR services connecting Madrid to large peripheral cities and vice versa. Madrid works as a hub for transfers connecting cities in different lines and mainly benefiting those cities located at the end of the line. However, for tourism trips (which are computed on Saturdays), these early HSR services are not available, limiting the possibilities for travellers to spend enough time in those peripheral cities.

FACTORS INFLUENCING THE EFFICIENCY OF HSR SAME-DAY TRIPS

Once the global values of efficiency are evaluated for all the HSR cities in the network, the factors influencing this efficiency measure are analysed more deeply. Figure 4.5 shows the graphs that result from the regression analysis of the efficiencies of all HSR connections obtained in the four different scenarios mentioned in the methodology. These are the actual (scenario 0) and the optimal efficiency (scenario 4) trends and also the scenarios considering the once-at-a-time factor optimisation, both for tourism and business trips. As the graphs show, the efficiencies obtained for all the scenarios can follow a negative potential expression with differences in the quality of the adjustment in relation to rail distance between city-pairs. For instance, the optimal efficiency is very well adjusted both for tourism and business trips (R^2 = 0.96, in both cases). The slight dispersion of the graphs, especially for short-distance trips, is due only to access/egress times in the origin city. Logically, the friction introduced by local accessibility to HSR stations becomes more relevant for shorter distances, as it represents a higher share of the total duration of the trip. Comparing optimal and actual efficiencies, the differences are higher for tourism than for business trips. On average, the actual efficiency for tourism trips rises to 35% of the optimal situation, while for business, it rises to around 46%. This is mainly related to the time needed at a destination: for tourism trips, the optimal scenario maximises the time available at a destination while for business, only six hours at a destination are needed, which is easier to achieve on a same-day trip.

The partially optimised scenarios also follow a negative potential expression. In general, scenario 1 (optimal ticket cost) is the one that provides a smaller improvement, followed by scenario 3 (optimal access/egress times in the destination city) and finally scenario 2 (optimal timetables adaptation). In addition, focusing on the trends, scenarios 1 and 3 present a higher distance decay ($\propto = 1.406 - 1.301$ for tourism and $\propto = 0.825 - 0.855$ for business) following a similar trend than the scenario zero (actual efficiency), while in the case of scenario 2, the effect of the distance is less pronounced ($\propto = 0.838$ for tourism and $\propto = 0.622$ for business trips). Although the improvement in efficiency is higher thanks to timetables optimisation, the graph of scenario 2 intersects the one of scenario 3 due to the different trends of the graphs mentioned above. This intersection occurs in the rail distances of 112 km and 140 km for tourism and business trips, respectively. That difference is because the influence of access/egress times becomes more relevant for shorter trips, being more efficient in optimising local accessibility to the stations than improving timetables, especially for business, where both the friction caused by access/egress values of times and the monetary costs are higher.

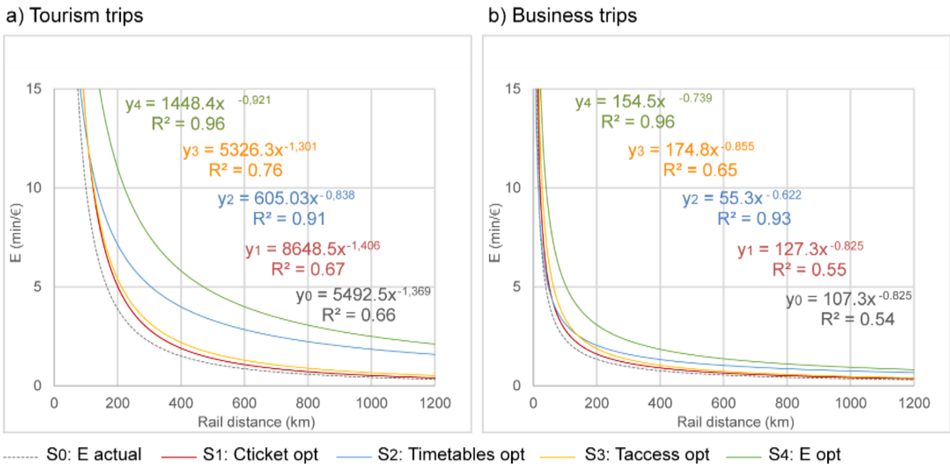


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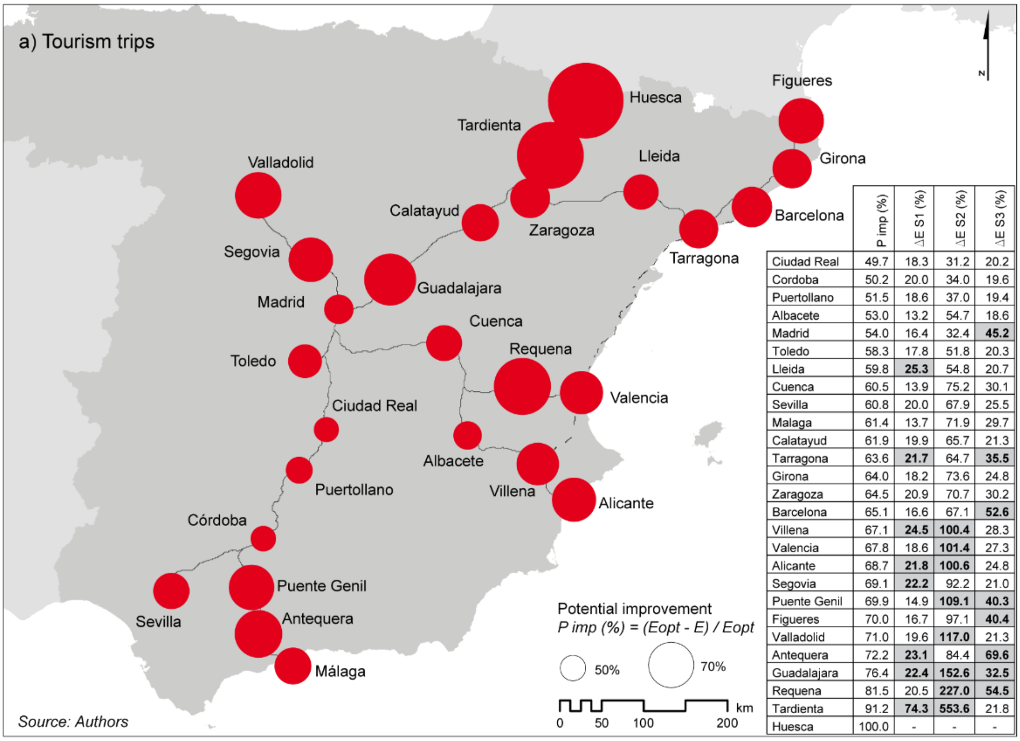
Figure 4.5: Comparison of the efficiency scenarios for tourism (a) and business (b) trips.

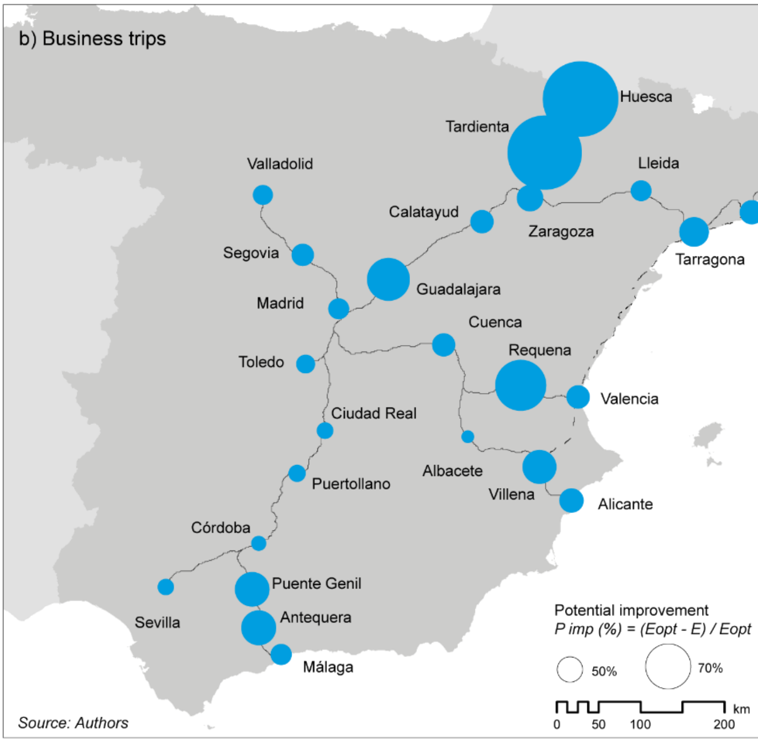
Nevertheless, these efficiency variations can be reflected in different ways, depending on the city analysed. In Figures 4.6 and 4.7, the range of potential improvement for each city is obtained; that is, the difference between the global value of the efficiency (E_G) and the optimal efficiency in each case (it is represented by the size of the circles). Also, these figures represent the percentage of efficiency improvement for each city considering the different scenarios proposed (see Section 3.2). This is a sensitivity analysis carried out in an attempt to identify the factors that have a higher influence on the efficiency measure for each HSR city. Within all the variables included in the calculation of the indicator, some have a higher influence than others in the global efficiency measure for cities. Due to the complexity of the proposed efficiency measure, this influence in each scenario cannot be compared between cities, because a higher or lesser value also depends on the characteristics of the rest of the variables in the formula. It should be analysed as an indicator for assessing the situation of a certain city itself. In the case of tourism trips, the opportunities for cities to improve their efficiency rise 66% on average, and oscillate between 100% for Huesca and around 50% for Ciudad Real or Córdoba (see the size of the circles in Figure 4.6). For business trips, the range of improvement is lower, in general terms (Figure 4.7).



	P imp (%)	ΔE S1 (%)	ΔE S2 (%)	ΔE S3 (%)
Ciudad Real	49.7	18.3	31.2	20.2
Cordoba	50.2	20.0	34.0	19.6
Puertollano	51.5	18.6	37.0	19.4
Albacete	53.0	13.2	54.7	18.6
Madrid	54.0	16.4	32.4	**45.2**
Toledo	58.3	17.8	51.8	20.3
Lleida	59.8	**25.3**	54.8	20.7
Cuenca	60.5	13.9	75.2	30.1
Sevilla	60.8	20.0	67.9	25.5
Malaga	61.4	13.7	71.9	29.7
Calatayud	61.9	19.9	65.7	21.3
Tarragona	63.6	**21.7**	64.7	**35.5**
Girona	64.0	18.2	73.6	24.8
Zaragoza	64.5	20.9	70.7	30.2
Barcelona	65.1	16.6	67.1	**52.6**
Villena	67.1	**24.5**	**100.4**	28.3
Valencia	67.8	18.6	**101.4**	27.3
Alicante	68.7	**21.8**	**100.6**	24.8
Segovia	69.1	**22.2**	92.2	21.0
Puente Genil	69.9	14.9	**109.1**	**40.3**
Figueres	70.0	16.7	97.1	**40.4**
Valladolid	71.0	19.6	**117.0**	21.3
Antequera	72.2	**23.1**	84.4	**69.6**
Guadalajara	76.4	**22.4**	**152.6**	**32.5**
Requena	81.5	20.5	**227.0**	**54.5**
Tardienta	91.2	**74.3**	**553.6**	21.8
Huesca	100.0	-	-	-

Figure 4.6: Potential improvement and comparison of efficiency scenarios for tourism (a)

Chapter 4



	P imp (%)	ΔE S1 (%)	ΔE S2 (%)	ΔE S3 (%)
Albacete	37,4	6,7	9,4	15,8
Cordoba	39,8	**10,9**	6,9	19,2
Sevilla	41,1	8,1	12,2	19,9
Ciudad Real	41,4	10,0	5,9	20,5
Puertollano	41,9	**11,6**	7,2	15,4
Toledo	43,6	9,1	4,6	16,1
Valladolid	44,7	**10,5**	7,7	13,0
Lleida	45,5	**11,7**	11,6	16,0
Madrid	45,6	8,6	4,2	**42,4**
Malaga	45,9	9,1	19,4	23,6
Segovia	47,1	**10,9**	3,5	17,4
Cuenca	47,9	9,9	16,3	27,8
Calatayud	48,0	10,2	13,8	16,0
Valencia	48,1	**11,3**	18,0	20,2
Barcelona	48,9	9,9	10,6	**35,5**
Alicante	49,1	7,2	23,5	20,5
Zaragoza	51,2	10,2	20,4	18,5
Tarragona	54,4	7,5	15,1	**43,8**
Girona	57,2	9,2	**40,1**	25,6
Villena	58,6	8,8	**46,4**	**38,9**
Figueres	59,2	8,5	**48,0**	28,8
Puente Genil	59,3	10,4	**42,7**	**35,1**
Antequera	59,6	9,6	**25,9**	**59,3**
Guadalajara	67,5	**11,5**	**61,8**	**35,9**
Requena	75,6	**11,4**	**140,8**	**43,3**
Tardienta	98,8	3,5	**5420,2**	3,3
Huesca	100,0	-	-	-

Figure 4.7: Potential improvement and comparison of efficiency scenarios for business (b)

Focusing on the efficiency increase (ΔE) represented by the different scenarios, in the case of tourism (Figure 4.6), adequate timetables (scenario 2) that allow travellers to benefit by having a long time available at a destination is usually the main factor of improvement, although it is higher in those cities with a lower quality of services, such as Huesca, Tardienta or Requena. Also, Valladolid and Segovia, whose HSR line is currently unconnected to the rest of the network, experience a higher improvement due to optimal HSR services. These cities will reach their optimal efficiency when the tunnel connecting the stations of Atocha and Chamartín in Madrid is completed. In addition, Guadalajara, mentioned in section 4 (Figure 4.3) is also highlighted here. Its potential improvement is higher than those in Toledo or Segovia (cities with similar territorial situation), and the share of the scenario 2 is the highest, even when it is served by a peripheral station and does not count economy ticket fares that could have increased the share of the other two scenarios.

The share of scenario 1 keeps more or less constant for all the cities, reaching around 20% in average, with the exception of Tardienta, whose ticket prices are dissuasive. In the case of scenario 3, it acquires a higher relevance for those cities with peripheral stations, especially in the case of Antequera, and also for big metropolitan areas such as

Madrid and Barcelona, where the access/egress times to/from stations can be very relevant for door-to-door HSR trips.

For business trips (Figure 4.7), access/egress to/from stations acquires a similar relevance than adequate timetables for many cities in the network. For business purposes, the extra cost generated by local accessibility introduces more friction in the efficiency measure than for tourism trips, in relative terms, because the value of time for business travellers is higher. Nevertheless, for those cities with low HSR frequencies, such as Huesca, Tardienta, Requena or Guadalajara, the share of scenario 2 maintains its value as in the case of tourism trips, but in this case, mainly due to the inadequate timetables that result in increased waiting times in the destination city.

DISCUSSION

In this section, the proposed efficiency measure considers the adaptability of the services to different travellers' needs and the associated costs, depending on the trip's purpose. In addition, these methods consider the HSR network as a whole, identifying and analysing the influence of the 'network effects' (different services, bypasses, transfers, etc.) on mobility choices, and evaluating the different factors influencing the efficiency of HSR connections.

The results obtained show that central locations generally benefit from better efficiency for tourism trips while peripheral settings present clearly business-oriented connections for same-day trips. The differences in travellers' needs and the temporal restrictions that depend on the purpose of the trip determine these results. In the case of tourism, the efficiency indicator achieves a wider range of values because the objective of maximising useful time at the destination makes the effect of the distance stronger: central locations reach higher values as the average trip length is shorter and, therefore, tickets prices are more economical. However, besides the distance, other aspects, such as access time to stations and waiting/transfer times, affect the efficiency of HSR for each city. On the other hand, in the case of business trips, the useful time at destinations is truncated to six hours, and therefore the efficiency results are more homogeneous as the closest cities do not benefit by having longer useful times available at the destination.

However, the efficiency analysis allows us to detect differences among cities located in a similar territorial situation. In addition, the efficiency analysis is applied to different scenarios of services' improvement: lower fares, more convenient timetables, improved accessibility to/from HSR stations, etc. This flexibility of the methods allows analysing the impact of those factors in door-to-door HSR trips.

To detect these differences and to support the discussion of the results the Spanish HSR cities are grouped according to their different location in the network (Figure 4.8).

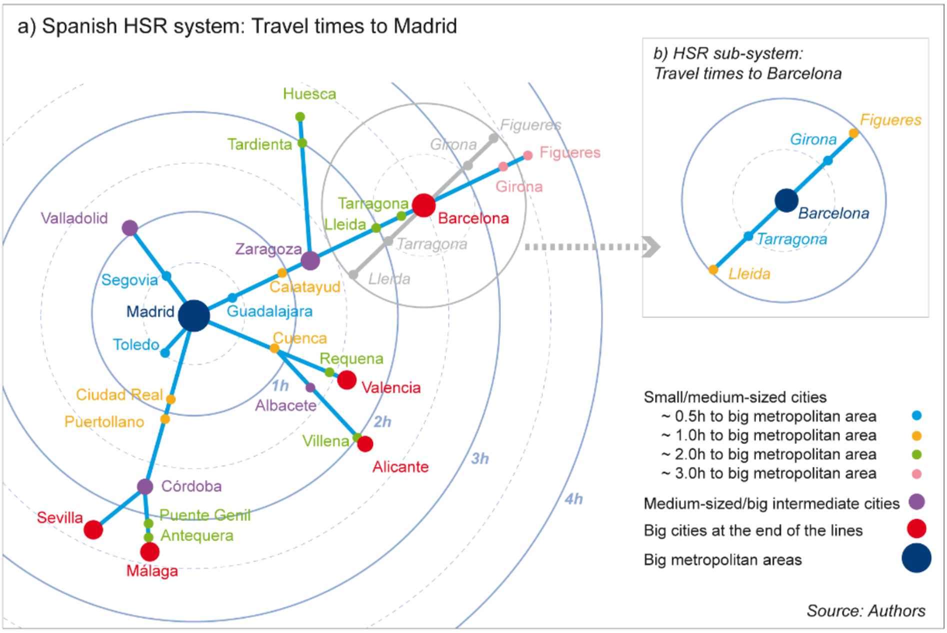


Figure 4.8: Grouping Spanish HSR cities in relation to their travel times to Madrid and their location in the network.

For example, small cities close to large metropolitan areas, around 0.5 – 1 h travel time, could have very efficient single-day tourism trip possibilities, because they benefit from short trips and well-adapted HSR services to Madrid, Spain's most important potential market, from where they can receive many visitors. In this group, we can find cities that are efficient HSR destinations for same-day tourism trips (Toledo, Segovia, Ciudad Real or Puertollano), and others that are penalised for different service-related factors (Guadalajara, Cuenca or Calatayud). On the one hand, within the efficient tourism destinations, Ciudad Real and Puertollano have higher efficiencies than Toledo or Segovia, which are penalised due to the need to transfer in Madrid. However, the latter two cities are included in the UNESCO World Heritage list, and therefore have many tourist-related amenities and potentialities, but the former are not very attractive as tourism destinations. Therefore, Ciudad Real and Puertollano should work on their possibilities as congress and events tourism destinations, making the most of their same-day HSR accessibility, while Toledo and Segovia should focus their efforts on negotiating convenient timetables for transferring at Madrid, thus improving their accessibility to the rest of the network. A similar situation happens in Tarragona in the context of the metropolitan area of Barcelona (see figure 7b) but, in this case, Tarragona should focus on improving the connection to/from its peripheral HSR station to the city centre. On the other hand, Guadalajara, Cuenca and Calatayud present lower HSR services' quality compared to the cities in their groups. They do not benefit from regional HSR services connecting them to Madrid, diminishing their daily frequencies and increasing ticket costs. In addition, Guadalajara and Cuenca have to deal with peripheral stations located far away from the cities (in scenario 2, Cuenca reaches 74% of a potential efficiency increase, and around 30% in scenario 3, while Ciudad Real and Puertollano present around 35% and 20% in each scenario. A similar situation is found for Guadalajara, compared to Toledo and Segovia; see Figure 4.6).

In the case of business trips, large cities at the end of the lines are well served, reaching higher efficiency values than other smaller cities close to them (Valencia higher than Requena, Alicante higher than Villena, Malaga higher than Antequera and Puente Genil) as they have more frequencies and more suitable timetables connecting them to Madrid. However, these big peripheral cities have less improvement possibilities as business destinations, because they are already important activity poles. Therefore, they should focus on improving access/egress to/from the HSR station, achieving a better integration in public transport and taxi services and favouring the intermodality of their stations. The above-mentioned small cities are located around two hours from Madrid, and their efficiencies are quite low, mainly because they do not benefit from many daily frequencies, and they are normally served by peripheral stations, diminishing their opportunities to be integrated in the HSR system. In this group there are two main exceptions. First, Huesca and Tardienta, which are the main losers of the Spanish HSR system in terms of the efficiency of their connections for same-day trips. The potential improvement is around 92-100% because nowadays it is almost impossible to visit these cities for a same-day trip as they are served only by one daily train to Madrid (Huesca cannot be visited and Tardienta can be visited only from Huesca). These cities should be focused on increasing HSR daily connections allowing them to receive visitors for same-day trips. Second are the cases of Tarragona and Lleida, which benefit from being integrated into Barcelona's HSR subsystem (see Figure 4.8b). The influence of the metropolitan area (with regional HSR services) increases their efficiency and, therefore, their potentialities as HSR destinations.

Finally, mainly for business trips, opportunities appear in medium-sized cities in intermediate locations accessible by HSR lines, such as Zaragoza, Córdoba or Albacete, which also reach high efficiency values. Their intermediate location opens opportunities for their own local enterprises to be connected, thanks to HSR with a larger business market located in large metropolitan areas, which increases their hinterland. Valladolid is a particular case in this group because, although it is similar in distance to Madrid as Zaragoza or Albacete, it is penalised by the need to transfer between stations in Madrid. This penalty increases its real distance (in travel time) to access the other cities in the network, diminishing its efficiency to similar values than those big cities at the end of the lines, especially for tourism same-day trips. Therefore, for Valladolid and Segovia (located along the same HSR line), the future HSR tunnel connection between Atocha and Chamartin stations in Madrid will be crucial for their potential opportunities (See Figure 4.6, potential improvement values). However, considering business trips for these cities, as long as the time available at the destination is achieved, the effect of transferring between stations is less important and their potential improvement is lower. Therefore, business trips are less sensitive to transfers than tourism trips, because the latter are influenced more by the distance/travel time, which increases the time available at the destination, while for business trips, achieving the available time at a destination is less conditioned by travel times.

5. EFFICIENCY OF HIGH-SPEED RAIL SAME-DAY TRIPS: COMMUTING

This section is based on the paper:

Moyano A. (2016) 'High-speed rail commuting: efficiency analysis of the Spanish HSR links' *Transportation Research Procedia*, 18, 212-219

It has been edited and adapted to fit the structure of this dissertation.

INTRODUCTION

In recent decades, commuting patterns have changed due to variations in working conditions and job accessibility. First, many enterprises and administrations today offer their workers flexitime conditions as a way of increasing their perception of job quality (Kelliher and Anderson, 2008). Studies have found that flexibility of work schedules favours labour productivity and work-life integration, enhancing workers' ability to balance competing demands at work and at home (McMenamin, 2007). Secondly, flexible arrival times at work favour job accessibility and, therefore, commuting relations. Departure time decisions become more adaptable to both working and household-related responsibilities, and are conditioned by the travel time needed to commute. Studies on the matter identify travel time as a key factor in job accessibility (Hu, 2015; Wang, 2000) and show differences among commuters' value of time, depending on this commute time (Asensio and Matas, 2008).

In this sense, the development and improvement of transportation infrastructures are clearly influencing workers' daily mobility, allowing them to travel longer distances in a reasonable time (Sandow, 2008). Especially, the HSR system constitutes an interesting alternative for medium and long-distance commuting (Garmendia et al., 2011), as it allows a significant reduction of travel times compared to road transportation. The accessibility provided by HSR opens up new labour markets that were once unreachable for many cities in the network, and favour different kinds of relations between regions (Mohíno et al., 2017; Vickerman, 2015). Therefore, travel time has been considered in the literature on HSR as a key element in journey-to-work analyses. Many studies have established different travel time limits, where the HSR is competitive depending on the travel purpose. For commuting trips, the limit of one-hour travel time is quite extended (Chen and Hall, 2012) as a reasonable time to invest every day in work-related travelling. Some other studies have established a wider range of travel time, between 30 and 90 minutes, where HSR can be considered an interesting alternative to private vehicles for commuting trips (Menéndez et al., 2002; Ureña et al., 2009). When the travel time is over two hours, HSR is competitive for business or personal purposes, because more than two hours is considered an excessive time to be invested in daily working trips (Ureña et al., 2009).

Apart from travel time, commuting-oriented transport policies are taken into consideration in the main HSR networks, which offer HSR services to connect smaller cities to large metropolitan areas with a commuting perspective (Garmendia et al., 2012b; Vickerman, 2015). In the Spanish case, the regional HSR services, AVANT, are an interesting alternative for commuting trips (Garmendia et al., 2012b; Guirao et al., 2017; Mohíno et al., 2017) as they offer an important reduction in travel times compared to road transportation, and more reasonable ticket prices in relation to long-distance HSR services. In addition, the Spanish rail operator RENFE offers different commuting-oriented ticket passes for these kinds of services (Guirao, 2013).

In this context, it is obvious commuting trips are very conditioned by travel times and associated costs, but they also depend on adequate timetables offered by HSR services, which should be convenient for travellers and adapted to their working timetable flexibility in order to make commuting between HSR cities feasible. Precisely, this section is centred on an analysis of the high-speed rail links currently available to commuters in the Spanish network. The focus here is on travellers' needs and working schedules constraints, which allow differentiating among connections and identifying those intervals of time spent and costs that are affordable for commuting.

METHODOLOGICAL HYPOTHESES ADOPTED IN THIS SECTION

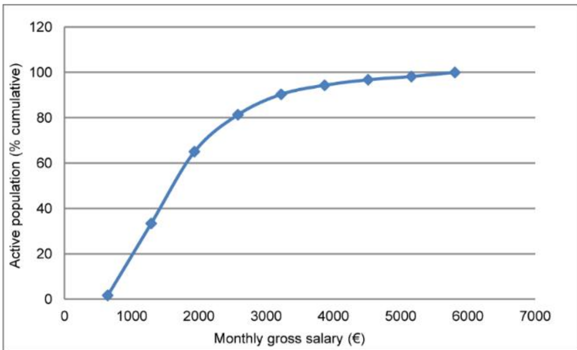
This section addresses evaluations of the efficiency of HSR same-day trips for commuting purposes. To carry out this assessment, it is necessary to establish certain requisites that every commuting connection must guarantee. First, commuting trips are generally conditioned by certain temporal constraints. The labour schedule considered in this analysis consists of 7.5 daily working hours (37.5 hours per week) and one hour for lunch; that is, 8.5 hours of total time needed at the destination. Second, the arrival time limit to the final destination will depend on the timetable's flexibility in each job. This study will consider four different scenarios that cover a wide range of working possibilities depending on these arrival time limits (Scenario 1: 8h00; Scenario 2: 8h30; Scenario 3: 9h00; Scenario 4: 9h30). Once the scenarios are defined, the most suitable inbound and outbound trains are selected for every city-pair, considering those that are better adapted to the working timetable. This data allow for the calculation of the efficiency of each HSR connection and its associated costs and time invested on the trip:

- Costs related to ticket prices: As commuters must usually travel from Monday to Friday every week, they normally acquire specific train passes that offer reduced ticket fares.

In the Spanish network, there are ticket passes for 40 trips, with a discount of up to 60% for AVANT trains, and passes for10 trips, with a 35% discount for AVE, Alvia and AVCity services. The equivalent ticket cost for a single-day trip considering these ticket passes is taken into account in the efficiency calculation.

- Total time invested: This is related to travel and waiting times spent during each commuting trip

Once having analysed the HSR connections, an assessment of their feasibility, in terms of cost and time, depending on workers' salary is carried out. On the one hand, the salary will condition the maximum amount of money workers can invest in travelling. According to the Salary Structure Survey of the National Institute of Spanish Statistics (*Instituto Nacional de Estadística – INE*), the active population distribution depending on their gross salary is shown in Figure 4.9.



	Monthly gross salary (€)	Active population (% cumulative)
1 SMI	645	1.7
2 SMI	1290	33.4
①		
3 SMI	1935	65.1
②		
4 SMI	2581	81.3
③		
5 SMI	3226	90.3
6 SMI	3871	94.3
7 SMI	4517	96.7
8 SMI	5162	98.2
> 8 SMI	>5162	100.0

SMI: Minimum wage in Spain
(Salario Mínimo Interprofesional)
SMI = 645 €/month (14 monthly wages)

Maximun ticket expenses (1/3 Salary)
① Limit 1: 425€/month ② Limit 2: 638€/month ③ Limit 3: 850€/month

*Source: INE

Figure 4.9: Cumulative population distribution depending on gross salary

Assuming that workers would use a maximum of a third of their salary (which is a very large amount of money in some cases) for travel expenses, three limits are established:

- Limit 1: maximum monthly expenses of €425. If the associated travel costs are higher than this value, 33.4% of the population would be excluded.
- Limit 2: €638 of total expenses. In this case, if the costs are higher, 65% of the active population would be excluded.
- Limit 3: €850 of total expenses. Only 19% of the active population would be able to afford this.

On the other hand, considering the time spent on the trip in both travel and waiting times, another three different limits are established, based on previous literature analysis:

- Limit a: less than 2 hours/day (Chen & Hall, 2012). This limit is the strictest one and implies a time investment of one hour for both inbound and outbound trips, including waiting times.
- Limit b: maximum of 3 hours/day (Menéndez, et al., 2002; Ureña, et al., 2009). This is identified in the literature as the maximum time spent commuting in competitive HSR connections.
- Limit c: up to 4 hours/day. More than 2 hours for a trip (inbound and outbound) is considered an excessive time to be invested in daily working trips (Ureña, et al., 2009).

ACCESSIBLE CITIES FOR COMMUTING TRIPS

Nowadays, network configurations and HSR services allow for a high number of links adapted to the temporal constraints established by different labour timetables. Figure 4.10 shows all the feasible connections depending on the different scenarios outlined in this section.

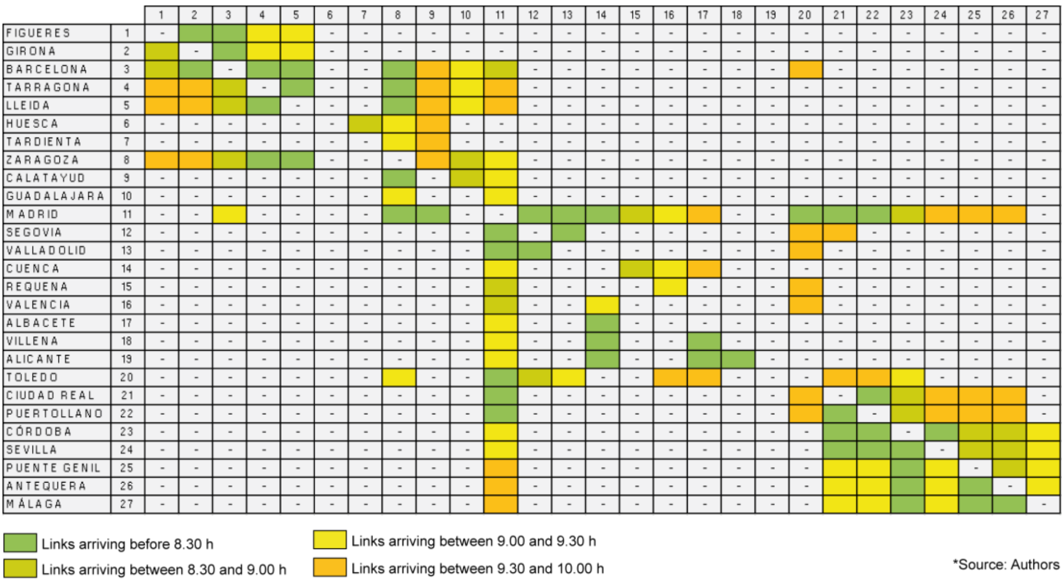


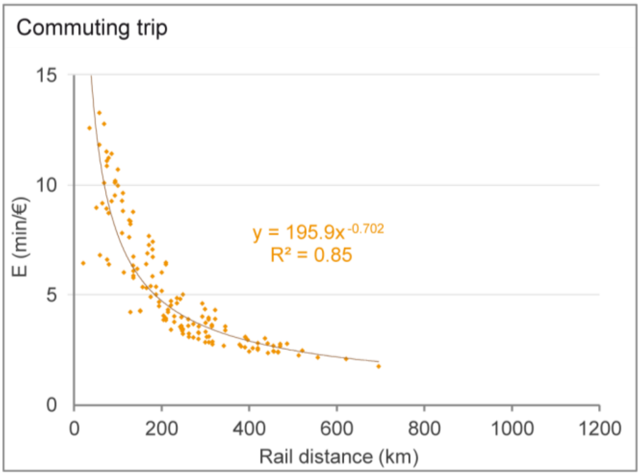
Figure 4.10: Possible commuting links depending on the arrival time limit

In scenario 1 (arrival time before 8.30 h), 49 connections between cities are feasible, mainly those between close cities generally located in the same HSR line. Madrid is the origin with more accessible destinations (8), followed by Barcelona (4). In this scenario, the most distant connection is made between Barcelona and Zaragoza, two cities located 314 km of rail distance apart. The number of commuting links increases to 71 in the second scenario (arrival time before 9.00 h), including a few distant connections between Madrid and cities located at the end of HSR lines such as Barcelona (621 km) or Valencia (391 km), cities that benefit from good HSR services to the capital of the country. In the third scenario, the number of links reaches 111 connections, allowing almost all connections between cities located in the same line, independently of their distance. The arrival time limit at 9.30 h allows reaching Madrid from 17 different origins; therefore, with a relatively flexible working schedule, most of the HSR cities can benefit from the wide labour market located in Madrid. In the last scenario, there are 151 links, making it possible to connect cities with no direct services (Barcelona – Toledo, where there are not direct trains, and travellers need to transfer in Madrid). In this scenario, only 4 cities are not linked to Madrid. This is due to the low quality of the HSR services (Huesca and Tardienta, with only one train a day) or a very large rail distance (Figueres and Girona).

However, although in many cases the HSR services are adapted to working timetables allowing commuting relations between cities, the efficiency of these connections, mainly in terms of ticket costs and time spent on the trip, may make these connections totally unfeasible or inefficient for commuters.

EFFICIENCY ANALYSIS OF COMMUTING TRIPS: TIME AND COSTS

This section focuses only on the last scenario (arrival time before 10.00 h), as it allows for the analysis of a higher number of connections (151). The efficiency of these links is shown in Figure 4.11 in relation to rail distance between the cities connected. Focusing on the trend, as in the case of tourism and business same-day trips (Section 4 of this chapter), the graph for commuting shows the adjustment of the efficiencies to a potential expression ($y = b \cdot x^{-\propto}$). In this case, the adjustment is higher (R^2 = 0.85) than for business and tourism trips because, for commuting, the useful time at destination is fixed as a restriction (see Table 4.1). Therefore, all 151 possible connections present the same numerator in the efficiency calculation. Those connections that do not allow commuters to be more than 8.5 hours at a destination are not considered as potential commuting links.



Source: Authors

Figure 4.11: Actual city-pair efficiency for commuting trips

Commuting trips in this analysis present a performance that is similar to business, and therefore, it can be considered a particular case.The value of the constant 'b' is similar to those found for business because the efficiency is limited due to the 8.5 hours at the destination established as T_{obj}. In addition, for commuting, the distance decay ($\propto = 0.702$) is less pronounced than for tourism and business ($\propto = 1.369$ and $\propto = 0.825$, respectively), because, in this case, connections are indirectly limited to less than 700 km (for longer distances, commuting is not possible due to temporal restraints), reducing the influence of the distance.

In addition to efficiency, the influence of ticket costs and time spent on the trip are also relevant in the evaluation of commuting trips' feasibility. Figure 4.12 shows the relation between total costs and time spent (expressed in total monthly expenses) and the rail distance between each city-pair. The graph clearly shows the differences between links with and without AVANT services, as they offer a more economic cost per km. For the same distance, AVANT services are much more efficient. On the other hand, Figure 4.12a also shows a high number of long-distance connections that are feasible thanks to the HSR services' timetables. However, for these distances, travel and waiting times may be key factors of travel efficiencies. In many cases, these times reach very high values, which would make travellers reject the commuting option. Figure 4.12b shows the relation between these travel and waiting times and the rail distance. The graph is much more scattered because many connections present low frequencies that make it difficult to have suitable HSR services. For instance, for rail distances around 200 km, the time invested may oscillate between 40 hours/month (around 1h40 per day) and almost 120 hours (5h30 per day).

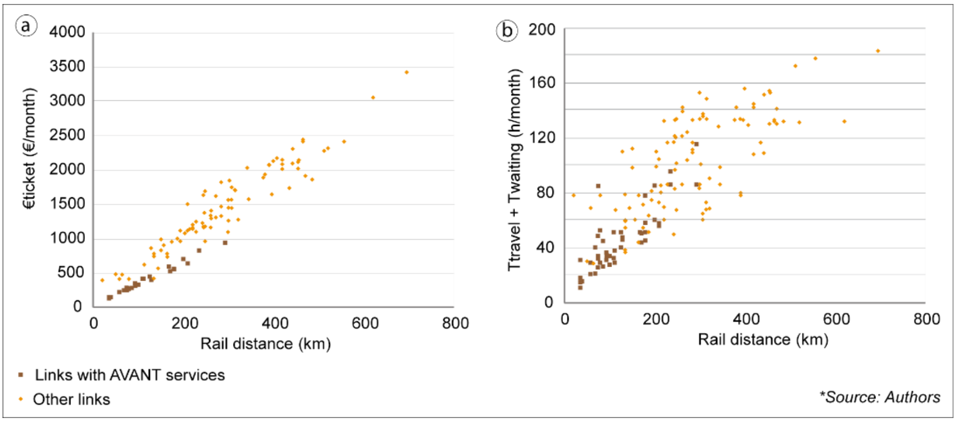


Figure 4.12: Dispersion graphs: a. rail distance – ticket cost; b. rail distance – time invested

Therefore, ticket costs and travel and waiting times could be decisive in the efficiency of HSR commuting links, as the existence of adequate timetables and the quality of the services play an important role. In addition, commuting links' feasibility is related to travellers' willingness to pay and travel, which allows for the establishment of certain limits for evaluation (see the methodological hypothesis of this section).

These limits allow us to assess the commuting links, depending on their associated costs (in time and money) and, therefore, their efficiency (Figure 4.13). Focusing exclusively on tickets costs, many links seem unaffordable for a high percentage of the active population. Only 36 out of 151 links can be paid by the 66.6% of the total workers (limit 1) while 88 out of 151 links are unaffordable for more than the 80% of the active population. When considering travel and waiting times, more than 60% of the links (93 out of 151) need more than three hours per day, which the literature considers an excessive time spent commuting. In this range, some connections with AVANT services can be found, showing that there are some of these services that could be the result of the addition of two commuting-oriented HSR services (for instance, the link between Sevilla and Malaga, stopping at Cordoba). Besides, as Figure 4.13 shows, there are many links that present reasonable travel and waiting times, under 3 hours (1h30 in each trip), but they incur significant ticket expenses, higher than €850 per month (limit 3).

Monthly expenses (€) \ Total time (h/day)	<1h (<22 h/month)	1h-2h (22-44 h/month)	2h-3h (44-66 h/month)	3h-4h (66-88 h/month)	>4h (>88 h/month)	Total
<425	7	18	6	5	0	**36**
425-638	0	4	9	3	0	**16**
638-850	0	2	4	3	2	**11**
>850	0	0	8	20	60	**88**
Total	**7**	**24**	**27**	**31**	**62**	

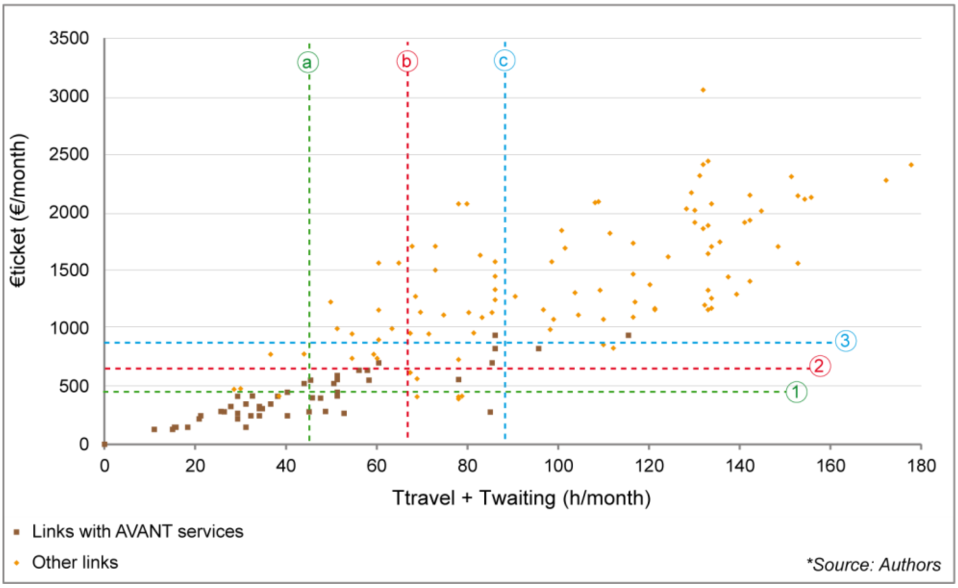


Figure 4.13: Links' distribution depending on ticket costs and time spent

DISCUSSION

In commuting relations is essential to have HSR services that allow workers to keep to working timetables. However, this is a necessary but not sufficient condition to guarantee an efficient commuting HSR connection, because the feasibility of commuting trips will be determined by the ticket expenses and the time spent on travel, which will play an important role in the efficiency of the trip.

In this section, an analysis of all the HSR connections are analysed, identifying those feasible commuting connections from the travellers' perspective. In many links analysed where the commute time is reasonable, efficiency could be increased by offering more economical ticket passes, which would significantly reduce the total expenses for travellers. However, in other cases, the trip becomes unfeasible because of the deficient adaptation between HSR services and working timetables, which increases waiting times significantly.

6. EFFICIENCY AND LOCATION-BASED MEASURES: A COMPARATIVE ACCESSIBILITY ANALYSIS

This section is based on the paper:

Moyano A., Martínez H.S and Coronado J.M. (2018) 'From network to services: A comparative accessibility analysis of the Spanish high-speed rail system' *Transport Policy*, 63, 51–60.

It has been edited and adapted to fit the structure of this dissertation.

INTRODUCTION

Does a city offer good accessibility if it can be reached within very short travel times but is served by only one train per day? To answer this question, it is necessary to assess high-speed rail (HSR) networks from different perspectives. Precisely, this section focuses on the analysis of HSR accessibility by reflecting on the difference between how a location can potentially be connected and how this connection is actually achieved by the services provided. This analysis evaluates the differences between accessibility measures, especially with regard to the extent to which the real opportunities the services supplied by the HSR system encompass the potential opportunities the infrastructure offers. At present, it is not sufficient just to have an HSR station; it is also necessary to achieve a certain quality of operating services, which will drive the potential contribution and, in general, the real utility of HSR to a city and its citizens.

METHODOLOGICAL HYPOTHESES ADOPTED IN THIS SECTION

For our purposes in this section, it is interesting to compare the location- and schedule-based approaches explained in section 2. Accessibility based on location provides an understanding of the network potential of the system and the relative positions of the stations within it, whereas the timetables' perspective yields a measure that is closer to the actual accessibility of the HSR system, considering services, frequencies and time budgets at destinations.

I) Indicators

The proposed methodology in this section is based on the computation of two major accessibility indicators that represent the convenience of using a certain transportation system, using a classical network approach and the 'efficiency' measure as a schedule-based approach, respectively. The first proposed indicator is a location-based (LB) measure, specifically, a potential accessibility measure for which travel time is treated as a distance or friction in the calculation. It is computed using the following negative exponential expression (4.9):

$$LB_{ij} = \exp[-\beta \cdot t_{ij}] \tag{4.9}$$

where t_{ij} is the travel time between the point of origin *i* and the destination *j* , and β is the cost sensitivity parameter. In this case, the value of this parameter is set as one, as in most accessibility studies. A value greater than one would overweight relations over short distances and would also increase the self-potential problem (Bruinsma and Rietveld, 1998; Gutiérrez et al., 2010; López et al., 2008).

As this indicator represents a classical network analysis, it is necessary first to define the different links in the network that represent the travel times between stations, considering the real travel time information obtained from the Spanish rail operator RENFE. Because the objective is to assess the potential connections provided by the network, the travel times are obtained by assuming direct connections between adjacent stations and deriving the rest by building the routes that follow the shortest paths, without including stops or transfer times. The outcome is a travel time value that is a proxy for the best possible connection the network offers, given its shape.

The second indicator is represented by "efficiency" as a measure oriented to a schedule-based (SB) approach, introducing the time available to a traveller at his or her destination for certain activities ($T_{u\,ij}$), which is conditioned by real timetables and the associated travel costs ($C_{total\,ij}$). The efficiency measure is calculated using the expression (4.1) mentioned in Section 3 of this chapter.

The application of the proposed method to this case study requires several considerations and preparatory procedures. The SB indicator represents a complete day trip chain through the HSR infrastructure, and includes all time constraints imposed by the transport system. It considers the real timetables and assumes several a priori hypotheses, which will differ depending on the purpose of the trip or the traveller's needs. Regarding this point, this section focuses only on business trips as a way of assessing real opportunities for enterprises and business workers to be connected to other economic markets.

II) Calculation procedure and assumptions

In this chapter, the SB indicator is calculated for business trips as a case study to apply the proposed measure[8]. We propose three different scenarios, which differ on the optimal time budget (T_{obj}) needed at the destination, depending on the duration of the meeting. In this way, the better or worse adaptation of schedules to the optimal time budget will enable a distinction to be made between well-served and low-served HSR cities. These three scenarios consider the following previous hypotheses:

a) Time budget at destination: In this case, the aim is to guarantee a return journey for a business day trip with the optimal temporal framework, which allows for having a meeting in each scenario and minimising waiting times. In this study, two, four and six hours of meeting duration are considered as the time available needed at destination (T_{obj}). For selecting outbound and inbound trains, the time at the destination is increased by an extra time corresponding to an estimation of the access and egress times from the station to the meeting venue, and vice versa (access/egress times are calculated following the procedure explained in Section 3 of this chapter).

b) Transfer time: The potential convenience of transferring at intermediate stations instead of taking direct trains is also considered in the calculation. When a transfer occurs between two trains at the same station, a required difference of at least 15 minutes between arrival and departure times is considered. When a transfer is made between the Atocha and Chamartín stations in Madrid, 45 minutes are needed.

c) Travel costs ($C_{total\,ij}$): These costs will be computed as a composite value, including both ticket prices and travel and waiting time costs, because, for business purposes, excess time at a destination must be penalised. For the ticket cost, the return fare (20% discount applied to the flexible fare) is used in the calculations. Nowadays HSR ticket prices follow a dynamic pricing system that varies depending on the day of purchase, the kind of service and travel time (differences between valley and peak hours). However, the proposed method considers the standard return fare. For same-day trips, users do not normally purchase tickets much in advance, and the possibility exists of finding

[8] Recent studies on Spanish HSR's main corridors, such as Madrid – Barcelona and Madrid – Sevilla, show that most of the trips are oriented to business/work purposes, and comprise between 60-80% of the total share (Pagliara et al., 2012; Ureña et al., 2012).

Chapter 4

reduced ticket offers. Travel and waiting times on business trips mean relevant additional costs, which will depend on travellers' value of time and the convenience of the timetables with regard to travel needs. The value of time for a business traveller was considered to be 23 €/h for in-vehicle travel times, 28 €/h for access/egress times and 73 €/h for waiting times (see Table 4.1 in this chapter).

d) Potential market/destination attractiveness: The 'accessibility' concept refers to the facility to reach certain activities from a given location through a certain transport system (Morris et al., 1978). Following this definition, a 'mass' factor, based on one or more attractive elements, should be considered when calculating accessibility indicators. However, in this section, the inclusion of such a "mass" factor was neglected because the method proposed wants to focus exclusively on the service-related factors in comparing the two different measures.

Based on all these a priori hypotheses, the most efficient outbound-inbound combination for each connection and scenario is determined to obtain the proposed SB measure (Efficiency). Finally, an average SB indicator from the results achieved in each scenario is obtained for all the cities in the Spanish HSR network.

Once both indicators have been computed, we are able to undertake an assessment of the actual accessibility provided by the HSR system based on a comparison of the potential accessibility with the accessibility achieved from the individual/customer perspective, given the currently provided services. In this comparison step, it is necessary to normalise the two indicators, as they are expressed in different units. The normalisation is made through the Z scores procedure, which uses the mean μ and the standard deviation σ to compute the standardised values:

$$Zscore = \frac{x_i - \mu}{\sigma} \qquad (4.10)$$

Finally, the last part of the analysis allows the winners and losers to be assessed, given the HSR service configuration, based on the comparison of the potential opportunities in terms of the accessibility provided by the spatial characteristics of the network and the real utility of each HSR connection given by the services supplied, oriented in this study to business purposes. In this last step, the global location and schedule-based indicators for each destination will be computed:

$$LB_j = \sum \exp[-\beta \cdot t_{ij}] \quad ; \qquad SB_j = E_{G\,j} = \sum_i E_{\,ij} \qquad (4.11)$$

The results of this comparison will reveal which stations are taking full advantage of their location-based potential, and which ones are gaining in accessibility because the operating services are allowing better access than that indicated by the potential measure based on the network location.

THE HSR ACCESSIBILITY COMPARISON: MAIN RESULTS

I) HSR network and services: Location- and schedule-based measures analysis

The first statistical analysis of both indicators reveals remarkable differences between the various cities in the network, as expected. First, a strong concentration of accessibility in central locations is expected because of the logical central-periphery pattern, which is strengthened by the radial shape of the HSR network, and such a concentration is indeed observed, as shown in Table 4.3: central locations (not only Madrid but also nearby stations such as Guadalajara, Ciudad Real and Cuenca) perform well in terms of the first indicator (see LB sum values in Table 4.3), whereas peripheral cities exhibit the opposite performance (e.g., Alicante, Sevilla, Malaga and Barcelona).

Comparison with the schedule-based indicator already reveals differences between cities that perform similarly according to the location analysis. The schedule-based measure brings to light certain differences between cities that could initially present similar accessibility patterns. For instance, Ciudad Real and Puertollano remain ranked among the most accessible stations; however, Cuenca and Calatayud, which have similar network locations, exhibit worse performance (see SB sum values in Table 4.3). Obviously, these differences are because of the different services supplied among cities.

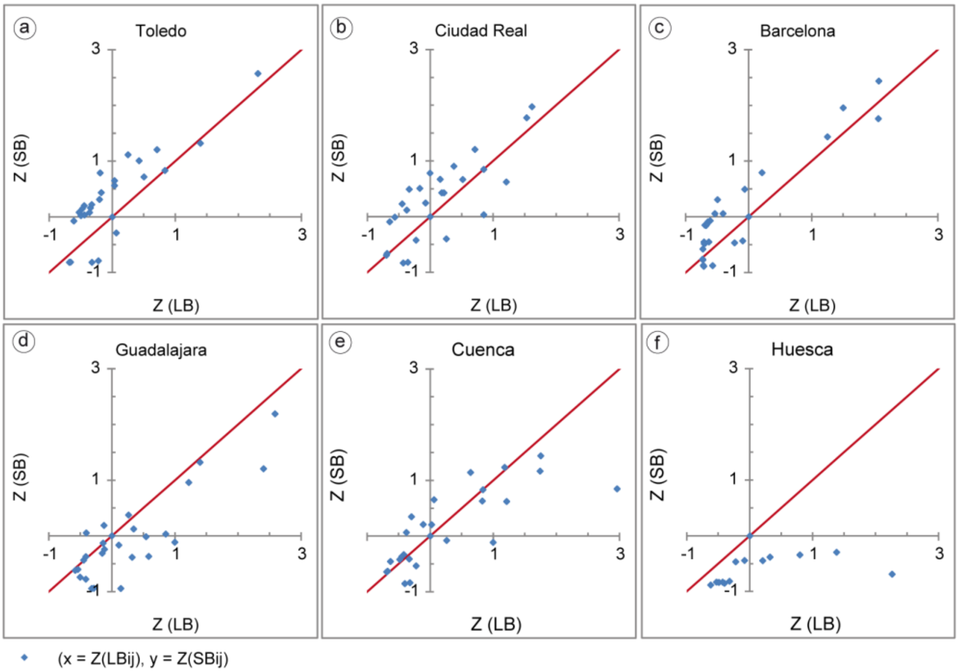
This first analysis also enables the detection of several remarkable situations. For instance, the maximum LB value is found in the Huesca-Tardienta connection, followed by Figueres-Girona and Ciudad Real-Puertollano, as all these city-pairs are located very close in the network and have very small travel times between them. However, considering the SB values, all these city-pairs do not present a similar performance. For instance, the services supply in Huesca and Tardienta is limited to only one outbound train per day to Madrid in the morning and another inbound train, Madrid-Huesca, in the evening, making it impossible to visit those cities on a same-day trip. Other remarkable cases are Valladolid and Segovia, which rank in nearly the lowest positions in LB measures because they are located on an HSR line that does not connect to any other stations, and also because the need to transfer between the Chamartín and Atocha stations in Madrid introduces an important travel time penalty (30 minutes of travel time is required simply to traverse the city centre). However, in the SB measure they perform in a much better position (see LB and SB sum values in Table 4.3).

Table 4.3: Descriptive statistics for normalised location- and schedule-based measures

	LOCATION-BASED MEASURE				SCHEDULE-BASED MEASURE			
	Sum	S.D	Max*		Sum	S.D	Max*	
ALBACETE	0.534	0.904	2.482	Villena	3.425	1.026	3.014	Cuenca
ALICANTE	-6.821	0.846	3.128	Villena	-1.669	0.949	2.730	Villena
ANTEQUERA	-0.736	1.179	3.634	Puente Genil	-4.125	0.988	2.303	Puente Genil
BARCELONA	-4.751	0.870	2.100	Girona	1.156	0.917	2.437	Girona
CALATAYUD	7.189	1.012	3.235	Zaragoza	5.025	0.852	3.118	Zaragoza
CIUDAD REAL	**7.730**	1.010	**4.165**	Puertollano	**13.492**	1.247	**5.506**	Puertollano
CÓRDOBA	4.010	1.162	3.212	Puente Genil	10.267	1.157	2.905	Puente Genil
CUENCA	6.800	0.920	2.575	Requena	6.739	0.889	3.014	Albacete
FIGUERES	-7.638	1.019	**4.114**	Girona	-7.995	1.379	**5.289**	Girona
GIRONA	-5.919	1.077	**4.114**	Figueres	-6.792	1.427	**5.289**	Figueres
GUADALAJARA	**7.448**	0.848	2.632	Madrid	-1.668	0.760	2.192	Madrid
HUESCA	-0.912	1.145	**4.473**	Tardienta	-21.823	0.281	-0.295	Calatayud
LLEIDA	1.130	0.973	2.942	Tarragona	3.095	0.905	2.312	Zaragoza
MADRID	**10.858**	0.910	2.632	Guadalajara	**17.316**	0.750	2.574	Toledo
MÁLAGA	-4.956	0.961	2.895	Antequera	-3.108	1.013	2.391	Puente Genil
PUENTE GENIL	1.611	1.233	3.634	Antequera	-3.407	1.205	2.905	Córdoba
PUERTOLLANO	6.892	1.065	**4.165**	Ciudad Real	**13.455**	1.288	**5.506**	Ciudad Real
REQUENA	0.197	0.923	3.108	Valencia	-12.307	0.697	2.111	Valencia
SEGOVIA	-5.063	0.731	2.448	Valladolid	3.091	0.814	3.037	Valladolid
SEVILLA	-6.816	0.697	2.035	Córdoba	0.509	0.858	2.530	Córdoba
TARDIENTA	2.316	1.241	**4.473**	Huesca	-21.483	0.294	-0.243	Calatayud
TARRAGONA	-1.277	0.922	2.942	Lleida	0.427	0.822	2.291	Lleida
TOLEDO	0.162	0.681	2.349	Madrid	8.881	0.768	2.574	Madrid
VALENCIA	-3.800	0.802	3.108	Requena	-0.609	0.702	2.111	Requena
VALLADOLID	-9.993	0.636	2.448	Segovia	-1.890	0.797	3.037	Segovia
VILLENA	-4.452	0.940	3.128	Alicante	-8.992	0.994	2.730	Alicante
ZARAGOZA	6.256	1.158	3.235	Calatayud	8.992	0.871	3.118	Calatayud

**Max values represent the best city-pair connection for each city, which correspond to the shortest path in the LB measure and the most efficient connection in the SB measure.*

Having analysed both measures, it seems interesting to delve deeper into the comparisons between them. Figure 4.14 shows dispersion graphs of the normalised LB and SB values for six cases in the network, although the same assessment is provided for each station in Appendix II of this chapter. These graphs differentiate between the connections favoured by the supplied services (Fig. 4.14a. Toledo; b. Ciudad Real and c. Barcelona) and those that are operating below their location-based potential for the same reason (Fig. 4.14d. Guadalajara; e. Cuenca and f. Huesca). In addition, this in-depth analysis allows us to detect dissimilarities between cities that are in a similar network location. For instance, Toledo and Guadalajara (Fig.4.14a and d) are very close to the metropolitan area of Madrid; however, the former benefits from a good services supply, with high frequencies of regional HSR services AVANT connecting to the capital of the country, while the latter is served by more expensive long-distance services and counts on lower frequencies. A similar situation is found between Ciudad Real and Cuenca (Fig.4.14b and e). Finally, Huesca is the best example of a very low quality of services supply (Fig.4.14f), which makes it extremely difficult to link this city on a same-day trip. Conversely, although it is also placed in a peripheral location, Barcelona benefits from the services supply oriented to connect the two big metropolitan areas of the country, Madrid and Barcelona.



Source: Authors

Figure 4.14: Dispersion graphs of the comparisons between normalised LB and SB indicators

II) Profiling HSR stations: winners and losers

Once the global LB and SB measures for every destination in the network have been computed, they are compared in order to identify the cities that benefit most from the currently operating HSR services, compared with their potential accessibility according to their locations in the network configuration. Regarding this point, to avoid misunderstandings, it is necessary to clarify that winners and losers are identified here in relative terms (using a comparative approach); that is, the winning cities are not always those cities with the best SB indicator values but rather those that achieve an increase in accessibility with respect to their location-based opportunities by virtue of their supply of services, and vice versa in the case of the losers. In this context, Fig. 4.15 shows the cities that are clearly winners by virtue of the HSR services with which they are supplied, and those that are losers. It also identifies the cities in the network where the accessibilities assessed using both the LB and SB approaches are very similar. Therefore, three different groups can be identified among the cities in the network (Fig. 4.15a): the first group consists of eleven winning cities, whose potential accessibility is actually improved because of the coverage provided by the operating services (such as Toledo, Segovia or Valladolid); the second group contains the nine cities, with a close balance between their values for both indicators (such as Cuenca, Lleida or Zaragoza); and the third group comprises the seven cities that are operating below the accessibility potential indicated by their locations because of their supply of services (such as Huesca, Tardienta or Guadalajara).

The presented results are supplemented by a spatial model showing the distribution of the accessibility performances on a map, enabling a geographic comparison (Fig. 4.15b). This spatial analysis reveals several patterns: First, peripheral locations generally benefit in terms of the SB indicator because, as mentioned previously, the configuration of services (direct trains and timetables) and the shape of the network are designed to facilitate the connection of large metropolitan areas. Second, the situations of central locations vary depending on the characteristics of the supplied services. For instance, cities located along the Madrid-Sevilla line are well served because of the existence of regional HSR services (to Madrid and among Andalusian cities) and long-distance services on several lines (North-South and East-South lines in addition to the lines to Madrid), which increase the daily frequencies of service and therefore improve accessibility when the 'efficiencies' of connections are considered (SB approach). However, services running on the Madrid-Barcelona and Madrid-Valencia lines are highly polarised with respect to the endpoints, and there are no regional HSR trains to Madrid in these regions; therefore, intermediate cities are generally penalised in terms of ticket costs and service frequencies, making it difficult to find an itinerary that provides sufficient available time at many destinations. Finally, the influence of the station's location is also an important penalty factor in the efficiency analysis. Many of the loser cities have a peripheral HSR station (see Figure 2.2), which negatively impacts the efficiency of the services supplied (for instance, in Requena, Guadalajara, Puente Genil or Antequera). Having a peripheral station increases access and egress times from the station to the final destination and diminishes useful time at the meeting venue. This factor also affects other winner cities such as Segovia. However, compared to Toledo, its influence is slighter and compensated for by the good supply of services.

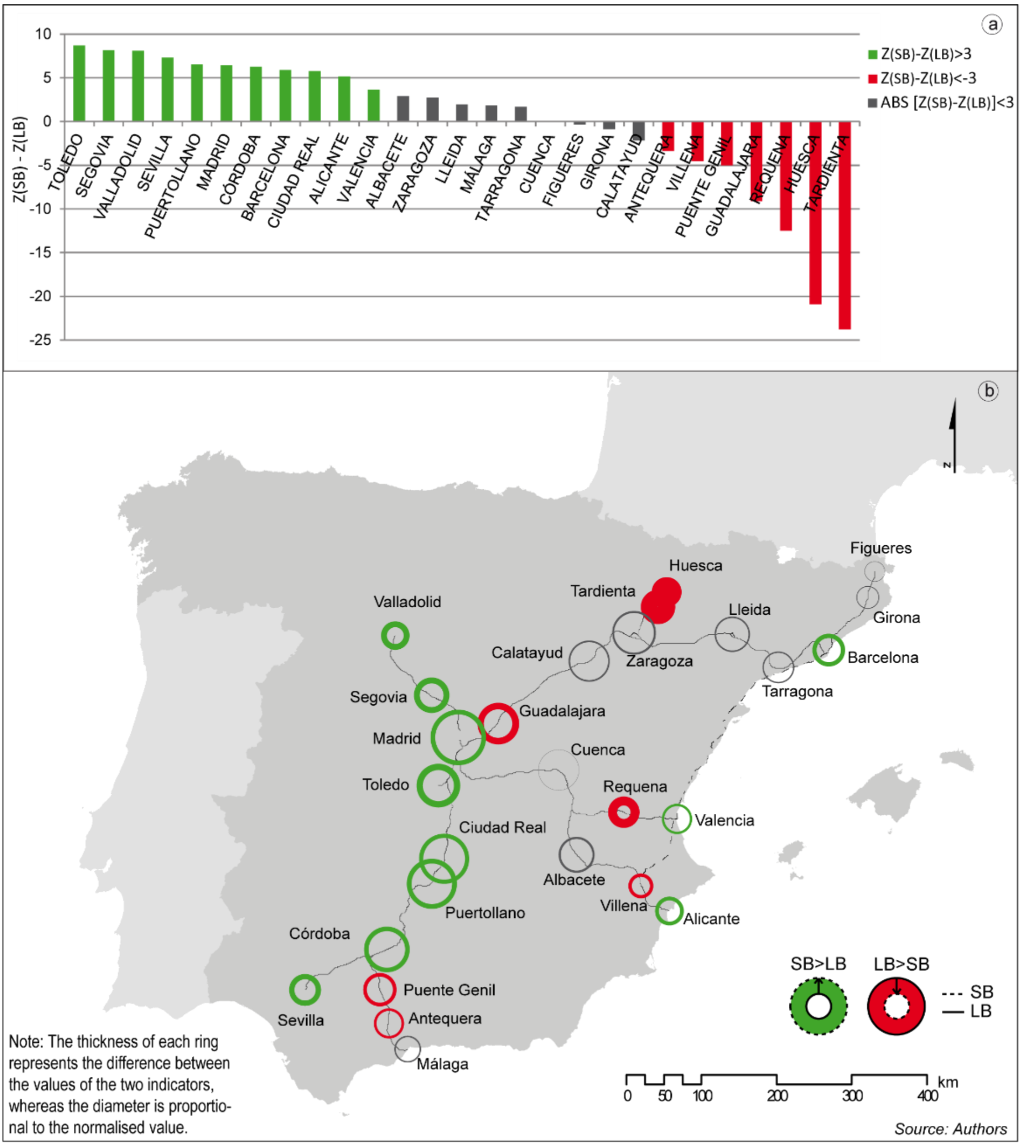


Figure 4.15: Winners and losers in the Spanish HSR system

Having analysed the results obtained in this study, some questions arise about the real influence of the quality of HSR services in the proposed method. In this sense, the methodology has been tested through a sensitivity analysis proposing a different scenario in the comparison of two cities that present a similar network location: Ciudad Real and Cuenca (see Table 4.3, LB sum values). Considering the scenario of adding economic ticket fares in the link Cuenca-Madrid (similar to those regional HSR services offered in the link Ciudad Real-Madrid) and maintaining its current frequencies, the city of Cuenca increases its SB indicator, passing from a normalised global value of 6.739 (see Table 4.3, SB sum values) to 8.544 in this new scenario. In the winners and losers assessment, this increase allows Cuenca to rise one place in the ranking. This scenario does not imply adding new services that could increase the operator's exploitation costs, but offering a certain number of economic seats in long-distance HSR services as is currently happening in the Figueres and Girona to Barcelona links. This analysis shows the sensitivity of the method and demonstrates the importance of considering the level of services in the analysis of schedule-based networks.

DISCUSSION

The comparative approach applied in this section reveals the extent to which the potentials offered by a network configuration are covered by the actual services supplied. The results show that in the Spanish network, there are some stations that, having a similar location in the network, present very different supplies of services, and this has a significant influence on the connectivity effects provided by the HSR system. For instance, there is a remarkable difference between those central locations which count with regional HSR services, which presents a better SB performance as they are served by more economic services and higher frequencies, and those cities in a similar territorial situation but benefiting only from low frequency long-distance services. Also, the results show that in general, large cities with peripheral locations in the network are identified as winners in the comparative accessibility analysis, as they benefit from adequate daily services connecting them to Madrid.

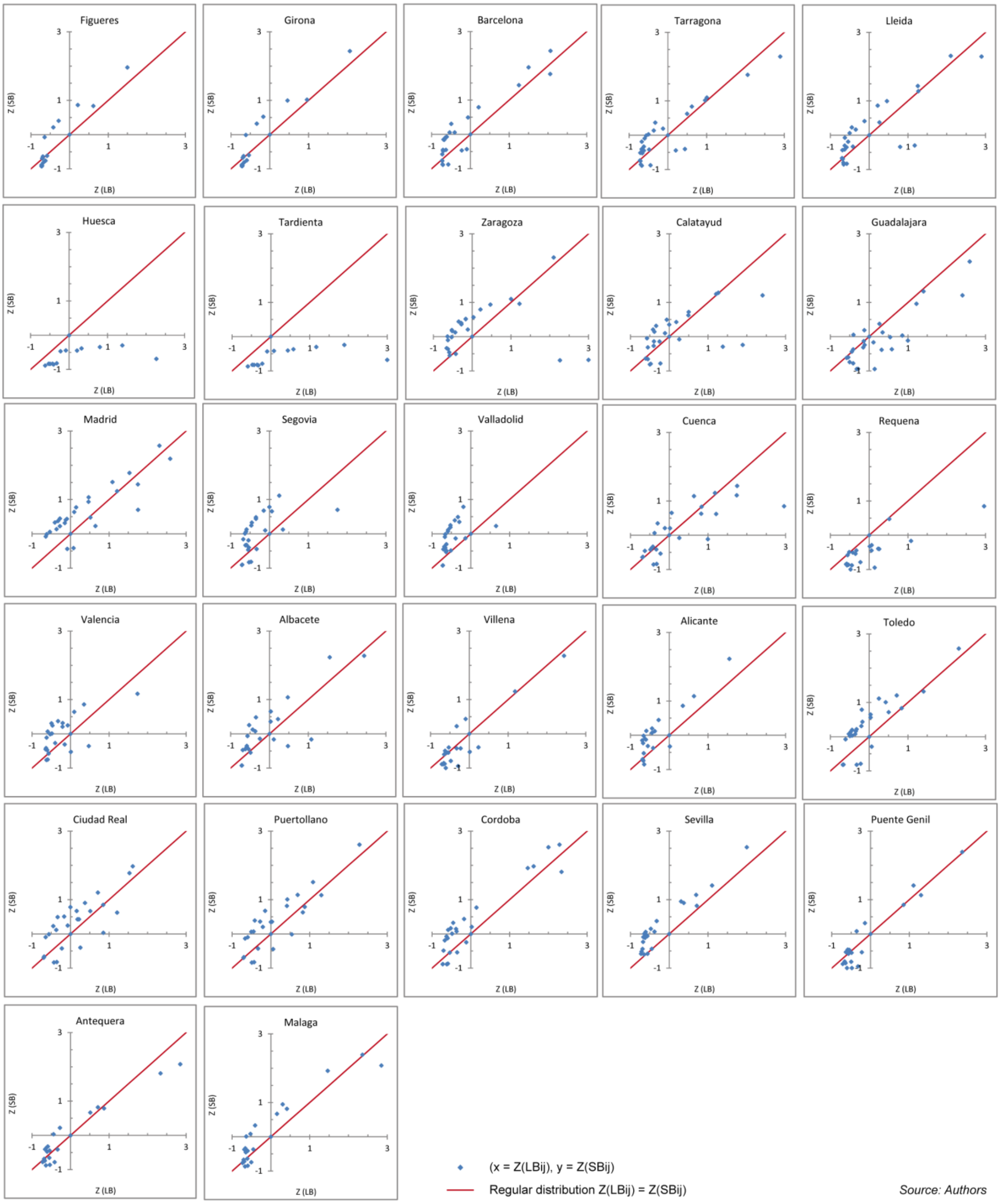
In summary, the measures used in this section and its comparison helps to explore the difference between the potential of the infrastructure itself (location-based accessibility) and the actual changes in accessibility (schedule-based accessibility). In this way, location-based measures are considered as a reference for analysing the newly proposed schedule-based method, thereby reinforcing the accessibility analysis.

7. DISCUSSION AND CONCLUSIONS OF THE CHAPTER

This Chapter presents an initial approach focused on **the need to incorporate the characteristics of the supplied services into the accessibility analyses** of means of transport that are limited to fixed timetables. Location-based analyses reveal the potentials of network configurations but generally overestimate the outcomes, as they assume that all nodes in a network are equally well served in terms of frequencies and costs. Considering the efficiency of each connection – the available time at a destination that can be gained with a given monetary investment – is a new approach to assessing the accessibility of networks, focusing on travellers' needs and introducing the requirements for different trip purposes. Throughout this Chapter, the **efficiency of HSR connections for different cities and trip purposes, such as tourism, business and commuting, is addressed, answering to the research question RQ2** presented in the Introduction of this dissertation. Also, this efficiency analysis serves as a useful tool for assessing the differences with regard to operating HSR services, not only between cities but also between connections, illustrating the adaptability of the proposed approach to different scales of analysis. In addition, not only the efficiency analysis but also its comparison to traditional accessibility measures helps to explore **the difference between the potential of the infrastructure itself (location-based accessibility) and the actual changes in accessibility (efficiency as schedule-based accessibility)**. In this way, location-based measures are considered as a reference for analysing the newly proposed schedule-based method, thereby reinforcing the accessibility analysis. This comparison addresses the **research question RQ3, exposing to what extend the efficiency of the services supplied for HSR same-day trips reaches the potentialities for travelling offered by the infrastructure**.

Generally, HSR analysis examines the way in which the local economic environment will benefit from enhanced connections with other cities, and the resultant expansion of their economic markets. This rational is used for medium and small cities, which normally urge the national authorities to grant them a station. However, in highly developed HSR networks, such as the Spanish one, big cities easily secure a high or, at least, a reasonable number of daily services, but small intermediate cities, which make an effort to secure an HSR infrastructure, finally run the risk of being bypassed by HSR services (Moyano and Dobruszkes, 2017). Because of that, **this kind of analysis is a useful tool for transport planning, both in evaluating existing HSR stations and assessing the real opportunities a new station could bring to the city it serves, guiding local strategies and decisions**.

APPENDIX I



Source: Authors

Dispersion graphs of the comparison between LB and SB indicators

APPENDIX II

a) Tourism same-day trips

Efficiency (*Eij*) for all the O/D pairs

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
FIGUERES	1	-	18.3	7.9	4.6	3.3	0.0	0.0	2.7	0.0	1.0	1.4	0.2	0.1	0.6	0.0	0.4	0.4	0.1	0.1	0.7	0.5	0.4	0.4	0.0	0.0	0.0	0.0
GIRONA	2	16.6	-	9.9	5.2	3.8	0.0	0.0	2.9	0.0	1.1	1.4	0.3	0.2	0.7	0.0	0.5	0.4	0.2	0.1	0.8	0.9	0.8	0.5	0.1	0.1	0.2	0.1
BARCELONA	3	7.1	9.3	-	8.4	6.4	0.0	0.0	4.2	2.9	2.0	2.1	1.1	0.8	0.7	0.2	2.5	0.7	0.1	0.4	1.5	1.3	1.2	0.8	0.4	0.4	0.3	0.4
TARRAGONA	4	4.6	5.6	8.6	-	11.0	0.0	0.0	6.0	3.7	2.4	2.4	1.4	1.0	0.9	0.2	3.9	0.4	0.1	1.3	1.4	1.1	0.9	0.9	0.5	0.5	0.3	0.3
LLEIDA	5	4.1	4.8	6.8	11.8	-	0.0	0.0	8.6	4.9	2.9	2.8	1.7	1.1	1.0	0.3	0.7	0.5	0.2	0.0	1.6	1.3	1.1	1.0	0.6	0.6	0.4	0.3
HUESCA	6	0.6	0.8	1.7	2.1	3.2	-	13.3	10.8	6.5	4.1	2.9	1.2	0.8	1.1	0.3	0.6	0.6	0.2	0.1	1.5	1.3	1.1	0.8	0.3	0.1	0.2	0.1
TARDIENTA	7	0.7	0.9	1.8	2.3	3.4	0.0	-	0.0	7.5	4.1	3.2	1.3	0.9	1.2	0.4	0.6	0.6	0.3	0.1	1.7	1.4	1.2	0.8	0.3	0.1	0.3	0.2
ZARAGOZA	8	2.9	3.3	3.8	6.0	8.9	0.0	0.0	-	12.9	5.9	4.4	2.5	1.8	1.4	0.3	1.2	1.9	0.6	1.2	3.1	2.4	2.1	1.8	1.1	0.6	0.8	0.9
CALATAYUD	9	0.1	0.3	0.7	1.5	2.7	0.0	0.0	6.6	-	8.2	5.4	2.9	2.0	1.7	0.4	1.4	2.2	0.7	1.4	4.2	3.3	2.9	2.0	1.3	0.6	0.9	1.1
GUADALAJARA	10	0.9	1.1	2.3	3.1	4.1	0.0	0.0	3.2	5.4	-	8.8	4.4	2.8	2.2	0.4	1.7	2.8	0.8	1.7	6.1	4.2	3.6	2.4	1.5	0.7	1.1	1.3
MADRID	11	1.3	1.5	1.9	2.5	3.2	0.0	0.0	4.6	4.3	8.8	-	9.7	6.0	5.6	2.9	3.4	4.6	3.3	2.9	10.7	7.8	6.9	4.6	3.2	1.9	2.7	2.5
SEGOVIA	12	0.1	0.2	0.7	0.9	1.3	0.0	0.0	2.2	2.0	0.9	11.0	-	8.3	2.3	0.4	1.7	2.8	0.9	1.6	5.1	3.8	3.2	2.1	1.2	0.7	1.0	1.3
VALLADOLID	13	0.0	0.0	0.5	0.3	0.6	0.0	0.0	1.6	1.6	0.7	6.9	9.5	-	1.8	0.4	1.4	1.9	0.7	1.0	3.4	2.9	2.5	1.8	1.0	0.6	0.5	1.0
CUENCA	14	0.4	0.5	0.8	0.7	1.1	0.0	0.0	1.8	1.6	0.8	6.1	3.3	2.4	-	5.3	4.1	9.0	6.2	5.1	3.8	5.0	4.3	2.7	1.7	0.7	0.9	1.1
REQUENA	15	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.8	0.4	0.0	3.2	0.9	0.6	7.2	-	7.6	4.1	2.5	2.1	1.8	1.6	1.4	0.8	0.3	0.3	0.1	0.2
VALENCIA	16	0.4	0.6	2.0	3.9	0.5	0.0	0.0	1.2	1.2	0.5	3.5	1.8	1.3	6.1	12.8	-	3.6	2.3	3.1	2.3	3.4	3.1	2.1	1.4	0.6	0.4	0.8
ALBACETE	17	0.0	0.0	0.5	0.3	0.6	0.0	0.0	1.5	1.4	0.7	5.2	2.3	1.6	12.2	0.7	1.2	-	9.3	7.2	3.0	3.1	2.7	1.9	1.2	0.6	0.5	0.9
VILLENA	18	0.0	0.0	0.2	0.2	0.5	0.0	0.0	1.0	1.2	0.5	3.4	1.8	1.2	6.8	0.5	0.9	10.9	-	10.1	1.7	1.6	1.4	1.2	0.6	0.5	0.4	0.6
ALICANTE	19	0.0	0.0	0.8	1.9	0.5	0.0	0.0	1.0	1.2	0.5	3.1	1.7	1.2	6.0	0.5	6.1	9.1	12.6	-	1.6	1.5	1.3	1.1	0.6	0.5	0.4	0.5
TOLEDO	20	0.5	0.6	0.9	1.4	1.9	0.0	0.0	2.8	3.0	1.1	11.0	5.4	3.7	2.4	0.5	2.2	2.8	0.9	1.7	-	4.2	3.6	2.6	1.7	0.7	1.0	1.3
CIUDAD REAL	21	0.6	0.8	1.1	1.6	2.0	0.0	0.0	2.8	2.5	0.9	6.8	4.3	2.9	2.9	0.5	2.0	2.5	0.9	1.5	5.3	-	19.4	7.6	4.0	3.1	3.2	2.9
PUERTOLLANO	22	0.6	0.8	1.0	1.5	1.9	0.0	0.0	2.7	2.3	0.8	5.9	3.9	2.7	2.6	0.4	1.9	2.4	0.9	1.5	4.7	20.9	-	9.0	4.6	3.5	4.4	4.3
CÓRDOBA	23	0.4	0.5	0.7	1.1	1.4	0.0	0.0	1.9	1.9	0.6	4.0	2.5	1.8	1.9	0.4	1.3	1.9	0.7	1.2	3.0	7.6	9.5	-	9.1	7.3	7.1	7.0
SEVILLA	24	0.0	0.1	0.6	0.7	1.0	0.0	0.0	1.5	1.6	0.5	3.4	1.8	1.3	1.5	0.3	0.9	1.3	0.6	0.8	2.6	5.0	5.4	10.4	-	3.7	4.4	4.6
PUENTE GENIL	25	0.0	0.0	0.3	0.3	0.6	0.0	0.0	1.1	0.4	0.0	2.3	0.8	0.5	1.6	0.0	0.7	0.6	0.2	0.0	1.5	4.8	5.4	11.5	5.2	-	9.6	9.4
ANTEQUERA	26	0.0	0.0	0.2	0.2	0.5	0.0	0.0	1.0	0.9	0.3	2.6	1.4	0.9	1.3	0.2	0.6	0.5	0.1	0.0	1.6	4.0	4.5	8.1	4.2	12.5	-	9.7
MÁLAGA	27	0.0	0.0	0.3	0.3	0.6	0.0	0.0	1.0	1.0	0.4	2.6	1.5	1.0	1.4	0.3	0.7	0.6	0.2	0.0	1.7	4.0	4.4	7.4	4.1	10.4	11.3	-

0.0 | 0 - 0.82 | 0.82 - 2.30 | 2.30 - 3.74 | > 3.74

Time available at destination (*Tu ij*) for all the O/D pairs

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
FIGUERES	1	-	10:41	10:22	9:40	8:16	0:00	0:00	8:18	0:00	4:13	5:58	1:19	0:51	3:28	0:00	1:28	2:21	0:57	0:22	3:38	2:53	2:21	2:22	0:16	0:00	0:00	0:00
GIRONA	2	9:38	-	10:31	9:49	9:19	0:00	0:00	8:27	0:00	4:22	6:07	1:28	1:00	3:37	0:00	1:37	2:30	1:06	0:31	3:47	4:40	4:08	2:56	0:53	0:33	1:06	0:43
BARCELONA	3	9:07	9:46	-	11:33	10:54	0:00	0:00	10:45	8:45	6:51	8:36	5:28	4:16	3:50	1:02	6:19	3:52	0:35	2:00	7:16	6:09	5:37	4:29	2:32	2:26	1:36	2:27
TARRAGONA	4	9:17	9:56	10:10	-	11:58	0:00	0:00	10:55	8:55	7:01	7:51	5:38	4:26	4:00	1:12	7:33	2:09	0:45	3:23	5:21	4:19	3:47	4:08	2:32	2:36	1:46	1:27
LLEIDA	5	9:32	10:11	10:25	11:48	-	0:00	0:00	11:10	9:11	7:16	8:06	5:53	4:41	4:15	1:27	3:46	2:24	1:00	0:16	5:36	4:34	4:02	4:23	2:47	2:51	2:01	1:42
HUESCA	6	2:25	3:05	5:32	5:31	6:42	-	11:20	10:32	9:12	8:30	7:18	4:04	3:11	4:17	1:29	2:48	2:26	1:02	0:18	4:43	4:36	4:04	3:27	1:21	0:29	1:12	0:46
TARDIENTA	7	2:35	3:15	5:42	5:41	6:52	0:00	-	0:00	9:22	8:40	7:28	4:14	3:21	4:27	1:39	2:58	2:36	1:12	0:28	4:53	4:46	4:14	3:37	1:31	0:39	1:22	0:56
ZARAGOZA	8	9:03	9:42	9:46	11:04	12:00	0:00	0:00	-	11:29	10:46	10:17	7:29	6:17	5:02	1:18	5:47	7:13	2:43	5:29	8:33	8:12	7:38	7:08	5:10	2:42	3:57	4:45
CALATAYUD	9	0:18	0:57	1:56	3:24	4:35	0:00	0:00	5:54	-	10:56	9:42	7:39	6:27	5:12	1:28	5:57	7:23	2:53	5:39	9:42	8:57	8:25	7:22	5:25	2:52	4:07	4:55
GUADALAJARA	10	3:56	4:36	8:00	9:18	10:27	0:00	0:00	5:45	7:51	-	9:36	7:33	6:21	5:06	1:22	5:51	7:17	2:47	5:33	9:36	8:51	8:19	7:16	5:09	2:46	4:01	4:49
MADRID	11	6:36	7:15	8:51	8:59	10:08	0:00	0:00	10:35	7:55	9:22	-	9:14	10:20	9:11	7:03	9:34	9:05	9:28	8:46	10:22	11:55	11:54	10:54	10:10	5:33	9:17	9:02
SEGOVIA	12	0:22	1:02	3:35	3:28	4:37	0:00	0:00	6:41	4:52	1:45	10:25	-	8:24	5:10	1:26	5:55	7:21	2:51	5:37	8:35	8:20	7:46	6:47	4:28	2:50	4:05	4:53
VALLADOLID	13	0:00	0:00	2:55	1:37	2:49	0:00	0:00	5:42	4:53	1:46	10:26	9:40	-	5:11	1:27	5:56	6:00	2:52	4:10	7:37	7:36	7:03	6:29	4:29	2:51	2:11	4:21
CUENCA	14	2:17	2:57	4:30	3:23	4:32	0:00	0:00	6:36	4:47	1:40	10:05	8:17	7:07	-	7:21	6:40	8:01	9:46	9:04	8:30	8:54	8:25	6:55	5:18	2:45	4:00	4:48
REQUENA	15	0:00	0:00	1:30	0:00	1:28	0:00	0:00	3:32	1:43	0:00	7:51	3:03	2:16	9:54	-	6:36	7:57	6:42	6:00	5:26	5:20	4:51	3:20	1:39	1:20	0:29	1:16
VALENCIA	16	2:19	2:59	5:00	7:24	2:45	0:00	0:00	5:38	4:49	1:42	10:07	6:40	5:28	10:00	11:06	-	8:03	6:48	7:14	7:33	8:56	8:27	6:57	5:20	2:47	2:07	4:17
ALBACETE	17	0:00	0:00	2:59	1:41	2:53	0:00	0:00	5:46	4:57	1:50	10:23	6:48	5:36	10:53	1:31	2:55	-	9:56	9:14	7:41	8:14	7:44	6:42	5:03	2:43	2:15	4:25
VILLENA	18	0:00	0:00	1:30	1:23	2:32	0:00	0:00	4:36	4:53	1:46	8:44	5:53	4:41	10:49	1:27	2:51	12:00	-	9:10	5:36	5:30	5:01	5:05	2:59	2:39	2:11	2:59
ALICANTE	19	0:00	0:00	2:36	4:58	2:32	0:00	0:00	4:36	4:53	1:46	8:44	5:53	4:41	10:49	1:27	9:32	12:00	12:00	-	5:36	5:30	5:01	5:05	2:59	2:39	2:11	2:59
TOLEDO	20	2:22	3:02	4:35	5:28	6:37	0:00	0:00	7:58	6:52	1:45	10:37	9:33	8:22	5:10	1:26	7:25	7:21	2:51	5:37	-	8:55	8:23	7:49	6:13	2:38	4:05	4:53
CIUDAD REAL	21	3:28	4:08	5:41	6:33	7:42	0:00	0:00	9:02	6:58	1:51	9:38	8:54	7:41	4:15	1:32	7:31	7:27	2:57	5:43	9:46	-	10:32	10:47	9:03	6:14	7:28	7:04
PUERTOLLANO	22	3:29	4:09	5:42	6:34	7:43	0:00	0:00	9:03	6:59	1:52	9:39	8:55	7:42	4:16	1:33	7:32	7:28	2:58	5:44	9:47	11:49	-	10:48	9:40	6:15	9:47	9:32
CÓRDOBA	23	2:26	3:06	4:39	5:32	6:41	0:00	0:00	8:02	6:56	1:49	9:34	7:41	6:29	4:13	1:30	5:04	7:25	2:55	5:41	8:45	10:57	11:12	-	11:12	6:00	9:44	9:29
SEVILLA	24	0:11	0:50	3:49	3:31	4:41	0:00	0:00	6:53	6:47	1:40	10:00	6:38	5:26	5:38	1:21	4:52	5:54	2:46	4:04	8:36	10:48	10:34	12:00	-	5:51	9:35	9:20
PUENTE GENIL	25	0:00	0:00	1:40	1:22	2:32	0:00	0:00	4:46	1:48	0:00	7:26	3:08	2:21	4:05	0:00	3:00	2:19	0:55	0:11	5:31	9:56	9:19	9:28	9:24	-	9:36	9:21
ANTEQUERA	26	0:00	0:00	1:15	0:57	2:07	0:00	0:00	4:21	4:23	1:16	8:11	5:23	4:11	3:40	0:57	3:16	1:54	0:30	0:00	6:06	9:31	9:47	10:58	8:59	9:51	-	8:56
MÁLAGA	27	0:00	0:00	1:41	1:23	2:33	0:00	0:00	4:47	4:49	1:42	8:37	5:49	4:37	4:06	1:23	3:01	2:20	0:56	0:12	6:32	9:57	10:13	11:24	9:25	10:17	10:21	-

0:00 | 0:00 - 3:15 | 3:15 - 5:00 | 5:00 - 6:45 | > 6:45

Note: The ranges of colors are only for guiding the understanding of the tables and *are established statistically considering the mean* (μ) *and the standard deviation* (σ) *as follows:*

1) $\mu - \sigma/2$ *2)* μ *3)* $\mu + \sigma/2$

b) Business same-day trips

Efficiency (*Eij*) for all the O/D

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
FIGUERES	1	-	4.7	2.3	1.4	1.5	0.0	0.0	1.1	1.0	0.6	0.8	0.6	0.4	0.6	0.2	0.6	0.5	0.3	0.2	0.6	0.6	0.5	0.3	0.1	0.1	0.1	0.2
GIRONA	2	4.8	-	2.6	1.6	1.6	0.0	0.0	1.2	1.1	0.7	0.8	0.6	0.5	0.6	0.2	0.6	0.5	0.3	0.2	0.6	0.6	0.5	0.4	0.1	0.1	0.1	0.2
BARCELONA	3	2.2	2.6	-	2.1	1.8	0.0	0.0	1.4	1.1	0.9	0.9	0.7	0.7	0.6	0.2	1.1	0.7	0.3	0.6	0.8	0.8	0.8	0.6	0.5	0.3	0.4	0.4
TARRAGONA	4	1.5	1.6	2.1	-	2.4	0.0	0.0	1.6	1.4	1.0	0.9	0.8	0.7	0.7	0.2	1.5	0.7	0.3	0.6	0.9	0.8	0.7	0.7	0.4	0.3	0.4	0.4
LLEIDA	5	1.5	1.5	1.9	2.5	-	0.0	0.0	2.5	2.1	1.2	1.1	1.0	0.8	0.8	0.2	0.7	0.8	0.3	0.4	1.0	1.0	0.9	0.7	0.5	0.4	0.5	0.4
HUESCA	6	0.4	0.5	1.1	1.1	1.2	-	0.7	0.8	1.4	1.2	1.1	0.7	0.5	0.7	0.2	0.4	0.3	0.1	0.0	0.9	0.8	0.7	0.5	0.2	0.1	0.2	0.1
TARDIENTA	7	0.4	0.5	1.1	1.1	1.3	0.0	-	0.8	1.5	1.2	1.1	0.7	0.5	0.7	0.2	0.4	0.4	0.1	0.1	0.9	0.8	0.7	0.5	0.2	0.1	0.2	0.1
ZARAGOZA	8	1.1	1.2	1.4	1.6	2.6	0.0	0.0	-	3.4	1.9	1.5	1.2	0.9	0.9	0.3	0.8	0.9	0.4	0.7	1.3	1.2	1.1	0.9	0.8	0.4	0.5	0.6
CALATAYUD	9	1.0	1.1	1.3	1.3	1.7	0.0	0.0	3.0	-	1.9	1.7	1.3	1.0	1.0	0.3	0.8	1.0	0.4	0.8	1.3	1.2	1.2	0.9	0.8	0.4	0.6	0.7
GUADALAJARA	10	0.5	0.6	0.8	0.8	1.0	0.0	0.0	1.3	1.4	-	2.5	1.7	1.3	1.2	0.3	1.0	1.2	0.5	0.9	1.8	1.5	1.4	1.1	0.9	0.4	0.7	0.8
MADRID	11	0.8	0.8	0.9	0.9	1.1	0.0	0.0	1.5	1.6	2.5	-	2.7	2.0	1.8	1.2	1.3	1.6	1.2	1.1	2.7	2.1	1.9	1.4	1.1	1.0	1.0	1.1
SEGOVIA	12	0.1	0.1	0.7	0.5	0.8	0.0	0.0	1.2	1.1	0.5	2.7	-	3.0	1.3	0.3	1.0	1.2	0.5	0.9	1.6	1.4	1.4	1.1	0.9	0.4	0.6	0.8
VALLADOLID	13	0.1	0.1	0.4	0.5	0.7	0.0	0.0	0.9	1.0	0.4	2.0	3.1	-	1.0	0.3	0.9	1.0	0.4	0.8	1.4	1.2	1.1	0.9	0.7	0.4	0.6	0.7
CUENCA	14	0.3	0.3	0.6	0.4	0.7	0.0	0.0	1.0	1.0	0.5	1.9	1.4	1.1	-	1.8	2.0	3.2	1.8	1.6	1.4	1.4	1.4	1.1	1.0	0.4	0.6	0.7
REQUENA	15	0.2	0.3	0.5	0.4	0.6	0.0	0.0	0.8	0.7	0.2	1.2	0.9	0.8	0.9	-	3.2	1.3	1.0	1.1	1.1	0.9	0.8	0.8	0.8	0.3	0.5	0.6
VALENCIA	16	0.3	0.3	1.0	1.5	0.6	0.0	0.0	0.8	0.8	0.3	1.3	1.0	0.8	1.7	2.4	-	1.2	0.9	1.4	1.1	1.1	1.0	0.9	0.8	0.4	0.5	0.6
ALBACETE	17	0.1	0.1	0.4	0.4	0.6	0.0	0.0	0.9	0.9	0.4	1.6	1.2	1.0	3.1	0.4	0.2	-	2.7	2.5	1.3	1.2	1.1	0.9	0.8	0.4	0.5	0.6
VILLENA	18	0.0	0.1	0.4	0.4	0.5	0.0	0.0	0.7	0.7	0.3	1.1	1.0	0.8	1.8	0.3	0.1	2.6	-	2.6	0.9	0.9	0.9	0.7	0.7	0.3	0.5	0.5
ALICANTE	19	0.1	0.1	0.8	1.0	0.5	0.0	0.0	0.7	0.7	0.3	1.2	0.9	0.8	1.7	0.3	1.3	2.5	2.9	-	1.0	1.0	0.9	0.7	0.7	0.3	0.5	0.5
TOLEDO	20	0.3	0.4	0.8	0.8	0.9	0.0	0.0	1.2	1.3	1.8	2.7	1.6	1.4	1.4	0.3	1.1	1.4	1.1	0.9	-	1.7	1.5	1.2	0.9	0.8	0.9	0.8
CIUDAD REAL	21	0.4	0.5	0.7	0.8	1.1	0.0	0.0	1.2	1.0	0.5	2.2	1.4	1.2	1.1	0.3	1.0	1.1	0.5	0.9	1.7	-	4.7	2.3	1.5	1.5	1.3	1.2
PUERTOLLANO	22	0.4	0.5	0.7	0.8	0.8	0.0	0.0	1.1	0.9	0.4	1.9	1.3	1.1	1.1	0.3	0.9	1.1	0.4	0.9	1.6	5.0	-	2.9	1.6	1.8	1.4	1.4
CÓRDOBA	23	0.3	0.3	0.5	0.7	0.7	0.0	0.0	0.9	0.9	0.4	1.4	1.1	0.9	0.9	0.2	0.8	0.9	0.4	0.7	1.1	2.3	2.6	-	2.7	3.0	2.1	2.2
SEVILLA	24	0.2	0.3	0.5	0.6	0.6	0.0	0.0	0.8	0.8	0.3	1.1	0.9	0.8	0.8	0.2	0.7	0.8	0.3	0.6	0.9	1.5	1.6	2.8	-	1.9	1.4	1.5
PUENTE GENIL	25	0.0	0.1	0.4	0.4	0.6	0.0	0.0	0.8	0.6	0.3	1.1	0.9	0.8	0.7	0.2	0.7	0.7	0.3	0.4	1.0	1.4	1.6	3.0	1.9	-	2.5	2.6
ANTEQUERA	26	0.0	0.1	0.3	0.4	0.5	0.0	0.0	0.8	0.6	0.2	1.0	0.8	0.7	0.6	0.2	0.6	0.6	0.3	0.4	0.9	1.4	1.3	2.2	1.5	2.6	-	2.4
MÁLAGA	27	0.0	0.1	0.3	0.4	0.6	0.0	0.0	0.8	0.6	0.3	1.1	0.9	0.7	0.7	0.2	0.6	0.7	0.3	0.4	0.9	1.4	1.4	2.2	1.6	2.5	2.1	-

0.0 | 0 - 0.54 | 0.54 - 0.90 | 0.90 - 1.27 | > 1.27

Time available at destination (*Tu ij*) for all the O/D pairs *

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
FIGUERES	1	-	6:00	6:00	5:50	6:00	0:00	0:00	5:46	5:45	4:29	5:57	5:04	4:12	5:27	1:48	3:53	4:17	2:59	2:20	4:55	4:44	4:12	3:34	1:34	0:41	1:43	2:20
GIRONA	2	5:59	-	6:00	5:50	6:00	0:00	0:00	5:46	5:45	4:29	5:57	5:04	4:12	5:27	1:48	3:53	4:17	2:59	2:20	4:55	4:44	4:12	3:34	1:34	0:41	1:43	2:20
BARCELONA	3	5:52	5:57	-	5:38	6:00	0:00	0:00	5:58	5:33	5:51	6:00	5:52	6:00	5:15	1:36	5:54	5:58	2:47	5:16	6:00	6:00	6:00	5:55	5:27	2:53	4:27	4:56
TARRAGONA	4	5:50	6:00	6:00	-	5:52	0:00	0:00	5:59	5:36	5:54	6:00	5:55	6:00	5:18	1:39	6:00	5:30	2:50	3:39	5:47	5:29	5:48	5:58	4:25	2:56	4:30	3:49
LLEIDA	5	5:58	6:00	6:00	5:57	-	0:00	0:00	5:54	5:45	6:00	5:31	6:00	6:00	5:26	1:47	6:00	5:38	2:58	3:47	5:49	5:37	5:56	5:58	4:33	3:04	4:38	3:57
HUESCA	6	2:40	3:11	5:57	5:49	6:00	-	6:00	6:00	5:45	6:00	6:00	4:13	3:21	4:31	1:48	2:59	2:34	1:07	0:26	4:55	4:44	4:12	3:34	1:34	0:41	1:43	0:58
TARDIENTA	7	2:44	3:15	6:00	5:53	6:00	0:00	-	6:00	5:49	6:00	6:00	4:17	3:25	4:35	1:52	3:03	2:38	1:11	0:30	4:59	4:48	4:16	3:38	1:38	0:45	1:47	1:02
ZARAGOZA	8	6:00	6:00	5:58	5:50	5:57	0:00	0:00	-	5:41	5:59	5:53	6:00	6:00	5:23	1:44	6:00	5:35	2:55	5:44	5:52	6:00	5:40	5:28	6:00	3:01	4:35	5:04
CALATAYUD	9	5:42	6:00	5:55	5:46	4:50	0:00	0:00	6:00	-	4:48	5:45	6:00	5:50	5:30	1:51	6:00	5:42	3:02	5:51	5:59	6:00	5:59	5:29	5:42	3:08	4:42	5:11
GUADALAJARA	10	4:12	4:43	5:51	6:00	6:00	0:00	0:00	4:50	6:00	-	6:00	5:58	6:00	5:21	1:42	6:00	5:33	2:53	5:42	5:42	6:00	5:51	6:00	5:23	2:59	4:33	5:02
MADRID	11	6:00	5:57	6:00	5:55	6:00	0:00	0:00	5:59	6:00	5:55	-	5:57	5:55	5:44	6:00	5:59	5:58	5:47	6:00	6:00	6:00	5:52	6:00	6:00	5:34	5:57	6:00
SEGOVIA	12	0:36	1:07	5:28	3:45	4:47	0:00	0:00	5:57	5:05	1:55	5:56	-	5:59	5:23	1:44	6:00	6:00	2:55	5:44	5:51	6:00	6:00	5:54	6:00	3:01	4:35	6:00
VALLADOLID	13	0:38	1:09	4:01	3:47	4:49	0:00	0:00	6:00	5:07	1:57	5:58	5:59	-	5:25	1:46	6:00	6:00	2:57	5:46	5:54	5:44	5:54	5:57	5:37	3:03	4:37	5:06
CUENCA	14	2:36	3:07	4:59	3:45	4:47	0:00	0:00	5:57	5:05	1:55	5:51	6:00	5:49	-	6:00	5:50	5:59	5:55	6:00	5:46	5:53	6:00	5:59	5:35	3:01	4:35	5:04
REQUENA	15	2:37	3:08	5:00	3:46	4:48	0:00	0:00	5:58	5:06	1:56	4:56	6:00	6:00	6:00	-	5:51	5:54	6:00	6:00	5:47	5:17	5:54	6:00	6:00	3:02	4:36	5:05
VALENCIA	16	2:35	3:06	5:26	5:42	4:46	0:00	0:00	5:56	5:04	1:54	5:59	6:00	5:42	4:44	4:17	-	5:52	6:00	6:00	5:50	5:52	5:59	5:58	5:34	3:00	4:34	5:03
ALBACETE	17	0:40	1:11	4:03	3:49	4:51	0:00	0:00	6:00	5:09	1:59	5:55	6:00	5:53	5:55	1:48	0:59	-	5:59	5:48	5:48	6:00	6:00	5:47	6:00	2:53	4:39	5:08
VILLENA	18	0:33	1:04	3:56	3:42	4:44	0:00	0:00	6:00	5:02	1:52	6:00	5:57	5:46	5:48	1:41	0:52	5:54	-	6:00	5:43	5:59	5:57	5:56	6:00	2:46	4:32	5:01
ALICANTE	19	0:36	1:07	5:27	5:34	4:47	0:00	0:00	5:57	5:05	1:55	5:51	6:00	5:49	5:51	1:44	4:11	5:57	6:00	-	5:44	6:00	6:00	6:00	6:00	3:01	4:35	5:04
TOLEDO	20	2:39	3:10	6:00	5:42	6:00	0:00	0:00	6:00	5:08	6:00	6:00	6:00	6:00	5:26	1:47	6:00	6:00	5:58	5:19	-	5:45	6:00	5:58	6:00	5:07	5:55	6:00
CIUDAD REAL	21	3:41	4:12	5:58	5:50	6:00	0:00	0:00	6:00	6:00	2:00	6:00	5:59	5:48	5:28	1:49	6:00	5:40	3:00	5:49	5:49	-	5:24	5:59	6:00	5:59	5:41	6:00
PUERTOLLANO	22	3:42	4:13	5:59	5:51	6:00	0:00	0:00	6:00	6:00	2:01	6:00	6:00	5:49	5:29	1:50	6:00	5:41	3:01	5:50	5:50	5:39	-	6:00	5:41	6:00	5:42	6:00
CÓRDOBA	23	2:38	3:09	5:01	5:47	6:00	0:00	0:00	6:00	6:00	1:57	6:00	6:00	6:00	5:25	1:46	6:00	5:37	2:57	5:46	5:46	5:45	6:00	-	6:00	5:56	5:57	5:38
SEVILLA	24	2:35	3:06	4:58	5:44	6:00	0:00	0:00	6:00	6:00	1:54	6:00	5:59	6:00	5:22	1:43	6:00	6:00	2:54	5:43	5:51	5:48	6:00	5:57	-	6:00	5:32	5:35
PUENTE GENIL	25	0:35	1:06	3:58	3:34	4:36	0:00	0:00	6:00	5:04	1:54	6:00	5:59	6:00	5:22	1:43	6:00	5:34	2:54	3:43	5:43	6:00	6:00	5:22	5:59	-	5:32	5:35
ANTEQUERA	26	0:29	1:00	3:52	3:28	4:30	0:00	0:00	5:57	4:58	1:48	5:56	5:53	6:00	5:16	1:37	5:58	5:28	2:48	3:37	5:37	6:00	5:57	6:00	5:53	6:00	-	5:29
MÁLAGA	27	0:36	1:07	3:59	3:35	4:37	0:00	0:00	6:00	5:05	1:55	6:00	6:00	6:00	5:23	1:44	6:00	5:35	2:55	3:44	5:52	6:00	6:00	5:51	6:00	6:00	6:00	-

0:00 | 0:00 - 3:30 | 3:30 - 4:30 | 4:30 - 5:30 | 5:30 - 6:00

** The time available at destination shown in this table are those obtained for optimising the efficiency values for the criteria established for business same-day trips. Therefore, in some cases, although is is possible to obtain six o more hours at destination, waiting times or ticket costs could make decrease the efficiency favouring an scenario with less than six hours at destination.*

Note: The ranges of colors are only for guiding the understanding of the tables and *are established statistically considering the mean (μ) and the standard deviation (σ) as follows:*
1) $\mu-\sigma/2$ *2)* μ *3)* $\mu+\sigma/2$

Chapter 5

Access and egress times to high-speed rail stations

OUTLINE OF THE CHAPTER

Accessibility by high-speed rail depends not only on station-to-station travel time, but also on access and egress times, which can be determining factors in total journey travel time. However, studies focusing on accessibility analyses of access/egress times to/from stations are less extended in the literature and centre mainly on the influence of access times to stations on HSR accessibility levels on a regional scale. This chapter is centred on answering the **research question RQ 4** and evaluates the importance of access and egress times to/from HSR stations in an urban context, carrying out a **spatiotemporal accessibility analysis that considers the variations of both taxi and public transport travel times** in the two largest metropolitan areas in Spain: Madrid and Barcelona. General Transit Feed Specification (GTFS) files for public transport and TomTom Speed Profiles data for cars are used to measure access/egress times. This accessibility analysis highlights that the first and last mile of the HSR trip usually account for a high percentage increase in the total travel time.

This chapter is based on the paper:

Moyano, A., Moya-Gómez, B. and Gutiérrez, J. 'Access and egress times to high-speed rail stations: a spatiotemporal accessibility analysis', ***Journal of Transport Geography*****, Accepted with major revisions.**

It has been slightly edited to fit the format of this dissertation.

1. INTRODUCTION

High-speed rail (HSR) networks are becoming fully developed transport systems encompassing a large number of cities and offering different services adapted to the purposes of the trip. However, there is an imbalance in the quality of service given to different cities in the network. Apart from the differences in service-related aspects, such as speed, frequencies, or ticket fares (Moyano and Coronado, 2017), the location of the station and its integration in urban public transport networks are identified as key factors related to the global quality of the rail connection (Brons et al., 2009; Givoni and Rietveld, 2007).

Many studies have focused on the station's location. Peripheral stations, located on a high-speed line out of the city make the connection to/from the city center difficult, while central and edge stations are potentially better integrated with the city, notably in terms of access by public transport (Troin, 2010). Nevertheless, in the case of large metropolitan areas even benefiting from a central and well-integrated HSR station, access and egress times can be very high due to the mere urban extension or low quality of urban transport systems in certain city areas.

The duration of a trip is a determinant for choosing HSR as a travel alternative (Keijer and Rietveld, 2000b; Rietveld, 2000). For that reason, in some of the most critical timing routes, there is significant concern about reducing in-vehicle travel times in an attempt to gain some minutes to compete with air transportation (Vickerman, 2015). At the same time, there is much less concern about the time spent on access/egress times to HSR stations and the quality of intermodality in the station itself (Tapiador et al., 2009b). However, access/egress times can tip the scale in favour of choosing one or another mode of transportation and, in some cases (Martín et al., 2014), it is more effective to make an effort (and investment) to improve accessibility to/from stations than applying this effort to improve HSR in-vehicle journeys (thereby, diminishing in-vehicle travel time). In fact, when HSR travel times are evaluated, consideration should be given not just to in-vehicle travel times but, more importantly, to door-to-door travel times and their variations in time (temporal variations during the day) and space (differences depending on the origin and final destination in the whole HSR trip). However, there are no examples in the literature that analyse this question in detail.

This studdy aims to perform a spatiotemporal analysis of access and egress times to/from HSR stations within metropolitan areas, and then to assess the influence of access/egress times in the whole HSR door-to-door trip. For the first time, the authors conduct a spatiotemporal accessibility analysis to/from HSR stations for both taxis and public transport, and precisely calculate the influence of the first and last mile of HSR trips using new Big Data sources. The results obtained have important implications for local transport and land use policies. Inter-urban accessibility can be decisively improved through actions at the local level.

The remainder of this chapter is structured as follows. Section 2 summarises the existing literature on HSR accessibility, particularly from the point of view of HSR stations access and egress times, and on the use of Big Data sources in accessibility studies. Section 3 describes the data and the methodology. Section 4 shows the main results regarding the temporal and spatial analysis of access and egress times to/from high-speed rail stations, and their influence on the total travel time between Madrid and Barcelona. Second, this section discusses the dynamics of access and egress times to/from stations, comparing between transport modes. Finally, Section 5 presents the main conclusions of the study.

2. LITERATURE REVIEW

2.1 High-speed rail accessibility: the importance of access/egress times to/from stations

High-speed rail accessibility studies are widely extended in the literature and focus mainly on the remarkable reduction in travel time this infrastructure enables (when it is accompanied by adequate services). These studies are very useful for understanding changes in regional accessibility generated by the new infrastructure in the cities it serves (Cao et al., 2013; Chang and Lee, 2008; Gutiérrez, 2001; Gutiérrez et al., 1996) or even for assessing different scenarios of network development (Jiao et al., 2014; Monzón et al., 2013). These studies assess accessibility improvements by using different indicators, all of them based on a station-to-station measure of travel time impedance. Some of these analyses tend to assume that the influence of an HSR system on accessibility extends far beyond each station because these indicators are applied to extensive surfaces, which could be regarded as an overestimation of accessibility in spatial terms (Martínez Sánchez-Mateos and Givoni, 2012). However, accessibility effects derived from HSR depend not only on station-to-station travel time, but also on access and egress times to/from HSR stations. In fact, the influence of the first and last mile can be a determinant in door-to-door HSR trips (Monzón et al., 2016), but are generally ignored in HSR accessibility studies. Monzón et al.'s (2016) paper had the merit of putting this issue in the foreground, but they calculated static access travel times in a relatively simple way from the centroids of the municipalities to the railway stations.

Access/egress times are particularly important in studies on modal choice between HSR and air transport. The main aim of these studies is not centred on access/egress times but on an analysis of air and high-speed rail competition (Dobruszkes, 2011; Román et al., 2007), where the stations/terminals' intermodality will be a determinant. In these studies, the access/egress time to/from stations and terminals is considered an average static measure conditioning user's mode choice: the less time taken from the origin of the trip in the home end (city of residence) and from the final destination in the activity end (visited city), the higher the probability of using one transport mode over another. One exception is a study by Martín et al. (2014), which considers different probabilities according to the spatial variability of access/egress times within the origin and destination metropolitan areas. Apart from this study, there are many others that assess users' choice of travel mode to conventional railway stations. Most of these studies focus on analyses of the different transport modes determining the local modal share, analysing the profile of the access/egress modes on journeys to and from railway stations (Givoni and Rietveld, 2007) and evaluating the predisposition to use railway services (Keijer and Rietveld, 2000b), and how important the 'access-to-the-station' part of a rail journey is to passengers (Brons et al., 2009). Other, more specific, studies evaluate the role of the bicycle as a feeding mode to railway stations, as an interesting alternative for multimodal trips (Martens, 2004; Rietveld, 2000).

Examples of analyses on access/egress times to/from HSR stations are less extended in the literature, although the importance of stations' local accessibility and their integration in the urban transport network are determinants in the assessment of high-speed rail trips. In fact, even benefiting from good local accessibility, access and egress times to/from HSR stations may be very high, especially in large metropolitan areas. They may experience high variations, depending on the time of the day and the transport mode chosen to reach or leave a station. Big Data sources offer new opportunities for spatiotemporal analyses of access and egress times and for the evaluation of their importance in total travel time for HSR travellers.

2.2 Big Data sources in accessibility studies

Dynamic accessibility measures are focused on the assessment of temporal variations in transportation travel times, due mainly to traffic congestion in the case of private vehicles, and due to frequencies and the adaptability of schedules in the case of public transport. In these analyses, new data sources (so-called Big Data sources) play an important role. New studies on transport accessibility and mobility have started to introduce this kind of data in their analyses. For instance, applications such as Google Maps Traffic Overlay and TomTom Live Traffic allow for collecting information such as traffic volume, average traffic speed, and actual journey times (Bartosiewicz and Wisniewski, 2015). Also, TomTom's historical information provides actual observed data on the daily variations in speed profiles for automobiles, allowing for an assessment of congestion impacts on accessibility (Moya-Gómez and García-Palomares, 2015 and 2017) or even an analysis of risk severity in transportation networks. These are defined as the effects of a link or network failure on the whole system (Cui and Levinson, 2017). Concerning public transport, variations on transit service frequencies are a key factor for dynamic accessibility analysis. In this sense, the General Transit Feed Specification provides a common format for public transportation schedules and associated geographic information (routes, stops, etc.), which is a very useful data that can be used in travelers' routing analyses. Such data have been used in recent transit research since Google launched the open platform in 2008. Some studies have used this data to evaluate transit accessibility in different metropolitan areas (Bok and Kwon, 2016; Farber et al., 2014) and compare it to that provided by cars (Salonen and Toivonen, 2013). Other studies have focused on analysis of the influence of transfers and timetables on transit accessibility (Hadas and Ranjitkar, 2012) and even of transit circuity (Huang and Levinson, 2015) to better understand the performance of public transport systems.

In addition to network performance, the analysis of daily accessibility should also incorporate the effect of the mass (attractiveness) of destinations. Most accessibility studies consider population or employment as mass factors (for example, Boisjoly and El-Geneidy, 2016; Merlin and Hu, 2017; Moya-Gómez and García-Palomares, 2017), but recently new data sources (Twitter) have also been used to reflect the attractiveness of destinations (García-Palomares et al., 2018). In contrast to these papers, our study focuses on the first and last mile of door-to-door HSR trips. Spatiotemporal accessibility by both public transport and taxis is measured using GTFS files and TomTom Speed Profiles data, respectively. The attractiveness of the activity end (visited city) is estimated through Twitter data using a new methodology that allows us to identify the areas visited by travellers in the visited city.

New data sources such as Twitter present certain advantages compared to traditional data sources. First, such information should reflect the location of the relevant city's main activity areas (areas in which there is a concentration of workers, tourists and/or residents) and allow for the measurement of temporal variations in these daily activities' hotspots. These social media data provide a large volume of spatiotemporal digital footprints[1], which are a valuable source of knowledge about the physical environment and social phenomena (Li et al., 2013). Twitter is exceptionally useful for understanding and quantifying mobility patterns (Hawelka et al., 2014; Luo et al., 2016; Salas-Olmedo and Quezada, 2016). In contrast, traditional data sources (census and/or employment, for instance) are static measures of cities' activity: Census data offer information on the

[1] Twitter activity is represented by people sending tweets. Receiving or reading messages do not leave a digital footprint.

spatial distribution of the population at night (place of residence) but not on their location throughout the day, while employment data are used as a proxy for population distribution during the day and ignores the fact that many people are at home during the day. Second, an important advantage of using these new sources of information (Twitter or similar) is that the data provided are comparable for cities during the same period; however, it is sometimes difficult to obtain updated employment data for the different case studies analysed. The main drawback of Twitter data is its bias, given that the penetration of this social network is different according to social groups. A more accurate data source for measuring the attractiveness of destinations is mobile phone records; however, obtaining this kind of data is very difficult due to its potentialities. In any case, the methodology proposed in the next section allows obtaining consistent results and it could also be applied in a similar way to both Twitter and mobile phone data.

3. DATA AND METHODS

3.1 Study areas delimitation

Our spatiotemporal approach was applied to the two largest metropolitan areas in Spain: Madrid and Barcelona, where the influence of access/egress times is highly relevant for rail-based trips. We consider the high-speed rail stations of Puerta de Atocha in Madrid and Sants in Barcelona. These stations have been chosen in this study because all the HSR connections between Madrid and Barcelona are made from/to them.

The delimitation used in this study was the area composed by all the municipalities that have more than 50% of their territory within a density isoline of 500 inhabitants/km^2 from the main city (Moya-Gómez and García-Palomares, 2015). This isoline was generated with the density kernel ArcGIS tool, using the 1 km^2 European Environment Agency of the European Union (EEA) reference grid with Eurostat population data. As there is no unique definition of the extension of a metropolitan area, the delimitation used in this study was defined following similar criteria than those used in the MUAs definition (Morphological Urban Areas, IGEAT, ESPON Database Project), but in this case, less population-dense areas are included, softening the influence of 'border effects'.

As a result, in the case of Madrid, the study area encompasses 5,801,809 inhabitants, 2,312 km^2 and 39 municipalities, while the metropolitan area of Barcelona has 4,462,615 inhabitants, 1,420 km^2 and 88 municipalities (Figure 5.1).

3.2 Data collection: Travel times and weights

Travel time data used in this study were obtained from different sources. Data for public transport (timetables, routes, trips, stops, etc.) were obtained from the GTFS files provided by different urban and regional transit agencies and operators[2] dated November 23, 2016. This public transport data were complemented with a pedestrian network, which will allow modelling real pedestrian access to public transport stations and stops. The pedestrian network was obtained from Open Transport Map data. In this study, 70 m/min is considered the average walking speed (Salonen and Toivonen, 2013). Finally, both pedestrian and GTFS data were integrated to develop the whole public transport network through the routing calculation extension 'Network analyst' of the GIS software ArcGIS 10.3.

Concerning the road network, this study used TomTom Speed Profiles data, obtained from the average journey times reported from users' navigation devices. The Historic Speed Profiles are defined as a percentage every five minutes with respect to the observed free-flow speed of the arc. This data structure has been prepared to be used with ArcGIS 10.3. Once the private vehicle travel times were obtained, they were increased by 10 minutes in order to simulate the time spent walking from home to take the taxi and then to pay and walk from the taxi to the station.

The origins/destinations for the access/egress time analysis are the centroids of cells in the 1x1 km grid[3], which follows the pattern of the EEA grid but includes not only the cells of the city with population but also those with Twitter users (Figure 5.1). Population data, obtained from Eurostat population data from 2011, were used for considering the weights of the cells in the home end of the trip (city of residence). Twitter data should reflect the attractiveness of the cells in the activity end (visited city).

[2] Madrid Transport Authority (Consorcio Regional de Transportes de Madrid) for Madrid and different sources for Barcelona: urban buses and metro operators (TMB), metro and commuting metro (FGC), commuting train (Renfe), tramways (TRAM), and all operators of buses of the Metropolitan Region (AMB).

[3] In this paper, we have used the centroids as an automatic procedure for calculations. However, the authors recognise that the centroid could not be representative of the population or activity distribution in each cell, especially in less dense areas located on the periphery of the study areas. For further research, a deeper analysis of the optimal centre of mass for each cell should be included.

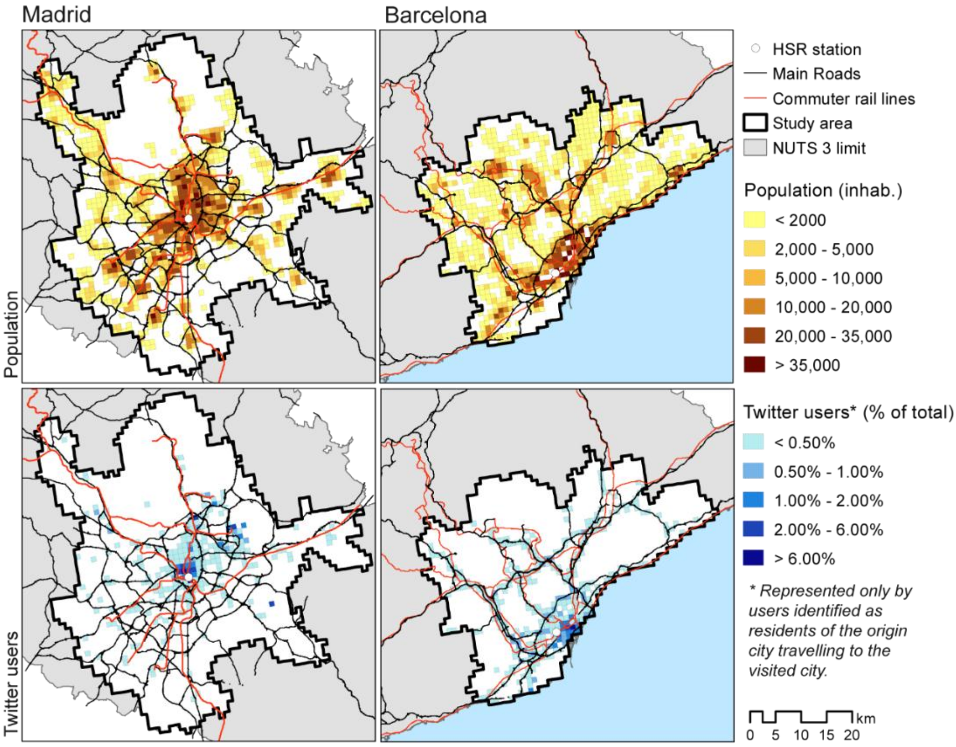


Figure 5.1: Study areas in Madrid and Barcelona: Population and Twitter users distribution

Available Twitter data encompass all the free-downloaded geolocated tweets registered in the Madrid and Barcelona study areas from April 2016 to March 2017. As the activity hotspots are represented mainly by users, that is, people doing their daily activities in certain parts of the city, the data of total tweets needs to be filtered. Data treatment includes first, the removal of those tweets corresponding to enterprises or robots, and second, the identification of the number of users in each cell of the study area every five minutes throughout the day. In addition, the rationale for using Twitter data is that it detects travellers at their destination. As the aim of this study is to evaluate access and egress times to/from HSR stations in the Madrid-Barcelona connection, the attractiveness of the destinations will be represented only by those users identified as residents in the city of origin in an attempt to simulate the potential destinations of people travelling between those cities. Some studies that have analysed users' locations within a city define 'home' as the place most frequently 'visited' by a user at night time (García-Palomares et al., 2018; Luo et al., 2016; Salas-Olmedo and Quezada, 2016). Since we are considering two cities (Madrid and Barcelona), we infer the city of residence of each Twitter user considering the city in which the user is more frequently registered during the night[4]. Finally, the average value of Twitter users between 8:00 and 22:00 hours in each cell of the visited city is obtained in order to measure the cells' attractiveness for HSR travellers.

As Figure 1 shows, the distribution of Twitter users, represented only by those travelling between Madrid and Barcelona at their destinations, allows us to detect potential destinations consistent with what was expected – working areas on the periphery, and especially the city cores, are identified as high-activity areas.

3.3 Travel time measures

The proposed methodology is based on a computation of spatiotemporal measures of travel time every five minutes, from 6:00 to 00:00. This every-five-minutes calculation increases computational complexity, but provides a precise representation of the evolution of travel times and accessibility during the day.

These travel time measures are analysed temporally and spatially for access/egress to/from stations considering both taxis and public transport. A weighted average measure is calculated for both access (T_{ac}) and egress (T_{eg}) times (1)(2), considering the population in the home end (city of residence) and Twitter users in the activity end (visited city) as mass factors. It is conjectured that the outbound trip starts at home in the city of residence and finishes in an activity place in the visited city (Twitter data as a proxy for the activity in each cell), and vice versa for the inbound trip. Second, the total additional travel time (t_{ij}) due to access and egress times is computed (3) for a specific high-speed train departure/arrival time between all the possible combinations of origin/destination cells between Madrid and Barcelona and vice versa (Figure 5.2).

Outbound trip | Inbound trip

$$T_{ac\,1} = \frac{\sum_i \left(t_{access\,i}{}^{HSR\,dt - t\,access\,i} . Po_i\right)}{\sum_i Po_i} \qquad T_{ac\,2} = \frac{\sum_i \left(t_{access\,i}{}^{HSR\,dt - t\,access\,i} . Tw_i\right)}{\sum_i Tw_i} \tag{5.1}$$

$$T_{eg\,1} = \frac{\sum_j \left(t_{egress\,j}{}^{HSR\,at} . Tw_j\right)}{\sum_j Tw_j} \qquad T_{eg\,2} = \frac{\sum_j \left(t_{egress\,j}{}^{HSR\,at} . Po_j\right)}{\sum_j Po_j} \tag{5.2}$$

$$t_{ij} = t_{access\,i}{}^{HSR\,dt - t\,access\,i} + t_{egress\,j}{}^{HSR\,at} \tag{5.3}$$

Where:

- $t_{access\,i}{}^{HSR\,dt - t\,access\,i}$ is the access time from cell i to the HSR station, computed considering the time needed to arrive at the station in order to take a specific HSR service ($HSR\ dt$ is the HSR departure time).

[4] The mode is used as the statistical means for identifying the place of residence for Twitter users.

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- $t_{egress\ j}{}^{HSR\ at}$ is the egress time from the HSR station to cell j, computed at the time of arrival of the specific HSR service ($HSR\ at$).
- Po is the population of each cell
- Tw refers to the Twitter users in each cell, during the day (temporal range between 8:00 -22:00 hours).

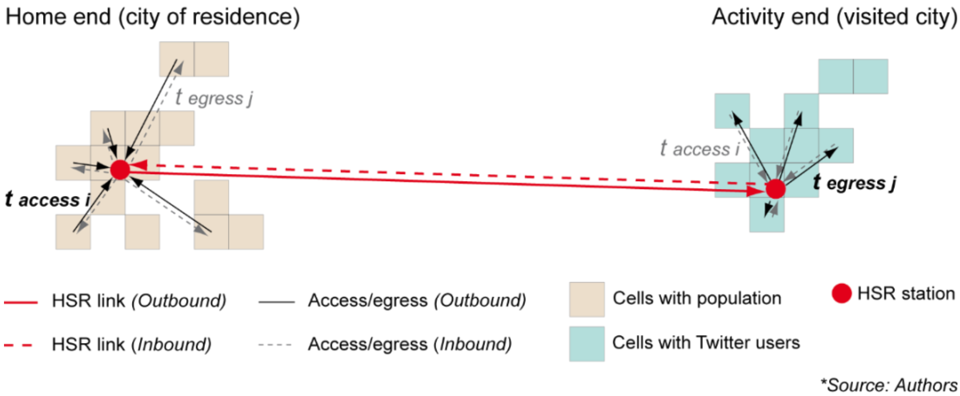

Figure 5.2: Origin/destination cells combination for assessing access+egress times

In addition, the disaggregation in the computation of travel times allows assessing the differences among cells in each city analysed. The average of travel times and their coefficient of variation during the day for each cell included in the study areas are obtained, for both access and egress times to/from stations. Also, the ratio between public transport and taxi travel times is computed for comparing the different performance of these transport modes in diverse peak and off-peak temporal scenarios.

4. RESULTS

4.1 Temporal variation in access and egress travel times to/from high-speed rail stations: Madrid and Barcelona

This subsection analyses the temporal variation during the day of access and egress travel times to/from high-speed rail stations for outbound trips, taking into account HSR departure and arrival times, respectively. Weighted access (T_{ac}) and egress (T_{eg}) times are computed in order to assess their influence on the whole HSR trip[5] (Figure 5.3),

[5] In order to avoid repetition, only access and egress times related to the outbound trip are shown in Figure 5.3.

considering the access time for reaching the station before a specific HSR departure time and the egress time just after the HSR arrival at the destination. Access times are weighted by population of origin cells, and egress times by activity of destination cells.

In general, both cities present similar trends in terms of temporal variation during the day. Egress times are generally lower than access times on outbound trips, mainly because of the central location of the destinations (activity areas represented by Twitter users) compared to the more dispersed location of origins (population) in the case of access travel times. Taxis show a better performance than public transport, whose travel times are around 20 minutes longer. In addition, access and egress times are higher in Barcelona than in Madrid, for both taxis and public transport, although the difference between cities is only around 4-5 minutes.

Focusing on access times, the highest travel times by taxi (Figure 5.3a) are around 8:30 hours and 17:30 hours, with the first peak of the day being more pronounced. The most favourable time for public transport is the morning peak hour, when the frequency of public transport services is higher (Figure 5.3b) [6]. In contrast to the congestion suffered by accessing a station in the city of origin early in the morning, travellers do not experience congestion when arriving at their destination city (because the HSR trip Madrid–Barcelona and vice versa takes 2 hours and 30 minutes. The lowest values of egress times for taxis are found for HSR services arriving at 21:30 hours (Figure 5.3c). At that time, congestion starts to decrease, which benefits taxi services. The lowest values for public transport are found a bit earlier, around 18:00-19:00 hours, especially for egress times from Madrid-Atocha station. Finally, public transport egress times increase abruptly for HSR services arriving after 21:00 hours, particularly in Barcelona, when the frequency of public transport starts to decrease (Figure 5.3d).

Total weighted access + egress times ($T_{ac\ 1}$+ $T_{eg\ 1}$) for outbound trips are represented in Figure 5.3e and 5.3f. In general, both directions of HSR trips present similar trends throughout the day. For taxis, the early morning HSR trains are those that present higher access/egress times in sum, while public transport curves exhibit almost the opposite picture, with the morning peak hour being the most favourable. On the other hand, for train passengers arriving at around 22:00 hours, egress times are particularly low in taxis (free flow conditions) but very high in public transport (low frequencies).

[6] In this analysis, it has to be highlighted that, for public transport access times, the potential origins that are able to arrive at the station to take a train reach the 90% of the cells in the study area only after 8:00 hours in the case of Madrid and 8:30 hours in the case of Barcelona, because public transport services start at 6:00 hours in the morning. Before these times, the cells unable to reach the stations (distanced areas to the station) are not included in the weighted average and, for that reason, the travel times' trend diminishes in the very early hours of the day. In the case of egress travel times, all local trips depart at the same time, when the HSR service arrives at the station.

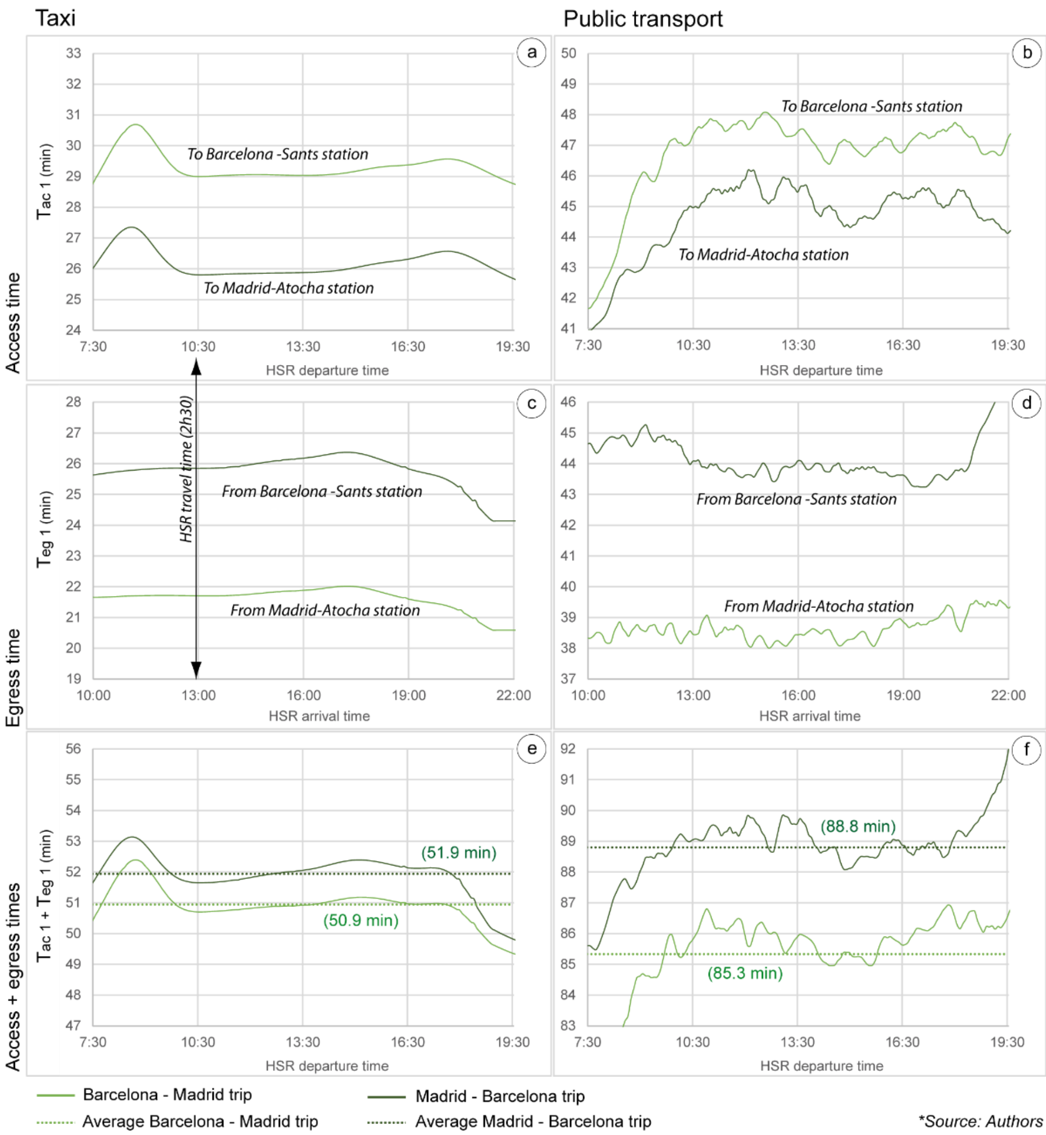

Figure 5.3: Weighted average access ($T_{ac\ 1}$) and egress ($T_{eg\ 1}$) times for outbound trips.

Focusing on average travel times during the day (horizontal lines in Figures 5.3e and 5.3f), taxi services imply extra travel time due to local accessibility of 51.9 minutes (an increase of 34.6% in total travel time) in the case of the Madrid–Barcelona trip, and 50.9 minutes (a 33.9% increase) in the Barcelona–Madrid link[7]. For public transport, average values are around 30 minutes higher (88.8 minutes for the Madrid–Barcelona link and

[7] Considering 2h 30 minutes of HSR in-vehicle travel time

85.3 for the Barcelona-Madrid connection) which represents an increase in travel time of between 59.2-56.8 % of travel time.

4.2 Spatial disparities in access and egress travel times

Figure 5.4 shows the spatial variation of access travel times[8] (average travel time during the day and coefficient of variation) for both public transport and taxis. Taxis almost reach the third part of the study area in less than 40 minutes and the whole metropolitan area in less than 60 minutes, both in Madrid and Barcelona.

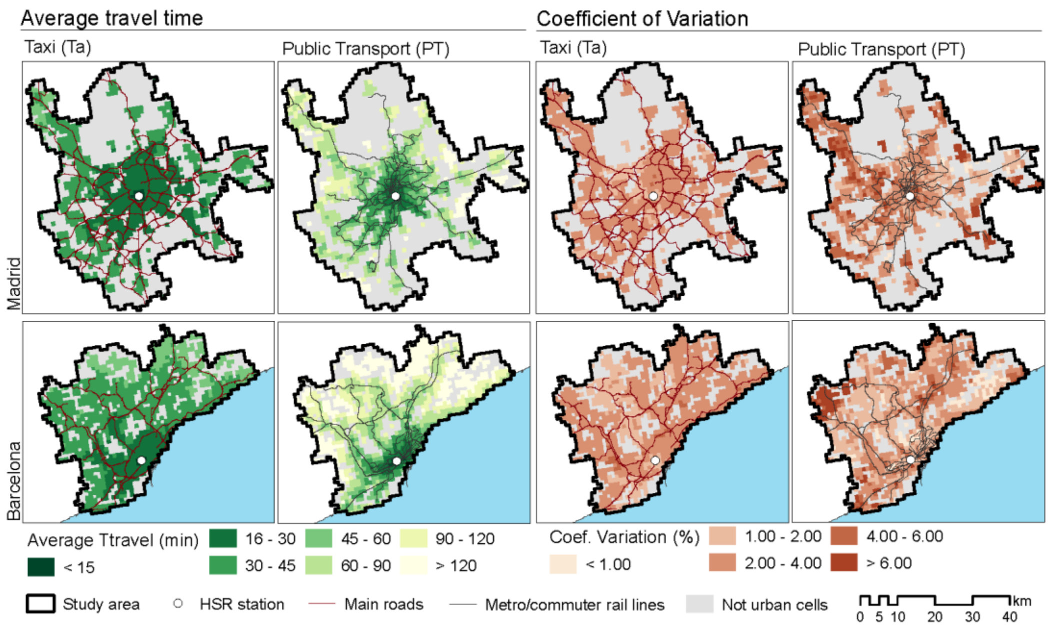

Figure 5.4: Average access travel time and coefficient of variation for taxis and public transport

In the case of public transport, only the core of the cities and the main metro/commuter rail corridors allow for competition with taxis in terms of average travel time values. Nevertheless, although these more favourable areas for public transport are represented by a small number of cells in the study areas, they concentrate high volumes of population (Table 5.1). For instance, in the case of Madrid, the cells that can access the station in less than 45 minutes represent only 9.1% of the total area (S), but they encompass around 52% of the population (Po) considered in the analysis. In a

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[8] Because of space limitations, Figure 3 shows only access travel times. Maps of egress travel times are very similar.

similar way, in Barcelona these percentages are around 10.2 % of the total area and 55% of the whole population.

Table 5.1. Percentage of population (Po) and area (S) involved by transport mode and travel time interval

	MAD				BCN			
Transport mode / Ttravel (min)	Ta		PT		Ta		PT	
	%Po	%S	%Po	%S	%Po	%S	%Po	%S
< 15	4.5	0.4	1.5	0.2	4.9	0.3	5.6	0.4
15 – 30	66.0	28.3	18.6	2.1	50.8	18.1	25.0	3.1
30 – 45	28.2	57.0	32.4	6.8	40.2	56.7	24.5	6.7
45 – 60	1.3	13.7	27.5	11.8	4.1	23.6	10.1	10.1
60 – 90	0.0	0.5	16.3	27.6	0.0	1.1	10.3	23.9
90 – 120	0.0	0.0	2.1	22.9	0.0	0.1	20.7	21.4
> 120	0.0	0.0	1.6	28.6	0.0	0.0	3.8	34.4

Coefficients of variation reflect the variability of performance of the networks in accessing railway stations (Figure 5.4). Public transport exhibits high values in certain distant areas, reflecting fluctuations in public transport frequencies. The coefficients of variation of taxi travel times are more homogenously distributed, but some spatial disparities can be observed, according to the congestion levels experienced in each area. Supplementary videos related to temporal variations of travel times for both taxi and public transport can be found in the supplementary material of this dissertation.

Total local travel times (access + egress) vary not only temporally (Subsection 4.1) but also spatially, depending on the location of the different origins/destinations and their connectivity, both for road and public transport networks. To catch all these spatial differences, the total amount of time spent accessing and egressing stations (t_{ij}) for all the O/D combinations is represented by quintiles in Table 5.2, for specific outbound and inbound high-speed trains:

Table 5.2. Total access + egress times (minutes) by taxi (Ta) and public transport (PT) according to OD combinations in outbound (Out) and inbound (In) trips: quintiles (P)

Round trip:	**Madrid – Barcelona – Madrid**				**Barcelona – Madrid – Barcelona**			
HSR timetables	*Outbound 9:00 h – 11:45 h* *Inbound 18:25 h – 20:55 h*				*Outbound 9:00 h – 11:45 h* *Inbound 18:30 h – 21:20 h*			
	P20	**P40**	**P60**	**P80**	**P20**	**P40**	**P60**	**P80**
Ta (Out)	49.9	56.1	61.7	68.5	48.7	54.8	60.1	66.2
Ta (In)	48.4	54.1	59.4	65.8	46.1	51.6	56.6	62.7
PT (Out)	79.0	94.3	108.5	126.3	73.3	87.6	100.3	115.7
PT (In)	77.9	93.3	108.2	127.9	75.3	90.4	104.1	120.4

In general, there are no important differences in total access+egress times between Madrid–Barcelona round trips or vice versa, as expected. However, significant differences are found between public transport (PT) and taxi (Ta). In the first quintile (P20), the differences between travel times by transport mode are around 25-30 minutes higher for public transport. These O/D combinations represent connections between central areas that are well covered by public transport services (as shown in Figure 5.4). The last quintile (P80) includes the combination of distanced and low-served (especially by metro/commuter rail) cells of the metropolitan areas, where total travel times increase around 2 hours by public transport and 65 minutes by taxi.

When comparing outbound and inbound trips, taxi travel times mean values are slightly higher in both cities for outbound trips, due to the more significant traffic congestion in the morning peak hour. For the inbound trip, access times may be also affected by the afternoon peak hour, but the egress time from the stations at the end of the day (around 21:00 hours), when traffic can run almost in free flow, decreases the total access+egress times for taxis. Concerning public transport, depending on the direction of the trip, the performance is nearly the opposite. In the Madrid–Barcelona round trip, public transport travel times are slightly lower for the inbound trip (HSR departure time at 18:25 hours), because the egress time from Madrid–Atocha at around 21:00 hours is still competitive and starts to increase some time after that (see Figure 5.3d). However, considering the Barcelona–Madrid round trip, for inbound trips arriving in the evening there is an increase in public transport travel times due to the lower frequencies supplied.

4.3 Comparison between transport modes: travel time ratio public transport/taxi

The public transport/taxi travel time ratio allows for a temporal and spatial comparison of the performance between taxis and public transport in accessing HSR stations (Figure 5.5). The temporal variation of this ratio shows that, on average, the values are higher than one, since taxi travel times are clearly lower than those by public transport (Figure 5.5a). However, there are some differences, depending on the time of day analysed. First, the morning peak hour is the most favourable for public transport for both cities because of the higher levels of congestion for private transport and the higher frequencies of public transport at this time. Second, in off-peak hours (12:00 hours), taxi travel time rises to its highest competitiveness. This travel time ratio shows a similar temporal pattern in both cities, and is always lower in Barcelona than in Madrid.

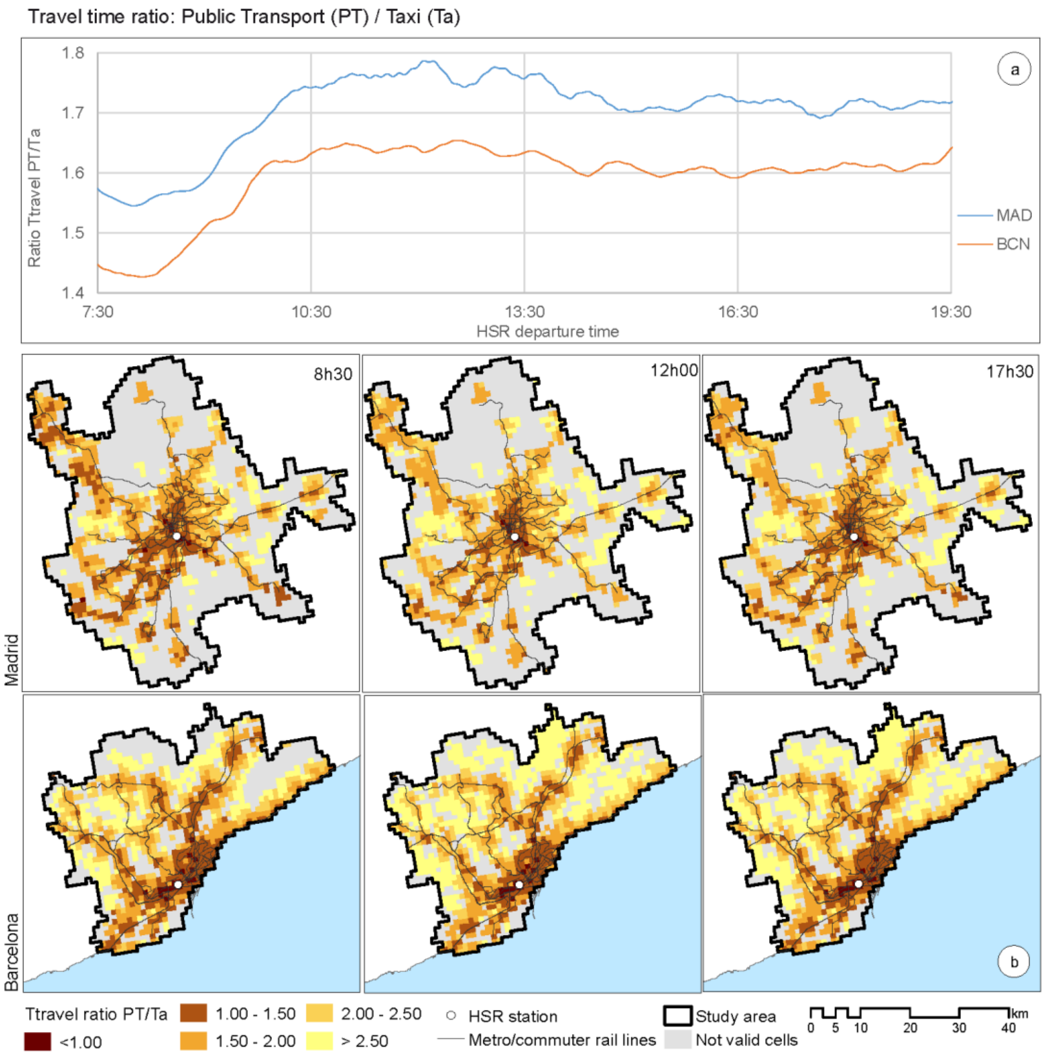

Figure 5.5: Access time ratio public transport/taxi: temporal (a) and spatial (b) variation

Travel time ratios between public transport and taxis can also be analysed spatially (Figure 5.5b). As expected, the lowest ratios (better performance of public transport) are found within the city centre and along the main public transport corridors, since these areas are well served, mainly by metro and rail. Cells showing particularly low values along the corridors correspond to the location of commuter train stations. In the comparison of the different time slots, higher changes can be identified in some distant cells, influenced by the effect of significantly lower public transport frequencies during the noon off-peak period. These changes are higher in Madrid than in Barcelona. For instance, in Madrid, the population involved in areas with ratios lower than 1.50 in the

8:30 h scenario rises to 49.3% while it decreases to around 31% of the total population in the 12:00 h scenario (Table 5.3). In Barcelona, the differences are smaller but also remarkable, reaching 65.4% of population, with ratios lower than 1.50 in the first scenario and diminishing to 58.8% in the off-peak hour. In both cities, the 17:30 h scenario shows an intermediate situation in terms of both population and area.

Table 5.3. Percentage of population (Po) and area (S) involved by scenario and ratio interval.

	MAD						BCN					
Scenario	8:30 h		12:00 h		17:30 h		8:30 h		12:00 h		17:30 h	
Ratio	*%Po*	*%S*	*%Po*	*%S*	*%Po*	*%S*	*%Po*	*%S*	*%Po*	*%S*	*%Po*	*%S*
<1.00	4.0	0.6	3.2	0.3	2.7	0.3	13.7	1.2	12.2	1.0	12.1	1.0
1.00 – 1.50	45.3	11.7	27.8	5.1	33.1	6.8	51.7	14.8	46.6	11.1	50.5	12.8
1.50 – 2.00	41.0	26.9	53.2	23.0	51.4	24.6	24.7	24.3	26.2	20.8	24.6	22.7
2.00 – 2.50	7.0	22.4	11.6	23.4	9.4	23.0	4.6	22.1	8.5	21.2	6.6	20.4
> 2.50	2.5	28.7	4.2	48.2	3.4	45.3	4.0	27.2	6.5	45.8	6.2	43.1
N*	0.2	9.7	0.0	0.0	0.0	0.0	1.3	10.4	0.0	0.0	0.0	0.0

**Percentage of population/areas that cannot access the station by public transport for a certain scenario*

5. DISCUSSION AND CONCLUSIONS OF THE CHAPTER

Access and egress times are determining factors in door-to-door high-speed rail trips. HSR competitiveness depends not only on in-vehicle travel times, timetables and fares, but also on the characteristics and efficiency of local accessibility. Although the first and last miles may represent a significant share of the total journey's travel time, especially in large metropolitan areas, access and egress times have been scarcely studied in the literature.

This chapter analyses the spatiotemporal variations during the day of access/egress times to/from HSR stations in the two largest metropolitan areas in Spain, Madrid and Barcelona. **Nowadays, reliable travel time data, such as GTFS (General Transit Feed Specifications) for public transport and TomTom Speed Profiles data for private vehicles, and computational capacity allow scholars to carry out in-depth travel time dynamic analyses. In addition, new data sources such as mobile phone records and social media data (such as Twitter) allow for the tracking of individuals.** In our case, using data from Twitter made it possible to ascertain the places most visited in Barcelona by travellers from Madrid and places most visited in Madrid by travellers from Barcelona. This variable has been included in an accessibility indicator to analyse the desirability of destinations.

The results obtained show that access and egress times vary significantly throughout the day, depending on variations in traffic congestion and the frequency of public transport services, which always favour taxi services. In addition, weighted average access and egress times in the home end are higher than those in the activity end, since population tends to show more dispersed spatial patterns than activities. Another interesting finding is that the first and last mile of the HSR trip account for a high percentage of the total travel time (about 35% or 55% for taxis and public transport, respectively).

Both Madrid and Barcelona present similar patterns in the temporal variation of access/egress travel times, with slightly higher values of travel times in Barcelona, both for taxis and public transport. In relation to spatial variations, the results allow us to identify areas in the cities that present higher/lesser levels of congestion at certain times of the day or better/worse public transport services. The temporal variation in taxi travel times (access and egress) is low, which reveals very low levels of congestion in both cities. These results are consistent with the paper by Moya-Gómez and García-Palomares (2017) comparing congestion levels in several European cities, with Madrid and Barcelona being the least congested cities in the sample. This fact is due both to large infrastructure investments in both cities before the economic crisis and to the sharp drop in annual average daily traffic during the economic crisis. In contrast, the spatial variation of local taxi travel times is very high, reflecting the relatively large size of both metropolitan areas.

These aspects have important policy implications. First, **in the analysis of HSR accessibility, not only the average, but also the temporal and spatial variations of access and egress times must be considered as key factors in door-to-door HSR trips**. HSR analysis should consider intermodal approaches, and not only the station-to-station approach, to assess the real impacts of HSR on accessibility improvements. In addition, **this kind of analysis could help urban and regional transport authorities to detect deficiencies concerning station integration in metropolitan transport systems and to evaluate the implications of local accessibility improvements**, such as opening of new metro lines or improving scheduling coordination between suburban trains and HSR services.

The results of the study also suggest that urban sprawl affects accessibility by HSR in a very negative way by lengthening travel times in the first and last miles. In fact, accessibility improvements derived from the construction of new HSR lines could be partially annulled if urban sprawl continues. In this sense, although the impacts of HSR stations' location for cities has been widely analysed in the literature, the consideration of central, edge and peripheral settings should be revisited, because **not only the location of the station, but also its integration within urban transport systems could**

make a difference, as this chapter has shown. In this sense, **improving the level of intermodality of stations favouring the link between HSR and local transport systems would help to reduce total travel times.**

Finally, the results obtained in dynamic analysis of access and egress travel times can feed mode choice models in order to analyse high-speed rail and air transport competition in a more realistic way. As demonstrated by Martin et al. (2014), the probability of choosing a plane or train changes spatially according to access and egress times to terminals. Future research will take advantage of new Big Data sources in order to analyse the influence of intra-urban spatiotemporal variations of access and egress travel times in modal choice.

PART III: CONCLUSIONS

Chapter 6

Main conclusions and future research

1. MAIN RESEARCH CONCLUSIONS

1.1 Research findings

The new panorama of HSR development, with its many possibilities of connections, services and cities involved, highlights the need for a global assessment to understand the real efficiency of HSR from a service-related perspective because, in this context of HSR expansion, the quality of the operating services is just as important as securing an HSR infrastructure. Precisely, **in this dissertation, the focus is set on the services and opportunities they provide for Spanish HSR cities** in terms of accessibility and mobility choices. The **main research findings** are focused on answering the four research questions presented in the first part of this document:

RQ1_ Are all HSR links similar? Is the 'HSR brand' the same for all the cities? Has HSR become a transport mode with many different roles in relation to the services supplied?

The growth of HSR networks and the variability in the services' supply suggest that the Spanish HSR system is experiencing a change of conception in relation to its role as a transport mode. To answer these questions, this dissertation presents a new focus to be considered in relation to high-speed rail studies, as it is centred on the links, on the 'vector' that characterises the quality of the services supplied in each connection. **This link-oriented approach may serve as a general basis for a better understanding of HSR connections and the services they provide**.

The dissimilarities that exist in terms of the services' quality help to distinguish different types of HSR links resulting from the addition and interconnection of several lines and the mixture of different HSR services. Among all the types identified, it is possible to recognise not only the 'early stage' HSR connections, which are the links between large cities located approximately 350 – 600 km apart, with high frequencies and speeds oriented to compete with air transport, but also other types, which were much less expected when the initial HSR system was conceived. The latter connections generally appear due to the development of the network (new lines and intermediate stops) and the bypasses connecting different lines. They offer a new perspective on the HSR service and establish a multirole network that can cover a wider range of possibilities from which travellers may benefit. These HSR types present interesting characteristics and broaden the potential of HSR as a transport mode: short distance regional HSR, very long distance HSR, transversal connections, etc. Although many of these new links may not be very relevant connections in terms of demand, they may represent a very important improvement in terms of connectivity, mainly for small cities in the network. Therefore, **the studies addressed in this dissertation elucidate the multiple roles the HSR system** can currently perform as a transportation mode, highlighting the fact that **not all the links branded as high speed fit into the same profile** because there is a wide range of variations.

This link's approach may be a useful tool in transport planning by helping to anticipate how new HSR systems may be developed in terms of types of future city-to-city links. The HSR links' typology obtained in this dissertation may help transport planners to estimate which kinds of services and frequencies should be planned when a new HSR city is included in the network, facilitating the implementation of new HSR connections. In addition, potential HSR cities would know a priori the different possibilities of connections that could serve it, according to their own characteristics, position in the network, and the entity of nearby cities. Therefore, this approach could serve to establish a benchmark for future HSR cities, helping them to adapt their policies and strategies according to their potential services.

RQ2_ How efficient is the HSR system as a transport mode for different same-day trip purposes? How can this efficiency of HSR connections between cities be measured? Which service-related factors influence the efficiency of HSR same-day trips the most?

The main contribution of this dissertation is the efficiency analysis of the HSR system for same-day trips in the Spanish HSR network. The methodological approach of this thesis is based on **the need to incorporate the characteristics of the supplied services into the accessibility analyses** of means of transport, which are limited to fixed timetables. Traditional accessibility analyses, usually location-based approaches that consider travel time as the main friction in network analyses, reveal the potentials of network configurations but generally overestimate the outcomes, as they assume all nodes in a network are equally well served in terms of frequencies and costs. However, in this dissertation, the **efficiency measure proposed – the available time at a destination that can be gained with a given monetary investment – is a new approach to assessing the accessibility of networks**, which is based on the concepts of 'time geography' and 'contactability' and is focused mainly on the adaptability of the services to travellers' needs and the associated costs, depending on the different trip purposes (tourism, business and commuting). It also considers the possibility of transfers at certain stations, simulating the multiple options travellers have when organising a same-day trip through HSR. This complex measure helps us understand the differences in HSR's contribution to cities and quantify in relative terms what HSR services can provide to each city. Therefore, this dissertation focuses on the analysis of the HSR network as a whole, **identifying and analysing the influence of the 'network effects' (different services, bypasses, transfers, etc.) in mobility choices**. Chapter 4 of this dissertation addresses the **efficiency of HSR connections for different cities and trip purposes, such as tourism, business and commuting**. In addition, the flexibility of these methods allows for an analysis of the **impact of different service-related factors in door-to-door HSR trips**. In general, HSR cities show greater improvement when adapting services' timetables to the needs of the travellers, especially for tourism trips, because adequate timetables allow travellers to make the most of a same-day trip and benefit from having more time to spend at the destination. However, in the case of business, the friction introduced by access/egress times to/from stations acquires higher relevance, especially in large metropolitan areas. Finally, when analysing commuting trips, first the adaptability of services to working schedules is key, but also the total investment on the trip, both in time and money.

Generally, HSR analysis examines the way in which the local economic environment will benefit from enhanced connections with other cities, and the resultant expansion of its economic markets. This rationale is used for medium and small cities, which normally urge the national authorities to grant them a station. However, in highly developed HSR networks, such as the Spanish one, big cities easily secure a high, or at least a reasonable, number of daily services, but small intermediate cities, which make an effort to secure an HSR infrastructure, finally run the risk of being bypassed by HSR services. Consequently, **this kind of analysis is a useful tool for transport planning, both in terms of evaluating existing HSR stations and assessing the real opportunities a new station could bring to the city it serves, guiding local strategies and decisions.**

RQ3_ To what extent does the efficiency of the services supplied in each HSR connection allow for the attainment of the maximum potential accessibility provided by the HSR infrastructure?

The efficiency analysis and its comparison with traditional accessibility measures helps explicate **how the efficiency of the services' supply meets the potentialities the infrastructure provides.** The main findings reveal that some HSR stations in the Spanish network **present very different supplies of services, even though they have a similar location in the network. This has a significant influence on the connectivity effects provided by the HSR system**. For instance, there is a remarkable difference between central locations that count on regional HSR services that are more 'efficient' because they are served by more economic services and higher frequencies than cities in a similar territorial situation, which benefit only from low-frequency long-distance services. Also, the results show that, in general, large cities with peripheral locations in the network are identified as winners in comparative accessibility analysis, as they benefit from adequate daily services connecting them to Madrid.

In summary, the efficiency measure proposed in this thesis and its comparison help to **explore the difference between the potential of the infrastructure itself (location-based accessibility) and the actual changes in accessibility (schedule-based accessibility)**. In addition, in the analysis of transport infrastructures limited to specific schedules, such as HSR, the most commonly used indicators, which generally consider 'travel time' as the main impedance, overestimate the improvement in accessibility provided by the infrastructure, as they consider that every city in the network is equally served. On the contrary, the **efficiency measure proposed in this dissertation tries to highlight the importance of considering services, schedules and costs (in both time and money) in the analysis of accessibility.**

Moreover, in this comparative analysis there are interesting implications in terms of policy and decision making, where the change (in favour) of accessibility is foremost among the reasons for building HSR lines. A place with a new high-speed rail station increases its opportunities for travel because of the facility itself. It brings a new, fast transport mode, but improved accessibility will come from the services and operations established later (Boisjoly and El-Geneidy, 2017). In this case, where having the station is used as the only element to assert an increase in accessibility levels, the lack of debate about how services are set is relevant in policy terms. For this reason, in the decision-making process it would be far more interesting and revealing to explore service- and schedule-based accessibility indicators rather than location-based ones, as is usual.

The measure proposed in this dissertation and its adaptability to a different kind of analysis may facilitate the definition of cities' strategies to make the most of the opportunities provided by HSR in terms of mobility and connectivity. Most of the cities have implemented different strategies in attempts to make the most of HSR but, in many cases, without real knowledge of what they could really expect from the new infrastructure. The efficiency analysis suggested here may help cities to identify weak points in the HSR service they receive, and therefore prove valuable in negotiations with rail operators in reaching a compromise between local and national economic/political interests. At the same time, rail operators could apply these methods to assess different scenarios and evaluate the effects of a specific change in the HSR operating services (adapting certain timetables to allow better transfers, reduced ticket prices, etc.) on the global efficiency of the HSR network for cities.

RQ4_ What is the influence of access and egress times to/from HSR stations in the efficiency of HSR connections? Is this influence affected by temporal and/or spatial dimensions?

As mentioned in the first chapter of this dissertation, an HSR station's integration in an urban and interurban context is a key factor in HSR trips, and the **influence of access and egress times could be a determinant in the efficiency of door-to-door high-speed rail trips**.

This dissertation shows that HSR competitiveness depends not only on in-vehicle travel times, timetables and fares, but also on the characteristics and efficiency of local accessibility. The **first and last miles may represent a significant share of the total journey's travel time**, especially in large metropolitan areas, such as Madrid and Barcelona in the Spanish case study. In those cases, the first and last mile of the HSR trip account for a high percentage of the total travel time and depend on the mode of transportation chosen (about 35% or 55% for taxis and public transport, respectively). Besides, this dissertation shows that access and egress times vary significantly throughout the day, depending on variations in traffic congestion and the frequency of public transport services, highlighting the relevance of spatiotemporal analysis for addressing this kind of study. Also, this spatiotemporal analysis helps identify areas in the cities that present higher/lesser levels of congestion at certain times of the day or better/worse public transport services.

These aspects have important policy implications. First, in **the analysis of HSR accessibility, not only the average, but also the temporal and spatial variations of access and egress times must be considered as key factors in door-to-door HSR trip**s. In addition, this kind of analysis could help urban and regional transport authorities to **detect deficiencies concerning station integration in metropolitan transport systems and to evaluate the implications of local accessibility improvements**, such as the opening of new metro lines or the implementation of more than one HSR station in large metropolitan areas (similar to the case of Paris in France)

1.2 Concluding remarks

In summary, this dissertation concludes that:

1) First, it should not be considered that the 'HSR brand' is the same for all the cities included in HSR networks. The evolution of HSR networks and services is opening up a new panorama in which the quality of the services determines different types of connections, showing that the HSR system could play different roles in terms of connectivity and mobility choices.
2) Second, this new scenario highlights the need to assess HSR systems from a different perspective. The different quality of services supplied in each case (frequencies, costs, timetables, etc.) requires an analysis of HSR systems as a whole, including all the possibilities of travelling through the HSR network and the needs and temporal restrictions of the different kinds of travellers, following the principles of Time Geography. The efficiency analysis proposed in this dissertation is a way of including all these aspects in accessibility analysis. In this approach, services matter much more than facilities.
3) Finally, this person- and schedule-based efficiency approach should not be understood without including the stations' integration in urban transport systems. In examining HSR trips the influence of all the links in the whole transport chain must be considered because the influence of access and egress times to/from HSR stations and their spatiotemporal variations are determinants in door-to-door HSR trips.

2. FUTURE LINES OF RESEARCH

This section addresses the future lines of research arising from the three main empirical analyses presented in this dissertation:

1. The first line of research relates to the analysis of the connections of other HSR systems through a link-oriented assessment. This dissertation focuses on the

Spanish HSR system and its links' typology, presenting a general view of the main types of HSR links that can be found in other cases, although other networks' analyses could highlight their own singularities. Precisely, applying this approach to other networks could offer a wider spectrum of connections, which would allow for a comparison of different network structures and different ways of developing the HSR system.

In addition, it could be interesting to **analyse and compare the links' characteristics in other European networks**, such as France or Italy, and develop an integrated assessment of them all. In this way, we will be able to analyse whether the Madrid – Sevilla or Paris – Lyon links, for example, are similar, considering both the territorial and service-related variables. Furthermore, this transport-oriented approach could establish the basis for a whole analysis of the European HSR system from a transport geography perspective.

2. The efficiency approach presented in this dissertation and the global analysis of same-day trips, considering transfers and including all the temporal constraints, present different possibilities for further research.

   2.1. First, the continuous evolution of HSR networks will require future analysis. In the Spanish network, **new network extensions are already under consideration**, such as the opening of the HSR tunnel between the stations of Atocha and Chamartin in Madrid, allowing the passing connection between the north-west HSR line and the rest of the network.

   Also, **new HSR services will be implemented in the near future**. This is the case of the EVA service between Madrid and Barcelona, which is considered a low-cost HSR service offering more economical ticket fares (discounted by 25%, compared to long-distance fares). This new service will have high capacity (five seats, instead of four per line) and offers less on-board services (there will be no cafeteria and business class seats, for instance). These network and service updates would have an **effect on the HSR connections for certain cities that can be analysed from the efficiency perspective presented in this dissertation**.

   2.2. Second, this global analysis considering the possibility of transferring between stations highlights the concept of HSR hubs. In the transportation studies literature, the hub concept is applied (almost exclusively) to air connections. In air transport, several studies have centred on an analysis of hub-and-spoke networks, providing information on the most adaptable and profitable networks competing in the airline industry (Adler et al., 2010; Adler and Smilowitz, 2007; Lin and Lee, 2010; Zhang, 1996), or assessing the allocation strategies and their effects on total routing costs in hub networks (Yaman, 2011).

In the Spanish HSR network, Madrid could perform a similar role to an air transport hub, where early morning trains reaching the capital of the country give travellers the option of transferring to a second train serving a different HSR line. For further research, **the role of HSR hubs can be addressed, analysing the effects on network connectivity, coordination between services and the profitability of this approach to services' operation**.

2.3. Third, **the efficiency measure presented in this dissertation could serve as a basis for developing a 'journey planner' integrating the different steps of the whole transport chain from a different perspective**. Nowadays, most journey planners are based on identification of the shortest route (in distance or travel time), including different alternatives of modes of transport and normally considering intermodal trips to satisfy travellers' requirements. For future research, improving journey planners can be addressed based on the concept of 'efficiency'. Time needed at a destination, specific temporal constraints and travel costs could be included as options for optimisation in the best route and transport modes' selection.

2.4. Fourth, another line for future research is related to methodological aspects. The efficiency analysis presented in this dissertation includes global measures, both linear and weighted sum indicators, which allow for comparisons between cities. The mass factors introduced in the weighted sum measure are related to potential markets that can be attracted for the destination city in each case. However, this approach can be improved in one more step, by including not only the potential market that can be attracted but also **the attractiveness of the destination city**. This attractiveness will be different for each city depending on the trip's purpose.

Figure 6.1 Scheme of efficiency and utility global measures

In the first steps of this dissertation, the study addressed the contribution by Coronado J.M., Garmendia, M., Moyano, A. and Ureña, J.M. (2013) 'Assessing Spanish HSR network utility for same-day tourism', *RTS - Recherche, Transport et Securité*, 29(3), 161-175 (Suppl. 4.4), a work that includes these aspects of cities' attractiveness for determining the real utility of HSR same-day trips for each city. Nevertheless, in this previous work, it was detected that the definition of cities' relevance for attracting travellers requires a more deep assessment of the cities' profiles. For instance, in this study, a number of BICs (Bienes de Interés Cultural) were used to define tourism attractiveness. However, this data presents two main concerns: first, the relevance of what was defined as BIC and second, these cultural facilities do not include other key leisure/tourism amenities such as sports events, natural resources, shopping, etc. For these reasons, a more detailed analysis is required about this last step in the efficiency and utility assessment.

3. This dissertation includes some aspects about local accessibility and its influence on the efficiency of same-day trips. Precisely, in this local scale of analysis, there are interesting opportunities for further research:
    3.1. First, the definition of the catchment area can be addressed from the perspective of the time available at a destination. In the paper by Martínez H.S, Moyano, A., Coronado J.M. and Garmendia M. (2016) 'Catchment areas of high-speed rail stations: a model based on spatial analysis using ridership surveys' *European Journal of Transport and Infrastructure Research*, 16(2), 364-384 (Supp.5.3), the areas of influence of HSR stations are analysed from a spatial perspective. For future research, it could be interesting to compare this assessment with an efficiency analysis that includes other transport networks (road and conventional railway) considered as feeders for the HSR station analysed. In this sense, **not only cities with HSR stations but also other towns in their surrounding areas should be included, trying to identify their possibilities of connections for different travel purposes**. Aspects such as services' coordination and intermodality would be of great importance.
    3.2. Second, the development of the Spanish HSR infrastructure also conditions the analysis of accessing HSR stations. The opening of the tunnel between Atocha and Chamartín stations in Madrid could be an interesting case for further research. The analysis addressed in Chapter 5 about access and egress times to HSR stations could be reoriented to a two HSR stations' scenario. In this new scenario of different HSR stations, access and egress times could be evaluated spatially and temporally for both public transport and taxi services. Having two HSR stations in Madrid will reduce access times, slightly increase in-vehicle travel time (as an average) and presumably reduce door-to-door total travel time. Precisely, a similar approach was developed by Givoni & Rietveld (2014), analysing the impacts on access/egress times in the scenario of having different railway stations in the same city.
    3.3. Third, the study of pedestrians' mobility to/from high-speed rail stations is an

interesting topic for further research. Pedestrian paths to/from stations, especially in small and medium-sized HSR cities, are a key factor for both tourists arriving to the city and residents commuting (or just travelling) by HSR. Following the basis established in the contribution by Moyano A., Coronado J.M., Ruiz R. and Romero V. 'Station Avenue: high-speed rail's missing link. Assessing pedestrian city-station routes for edge stations in Spanish small cities', *Journal of Housing and the Built Environment*, Accepted with major revision (Supp. 5.2), and including new procedure for collecting information about travellers, such as GPS tracking, it could be interesting to identify which are the preferable pedestrian routes to city centres for visitors/travellers arriving at HSR stations. This analysis could help promote an adequate, readable and comfortable itinerary, which would enhance the experience for visitors and promote a sustainable transport mode.

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