The connection of Madrid – Barajas airport to the high-speed rail network
THE CONNECTION OF MADRID-BARAJAS AIRPORT TO THE HIGH-SPEED RAIL NETWORK

Minor thesis

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Abstract

The practices of the air-rail intermodality in Europe, specifically for high-speed railway, started in 1994 with the connection of Paris-CDG airport. In the following years it developed a remarkable expansion around other different European hub airports. The implementation in Spanish airports, though, has not been initiated due to unproductive political discussion of its suitability. This paper analyses the reasons behind the execution of a rail-air intermodal connection in the airport hub, Madrid-Barajas (MAD), and the factors contributing to stimulate this transit link, including significant similarities to other paradigmatic cases, like in CDG or FRA airports. Providing extensive representation of different examples of intermodality in Europe, identifying the essential characteristics of MAD airport, and detailing the high-speed network in Spain (and Madrid) will support to distinguish the motives of this air-rail link proposal. The characterisation also includes a description of its specific determinants to technically and functionally accomplish an intermodal node, such as the location, the current air-rail interaction or the possibilities of complementarity/connectivity between the air transport and the rail network.

After detailing the interest of the airport connection, the process continues defining how to specify the connection to the actual terminals. The determination and analysis of different corridor alternatives according to the location of MAD airport in relation to the surrounding high-speed lines is one of the key aspects reflected in this paper. The main goal to pursue during this analysis is developing a study of the feasibility of a new rail infrastructure connecting to the existing intermodal station of terminal T4. The technical viability and the functional enhancement of the connectivity are, both, the most significant attributes to apply in the planning methodology. The definition of the corridors to link up the high-speed lines with the air terminal facilities is also associated with the general infrastructure characteristics, like the line length or the reference speeds, highly influenced by the urban constraints. The economic point of view complemented with an estimation of the intermodal traffic, provides an assessment of the viability of each alternative in relation to the potential demand using the airport high-speed station.

The study is completed with some recommendations towards a beneficial intermodality integration and supply, comprising the creation of an intermodal product, similar to TGVAir or AiRail, and the factors to be contemplated by transport operators and other policy managers. The physical specification of an efficient intermodal interface in terminal T4, plus several measures for the enhancement of the intermodality conclude the feasibility study of the connection of MAD airport to the high-speed network.

KEYWORDS: intermodality, Madrid-Barajas airport, high-speed rail, airport connection, feasibility, integration, connectivity, transport complementarity
**Resumen ejecutivo**

Los precedentes de la intermodalidad entre el transporte aéreo y la alta velocidad ferroviaria se iniciaron en 1994 con la conexión aeroportuaria en Paris-CDG. En años posteriores se ha desarrollado una clara apuesta en diferentes aeropuertos ‘hub’ europeos. En cambio, la implementación en España no ha sido posible para ninguno de los aeropuertos del país, después de infructuosas discusiones políticas sobre su idoneidad. Esta tesis analiza las razones para ejecutar la conexión ‘hub’ aéreo de Madrid-Barajas a la alta velocidad ferroviaria y aquellos factores que contribuirían a materializar esta conexión, en condiciones similares a otros paradigmas, como las de aeropuertos CDG o FRA. La introducción de una extensa representación de los diferentes ejemplos en Europa, la caracterización del aeropuerto de Madrid y de la alta velocidad en España (y en Madrid) contribuirá a discernir los motivos del proyecto de una conexión aéreo-ferroviaria. A su vez, se incluirá una descripción de sus condicionantes, tanto técnicos como funcionales, para construir un nodo intermodal, como la localización, la interacción actual entre los modos o las posibilidades de complementariedad/ conectividad entre el transporte aéreo y la red ferroviaria.

Una vez detallado el razonamiento de la utilidad de la conexión, el desarrollo continúa con la concreción de la conexión a las terminales. La identificación y el análisis de las diferentes alternativas de corredores, en relación a la localización del aeropuerto de Madrid respecto a las líneas de alta velocidad, es uno de los mayores aspectos reflejados en este estudio. La principal pretensión en la presente memoria es desarrollar el estudio de viabilidad de la conexión de la infraestructura ferroviaria a la existente terminal intermodal en la terminal T4 en MAD. Ambas la viabilidad técnica y la mejora funcional de la conectividad son los atributos más significativos a considerar durante esta planificación. La definición de los corredores de unión de las líneas de ferrocarril a las instalaciones aeroportuarias va del mismo modo asociada a la caracterización general de la infraestructura, con atributos como la longitud de línea o las velocidades de referencia, altamente afectadas por las restricciones en el ámbito urbano. El punto de vista económico complementado con una estimación del tráfico intermodal ofrece una evaluación de la viabilidad en la construcción de las variantes en relación con la demanda potencial de usuarios de la estación ferroviaria en el aeropuerto.

El estudio se complementa con una serie de recomendaciones en dirección hacia una integración de modos y un servicio intermodal adecuados, contemplando la creación de un producto intermodal, como TGVAir o AiRail, y otros factores a considerar por los operadores del transporte y otros gestores. La definición física de una interfaz intermodal eficaz en la terminal T4 en conjunto a una serie de medidas para el estímulo intermodal completa la posibilidad de la conexión de la red de alta velocidad con MAD.

**PALABRAS CLAVE:** intermodalidad, aeropuerto Madrid-Barajas, alta velocidad ferroviaria, conexión aeroportuaria, viabilidad, integración, conectividad, complementariedad del transporte
Acknowledgments

This minor thesis is the result of the research and determination of a particular point of view of the passengers’ intermodality between the railway and the air transport. My high level of interest in the transportation field, especially in railway systems, has been decisive for accomplishing such a study. The result has carried out a development for 6 months between late 2013 and early 2014.

The final thesis has been especially possible thanks to the guidelines and experience of my tutor Dr. Andrés López Pita, professor of railways at ETSCCPB, who came up with the core idea of the study.

I would also like to show my gratitude to all the people who has supported and encouraged me in the meantime, particularly my family and friends.

Rafael Amador

June, 2014
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</tr>
<tr>
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<td>STR</td>
</tr>
<tr>
<td>Toulouse/Blagnac airport</td>
<td>TLS</td>
</tr>
<tr>
<td>Torino airport</td>
<td>TRN</td>
</tr>
<tr>
<td>Venezia/Tessera airport</td>
<td>VCE</td>
</tr>
<tr>
<td>Vienna/Schwechat airport</td>
<td>VIE</td>
</tr>
<tr>
<td>Zurich airport</td>
<td>ZRH</td>
</tr>
</tbody>
</table>
Introduction

The purpose of the present paper is the analysis of the opportunities of new intermodality synergies between the high-speed train and the air transport in Madrid-Barajas (MAD) airport, in Spain. The method followed is basically the research of the international experience in Europe about the subject for the subsequent application of successful patterns to the airport in Madrid. The development of the topic also includes some operative aspects of both the high-speed and air transport systems in Spain. The particular description of the two modes of transport enables the extraction of the possibilities of intermodality between both of them. Specifically, the evaluation of the potential of MAD as a hub node and the location of the terminals in relation to the current and projected high-speed corridors in Madrid allows illustrating the physical and functional feasibility of performance of the connection. The objective of the connection is to enhance the substantial development of the potential of the rail-air intermodality demand in Madrid in order to improve and benefit the efficiency and efficacy of the transport system. The paper includes the determination of the most efficient possible solutions, their respective railway infrastructures and the final discussion of the different alternatives concerning planning, functional and sustainable approaches (environmental, social and economic).

The thesis is structured in 10 basic chapters describing and examining general aspects of the transportation field. This form is submitted in order to elucidate a general vision of the situation and to prove the feasibility and interest of the airport connection in Madrid.

The first section starts with the description of the general framework and the definition of theoretical concepts that are involved in the development paper, such as high-speed system, intermodality or interconnectivity between high-speed and the air transport.

The following section examines the list of different airport links to the high-speed rail (HSR) network in Europe. The state-of-the-art study encloses the most significant current and future connections, studying their differences and identifying either reasons of success, like in Charles de Gaulle or Frankfurt airports, or inefficacy, like in Lyon airport. The examples are illustrated not only by the technical elements of the connection, but including other general details affecting the current situation and describing the reasons of their layout.

The third chapter continues with the evolution of the high-speed network in Spain and its fast extension in the last few years. The future of the railway system denotes a fully coverage of the high-speed network in the Spanish territory. This part includes a glance of initial proposals to connect the high-speed network to some Spanish airports, in cases where the rail layouts are considerably close to the terminals.

Chapter four enlarges the vision of the previous part focusing on Madrid as the capital of the high-speed in Spain and also describing all the prospects of current and future connectivity with other cities in the country as part of the extensive development of the network. The general perspective is also represented by the description of the high-speed corridors with
origin in Madrid. The configuration of the high-speed system within Madrid urban area and the future projects complete the view.

After detailing the high-speed system, the next phase, enclosed in chapter five, consists of a description of MAD airport and its status within Europe. The characterisation of the influence of the airport hub and the most representative peculiarities, concerning the air supply, the traffic demand and the air-rail modal split, are incorporated in order to guide the assessment of the intermodality.

The identification and description of the rail connections to the airport is the aim of chapter six. The existing metro and suburban rail infrastructures are attended with other future plans of connection of the airport with the high-speed network.

Once the categorization of both transport modes is discussed, the succeeding part starts specifying the reasons behind the interest of performing a high-speed connection in MAD airport terminals. The point of view is centralized in aspects relating to the infrastructure in project, the supply and demand justification of the intermodality at the airport, the actual physical space of interchange and other social and environmental aspects.

The feasibility of the connection is the aim of chapter seven regarding all the elements integrating the elaboration of the study of rail corridors and successive variants. This phase introduces different alternatives of corridor, the accomplishment of a comparative analysis, the selection of diverse variants and a preliminary inform of the possible environmental impact. The introductory study of alternatives encloses technical, geographical, geological and functional specifications in order to identify the contrasts and extracting the positive values towards a final selection.

A point of view of the air-rail intermodality is provided in chapter eight gathering all facts in the direction of achievement of a successful connection between the high-speed train and the aircraft. The factors operating in the co-modality are brought up relating to the interaction of the actors and stakeholders, the provision of an efficient service and the easiness of the actual intermodal facility. The generation of amendments and agreements is specified towards the interchange benefits for potential users.

Finally, the last descriptive part exposes a descriptive and basic economical analysis in terms of the investment required for the construction of the infrastructure. An estimation of the demand for the co-modal service is determined with regard to verify a general viability study of the strategy in comparison to other high-speed projects.
1. - High-speed and intermodality

Previous to the development of the scope of this paper, it will be relevant to define a few key concepts which are essential in the understanding of the presented purpose. The general insight of what high-speed means in the railway discipline will be the first notion to be described. After this characterisation, the concept of intermodality / co-modality will represent the centre of the thesis and will direct the discussion of the subject involving all its particularities. The preliminary section will also include a brief mention about the competition versus cooperation of two means of transportation and its respective consequences in the intermodal field.

1.1. - The meaning of high-speed

High-speed is not only a technical subject but a complex idea, and it contains a variety of meanings according to the criteria used. The International Union of Railways (UIC) establishes a plural definition of the concept in order to comprise all the characteristics of the term. Therefore, to reflect the wide range of conceptions included in the definition, high-speed will be explained as a conjunction of elements that configure the high-speed system. UIC formulates the system as a combination of the infrastructure, rolling stock and operating conditions. Apart from the combination of those 3 elements, high-speed also includes the crossector issues such as financial, commercial, managerial and training aspects.

New high-speed lines would include those with maximum speeds above 250 km/h and upgraded lines for speeds up to 220 km/h. This statement has to be understood not as a limitation, but as a distinctness of the high-speed mode. For instance, in certain parts like very dense populated areas or in tunnel sections, the speed can be limited up to 110 km/h for noise nuisance or other safety reasons. To avoid the contradiction, it is also said to be high-speed traffic the movement of this kind of trains in conventional lines but at lower speeds than those permitted on the new high-speed infrastructure due to local constraints.

After analysing the fundamental basis of high-speed systems, high-speed rail definition considers another main principle. It is important to understand that high-speed systems are different everywhere. It all depends on how all the combination of the elements are considered and adapted. Depending on the circumstances of each country or region the performance of high-speed will be understand under different conceptions regarding the commercial approach, the operation criteria or the cost.

The European Union Directive 96/48/EC Appendix 1 classifies the infrastructure, rolling stock and the compatibility of both, in order to define the high-speed concept. It basically classifies the infrastructure specially designed for high-speed travel (for speeds above or equal to 250 km/h) and the infrastructure specially upgraded for high-speed services (for speeds of the order of 200 km/h). It also includes that infrastructure with special features with topographical, relief or town-planning constraints, with an adapted speed to each case. The
high-speed advanced-technology trains have to be designed in such a way as to guarantee safe, reliable and uninterrupted travel for the infrastructure typology just mentioned. The high-speed rolling stock design will adapt to speeds of each kind of infrastructure and for the specially constructed one will enable top speeds of over 300 km/h in appropriate circumstances. The service will be the response of the compatibility of infrastructure and rolling stock and it will define the performance levels, safety, quality of service and cost upon that compatibility.

1.2. - From intermodality to co-modality

The intermodality is the main concept that interacts in the connection of two modes of transport, in this case the air and the rail modes. The traditional unimodal point of view of the transport strategies is today one of the main drawbacks in intermodal trips. The present paper focuses exclusively in the passenger point of view of the air-rail intermodality. The freight perspective has been more studied than the intermodality of the passengers, but lately there is an increasing rise in the long-distance mobility of people. The current study will specially encourage the passengers’ intermodality in an international scenario often still complex due to technical, operative and political contrasts in the different countries.

According to European Commission (1997), **intermodality** is the characteristic of a transport system that allows at least two different modes to be used in an integrated manner in a door-to-door transport chain. However, the intermodality encompasses a great number of factors of different kind that influence the success of the integration of both modes. Particularly, it contains two key concepts like the modes and the corresponding connection of the modes. From a passenger point of view, the European Commission (2006) defines the term as a policy and planning principle that aims to provide a passenger using different modes of transport in a combined trip chain with a seamless journey.

A more complex definition of **intermodality** is the coordinated/organised usage of more than one transport mode for a journey. This means that there is a scheduling/ticketing/commercial agreement between the interested transport operators. For freight it is the segment of multimodal transport that applies to unitized (e.g. container) freight (European Commission, 2013). An important factor that helps to succeed in the intermodality is that passengers experience the entire journey as a seamless one. To perform this concept, the combination of the modes and the resultant transfer has to be efficient with a minimum time and within an optimal physical connection at the station/terminal, the intermodal facility.

A global understanding of the high-speed rail-air intermodality will contribute to potentiate the efficiency and safety of a transport network. Hence, it enhances the sustainability of the mobility of people and, in general, the compensation of social and environmental impacts. This concept was gathered under the name of **co-modality** by the European Commission in 2006. The co-modality is the efficient use of different modes on their own and in combination. The policy principles include the optimisation of each mode, the integration of the modes (intermodality) and the modal shift for different scenarios. In this paper, intermodality and co-
modality will be used as the same term including all aspects immersed in the transport performance.

1.3. - The role of the interconnectivity

The connection of two modes shall be created in an integrated manner in order to succeed in the co-modality process. The integration is not only a question of the technical dimension; it also includes an organisational and strategic perspective. The interconnection consists in connecting two heterogenic modes of transport in technical, institutional and organisational aspects. The interconnectivity is based then on the appropriate connection of the networks, the landside access for all modes with good frequencies, as well as the integrated scheduling and ticketing and the information provision. The greater the integration of modes, the larger will be the capacity of the entire transport network. To discern all the insights of the concept it will be essential to consider the door-to-door trip, from the origin of the journey until the destination and including all access and transfer times. All these points and their correct interrelation and integration will lead the intermodality to become effective.

1.4. - The scenarios in the air-rail interaction

There are three different types of relationship between two means of transportation: a competition on the same route, the complementarity and the cooperation between the two modes. The strategy chosen by the one or more operators managing each mode of transport will clearly define the way of interaction of the air transport and the HSR. However, each scenario involves a complex multi-stakeholder and competitive environment. The most favourable option to promote the intermodality will be the cooperation role leading to a code-sharing agreement between all the implicated actors.

The competition is produced when two modes can be mutually replaceable, thus satisfying the same transport need (Chi, 2004). Originally the competition between the rail company and the airline was the automatic scenario in the supply of common routes and it determines the market share. Recently, the increasing demand of the HSR has produced a negative impact in the short-haul air traffic being a competitive mode of transport over distances that may be covered in no more than three hours. The central location of the train stations compared to the airport location in the periphery gave a further accessibility for the rail mode. The time consumption and costly transfer from an out-of-town airport to the final inner-city destination of the journey is not needed. The fuel consumption per route km in short distances is more expensive than in long haul flights due to the take-off operation. In addition, the landing fees, the long access time to the airports, airport congestion, check-in time and security controls turn to be weaknesses for the air mode. Regarding all the mentioned aspects, HSR is a perfect alternative to cover 600 km distances offering a higher service quality (Figure 1.1). There is a high elasticity of the demand for both means of transport, when it comes to similar characteristics offered by the train and the air. In these cases, the price is normally one of the most decisive factors to determine the choice of the mode.
Two modes of transport will be regarded as complementary for the user when their successive utilization is either necessary or simply preferred to the utilization of a single transport mode for a journey between two cities (COST 318, 1998). It normally involves different operators. The complementarity scenario will guide to an elimination of some of the congestion constraints plus many other benefits reducing costs and optimizing the productivity of the entire transport network of the country. Whereas, a point of view based on the competition can be detrimental for both modes affecting the general efficiency of the transport performance.

A cooperative scenario seeks the creation of numerous synergy effects. This situation is not naturally arisen from the market forces as the companies tend to competition to gain more users. The cooperation of air and HSR is based on the promotion of the intermodality and the complete integration of the modes of transport offered as a single product. The complexity of the cooperation role will be beneficial for the satisfaction of customers; for the air and rail agents, promoting a cost-effective use of the means of transportation; and for the society, with improvements in environmental impacts and congestion issues. The cooperation will be especially productive for routes where the modal split is in favour of the train selecting the air mode for routes above that distance limit (600 or 800 km depending on the literature) and opting for the HSR for shorter routes.
2. - High-speed rail-air connections in Europe

2.1. - The interaction between airports and the high-speed rail in Europe

The high-speed rail (HSR) system was implemented in Europe in the 1980s with a fast development of its network during the following decades. After the rapid growth, the network in Europe is expected to exceed the length of 18,000 km in 2025. In light of this considerable expansion, the total demand of high-speed trains has been also increasing significantly in the past years. These HSR lines mainly cover the transport of passengers for the middle and long distance (up to 600-800 km). Hence, it is generally serving a domestic market either between small regions or countries where the rail system interoperability allows to do so. For those passengers completing longer journeys, using the air transport, they can find an additional feeder service in the high-speed train to reach their final destinations in regions with no interconnected or hub airports. As a result of the transfer of passengers, it will be relevant the study of the connectivity and intermodality between both means of transportation. To ensure the transport continuity, the integration of both services has to be adequate to promote a satisfactory transfer of passengers from one mean to the other. Furthermore, the elimination of short-haul domestic air services from the airports in support of the railway mode will contribute to liberate some air slots and therefore the airport hub influence and capacity. In this situation, the future tendency of distribution of transportation modes between the rail and the air transport will lead to a reduction of air congestion and the improvement of energy consumption. Thereby, the transport system in Europe will be forwarded in the direction of sustainable patterns, environmental and economically more efficient.

The rail access to airports in Europe started back in the 1950s with stations in terminals at the airports of Brussels-BRU and London-LGW and afterwards extended to other major airports, such as Paris-ORY, FRA, BCN, DUS, Paris-CDG, London-LHR or AMS. Nevertheless, the main utility of these train links was to cover short distance journeys to the respective city. Only at some of these airports, like ZRH, AMS and FRA, the long distance network was integrated into its railway services.

The idea of interconnection between the air transport and high-speed trains at airports was originated in France in the second half of the 1980s. The first connection was projected in order to link up the TGV South East, TGV Atlantic and TGV North high-speed lines to CDG airport in Paris. The establishment of HSR services to the airport took place in November, 1994. A few months earlier, another high-speed train connection had been also opened at LYS airport. The same year, another HSR link started operating at FRA airport. Subsequently, CGN and AMS airports also initiated operating high-speed trains to the terminals.

It is significant pointing out that the coexistence of high density traffic airports and important HSR stations at the main European capitals is slowly becoming complementary under similar journey scenarios. This situation is often caused by important urban agglomerations with high demography and a beneficial and dynamic economic activity. For this
reason, the simultaneity is produced at extended metropolises and it is important to promote a well-planned and powerful transport intermodality and integration within the region. This chapter comprises a presentation of the main European airports with a HSR network connection in service or under planning (Figure 2.1). The information provided will include technical and operational details of each connection and its particular circumstances.

The information about the air passenger traffic flow per airport in Europe is detailed in Table 2.1. It is also indicated whether the city is served by HSR services or not and the fact of including a direct access to the high-speed network at the airport (if favourable it contains the first year of commercial operations or the statement

Table 2.1 High traffic European airports and the respective high-speed airport connections (Current-planned situation). Source: Compiled by author from EUROSTAT Statistics, LÓPEZ PITA (2003) and other sources.

<table>
<thead>
<tr>
<th>AIRPORT</th>
<th>Air traffic (2012) [pax]</th>
<th>High-speed rail service</th>
<th>High-speed rail connection at the airport</th>
</tr>
</thead>
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<td>61,620,823</td>
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Figure 2.1 High-speed network in Europe and the current airport connections to the HSR.
Source: Adaptation from Réseau Ferré de France
2.2. - France

The first high-speed line in France was opened in 1981, serving the route between Paris and Lyon (TGV South – East route). The reason behind the construction of the new line was the excessively congested traffic operating the old infrastructure between both cities. This route determines the beginning of the new HSR network in Europe integrating a high-performance rail infrastructure with a HSR service.

The development of the French rail network was accelerated between the 1990s and the 2000s. In 2009, the total network length corresponded to 1,872 km and it is currently divided in 4 main corridors connecting the capital (Figure 2.2). The demand of HSR users after the network expansion has been growing at the same high speed, progressing from 15 million passengers in 1985 to 100 million in 2007. In contrast, the domestic air traffic within the French territory has become constant in the last few years matching a total of 20 million passengers per year.

![Figure 2.2 High-speed network in France and the current high-speed rail-air connections.](image)

Source: Adaptation from Réseau Ferré de France

The HSR network in France was the first one in Europe integrating and promoting the complementarity between two alternative means of transport, the rail and the air transport. For the first time ever, the sense of competiveness between rail and air services would take a new direction towards complementarity when the French government decided to implement direct access to the HSR network at CDG airport, the main airport in France, and LYS airport.
2.2.1. - Paris-Charles de Gaulle airport (CDG)

2.2.1.1. - From the first project to the TGV Interconnection East line

The original idea of CDG airport rail connection was to link up different high-speed corridors of the HSR network in France. It became a definite planning program when the project of the line between Paris and Lille (TGV North) was announced in 1967, but the delay in the project lasted until the 1980s. The final decision to construct this new line and the interconnection junction that would join the TGV Atlantic and TGV South-East lines was not made until late 1987. The time difference between the first announcement, in 1967, and the final conclusion was caused by the extensive planning discussion of the inclusion direct HSR access to CDG airport, located 20 km north-east from the centre of Paris and very close to the planned rail infrastructure.

The ‘Rudeau Report’ in 1987 considered many different route alternatives for the TGV North high-speed line. However, three of them are especially important to mention, as shown in Figure 2.3.

- The goal of alternative A (and A’) was to provide direct service to the city of Amiens, with a reasonable population of 154,000 inhabitants.
- Alternative B was based on a rail infrastructure parallel to the existing A1 motorway, thus helping to minimize the environmental impact and establishing a more direct route.
- Alternative C, via St Quentin, would share some of the alternative B route and it would also have a common section with the future TGV East line.

The final decision was announced to be solution B as the most suitable option. In the chosen alternative, a direct access to CDG airport was already included in the project.

Once the TGV North line outline was decided, a reconsidered HSR line project came up as the TGV Interconnection East line. It was based on the connection of all the high speed routes surrounding Paris, but in this case avoiding the entrance in the city. In any case, the new line would pass through CDG airport. As a result of this new reassessment, the configuration of the
The connection of Madrid-Barajas airport to the high-speed rail network

rail station at the airport terminals was firmly determined. The HSR line would cross the Terminal 2 from north to south (in pink on Figure 2.4). On one hand, traversing the airport would imply a higher length between the TGV North and TGV South East lines. On the other hand, the rail alignment curve radiuses were reduced to 2,200 m in some sections, instead of the conventional HSR lines radiuses of 4,000 or 6,000 m, and thus reducing the infrastructure cost. However, the final rail infrastructure allows maximum speeds of 230 km/h.

![Figure 2.4 CDG airport rail transport diagrams at the terminals (RER, CDGVAL and TGV). Source: Aéroports de Paris](image)

An additional point in question, given this new scenario, was whether connecting the airport station with trains using the TGV Interconnection East route, which would support the improvement of the connectivity throughout the country, or trains directly linking the capital, which would mean a fastest way for the transfer of passengers. The final solution was connecting the airport exclusively with trains coming from other domestic HSR lines and linking this one up to the capital through the alternative route B, which has been explained previously. The direct connection with the centre of Paris was already supplied by the suburban express rail line RER B3 in 50 min. In the future, though, it is planned the construction of a new connection to Paris via high-speed line, the Airport Express (Figure 2.5).

![Figure 2.5 Current and projected HSR network in Greater Paris (Île-de-France). Source: Adaptation from Agir pour Orgeval, http://www.agir-pour-orgeval.fr/](image)
2.2.1.2. - The situation today

The HSR connection to CDG airport, opened in 1994, was the first example in Europe of successful complementarity and interconnection between a HSR infrastructure and the air transport. The airport terminals held more than 61 million in 2012, and it is the second main airport in Europe in terms of traffic. The keys of success lie on some particular aspects:

- The connection of the airport supposed an improvement in the competitiveness of CDG airport in the European market. This is caused, mainly, because of the substitution of non-profitable domestic routes with the reinforcement of long-haul destinations.
- Simultaneously, as well as facilitating a perfect journey continuity in the TGV station facility for the users, including a bimodal integration of services between SNCF and various airlines, TGV Air intermodality product enhances the connection under one single boarding ticket and also allowing the baggage check-in at the origin point.
- The construction of the station meant a great development of the surrounding area creating a multi-service node, due to the high degree of development of the transport network.

In 2011 a total number of 58 destinations of the HSR network were served by 29 round trip trains a day (TGV, Thalys, Eurostar) with stop at TGV-Charles de Gaulle station connecting to nearly 20 French provinces (Figure 2.7). The TGV station was used by nearly 4 million passengers in 2011, 80% of whom used the air-rail connection. This percentage corresponded to a 4.5% of the total traffic flow of CDG airport compared to the initial value 2.1% in 1999, as it is observed in the progression of passengers using the TGV facilities in Figure 2.6.

![Figure 2.6 Evolution of rail-air intermodal users in CDG airport. Source: Ministère de l'Ecologie, du Développement durable et de l'Energie](image)

![Figure 2.7 Main domestic high-speed destinations from CDG airport. Source: Air Austral, http://www.air-austral.com/a-propos-dair-austral/nos-partenaires/TGVair-train-et-avion.html](image)
The connection of Madrid-Barajas airport to the high-speed rail network

2.2.2. – Lyon - Saint Exupéry airport (LYS)

The first European high-speed connection to an airport took place in June 1994 as a result of the opening of an adjacent TGV station connecting LYS airport, 20 km in the east of the city centre. The connection was produced by the new extension of TGV line from Lyon to Valence. The rail infrastructure for this new extension traverses the suburban areas nearby LYS airport terminals as shown in Figure 2.8. The final project included the construction of a HSR station providing direct access to the airport (Figure 2.9).

Lyon Saint-Exupéry TGV station includes two underground platform tracks and two extra tracks for express rail services not stopping at the airport and allowing top speeds of 300 km/h. In 2011, an average volume of 10.5 trains per day were serving LYS airport, a low frequency compared to CDG airport station. The number of people transferring between both modes of transport was 73,000 in 2011, which involved less than the 1% of the total traffic of the airport (Figure 2.10) and 14% of the passengers using the rail station at the airport. This value is a very much reduced percentage compared to CDG airport with more intercontinental traffic. The service also offers the TGV Air intermodality product arranged by some airlines.

LYS airport is located near many large French urban agglomerations and its influence area serves a total population of more than 4 million people. Thereby, the potential extension of the area surrounding the airport terminals gives the rail connection a considerable capability of increasing the future operability and influence in Europe. However, some improvements should be applied, like the increment of the current frequency and regularity of HSR services, the local connectivity or the development of the airport hub capacity for other intercontinental markets. All these aspects would contribute for enhancing higher intermodal passengers’ attraction from the airport to the rest of the TGV network and vice versa.
2.2.3. - Other airports in France

Marseille inaugurated a HSR connection to Paris in 2001, caused by the extension of TGV South-East route from Lyon merging with TGV Mediterranean line. The project excluded a direct access to MRS airport, even though the high-speed line was only 7 km away from the terminals. The adopted solution included a rail station in the vicinity, the so-called TGV Aix-en-Provence station, enhancing the connection with the terminals. The station is located half way from the airport and the actual town and the placement of the TGV station was planned according to the minimum perpendicular distance to the airport (Figure 2.11). A shuttle bus runs from the station to MRS airport, providing direct connection between both modes.

![Figure 2.11 Aix-en-Provence TGV station and respective distance to MRS airport. Source: Adaptation from France One Transfer, http://franceonetur.com/xfer/railway-station-TGV-transfers-france.htm](attachment:image.png)

Other airports like BOD and TLS do not incorporate a TGV station plan in their terminals as a result of the excessive relative distance to the rail infrastructure. In the future, it is expected the construction of a new HSR line between Bordeaux and Toulouse of which infrastructure will be closer to TLS terminals location allowing a direct access from the HSR network.

The French government is developing the project of the connection of the second busiest airport in France, ORY airport with the new TGV line connecting Massy and Valenton (Figure 2.12). The lack of an efficient connection between TGV South-East and TGV Atlantique lines would be a reason justifying the new South Interconnection project originated in 1990. The current rail capacity has become oversaturated with suburban rail services and also freight trains. The expectations of growth of the airport with respect to international traffic would be another justification of projecting a direct access from the HSR French network.

![Figure 2.12 Influence area of the project of the Interconnection South TGV line. Source: CNDP](attachment:image.png)
2.3. - Germany

The implementation of the HSR network in Germany was mostly developed as a result of the upgrade of the existing long-distance/intercity lines and their corresponding train stations. However, some other HSR lines were completely new, fully designed and constructed. The first high-speed lines to be functionally opened were Hannover-Würzburg and Mannheim-Stuttgart in 1991 and later in time, Frankfurt-Cologne and Karlsruhe-Bassel lines, as shown in Figure 2.13. All new lines enabled maximum speeds of 300 km/h for the high-speed trains.

![Figure 2.13 High-speed network in Germany DB AG in 2006-2007 (in black the conventional rail lines (max. 160 km/h). Source: ETR](image)

The new high-speed routes are basically connections between major urban areas with numerous intermediate stations and also including some relevant intermodal stations connecting the ICE (HSR in german) rail network with the air transport, like in the HSR Cologne Rhine/Main line with some airports like FRA, DUS or CGN. These new connections were planned in order to encourage the railway transport for short-middle distance (approximately up to 500 km), and in a way to constrain the environmental impact, reducing the road traffic and contributing to the expansion of capacity to operate intercontinental air services.

Some other main airports, like MUC or HAJ, remain exclusively connected to the regional and suburban rail networks. Currently, at these airports there is no intention to provide direct access to the HSR network due to the impossibility of connectivity for the excessive relative distance between both transport infrastructures.
2.3.1. - Frankfurt airport (FRA)

FRA airport is located in the southwest, 12 km from the centre of Frankfurt am Main. It is the third most transited airport in Europe, with more than 55 million passengers per year, 54% of whom are transit passengers using the airport as a connecting hub. At the moment, the airport holds a total of 275 destinations, between domestic and long-haul.

The HSR connection to the airport was originated by the construction of the new high-speed line between Frankfurt and Cologne in 1995. It complements the original direct rail connections to the city, one of the first implementations in Europe, which was established in an integrated railway station in Terminal 1. From 1971, the station was connected to the city with suburban services (S), and afterwards included Intercity long-distance services (DB). The new station, inaugurated in 1999, exclusively relocated all long distance services after its construction. However, the capacity was limited to hold a regular service of ICE trains, so the majority of transfers were located at the main station in the city (Hauptbahnhof) (Figure 2.14).

![Diagram of rail links around FRA airport](image)

Figure 2.14 Diagram of rail links around FRA airport. Source: Adaptation from Various Authors, 2011

The new adapted HSR station at FRA airport is located 200 m away from the original one and it was opened in 2002. The facilities include a check-in area (AiRail service) avoiding the walking time to the actual terminal check-in hall, which is 250 m from the rail station (Figure 2.15). This new service transformed the entire airport infrastructure into a new intermodal centre ready to facilitate a continuous interchange between the aircraft and the railway (Figure 2.16). AiRail also includes an intermodality product for the users allowing prior check-in at Cologne or Stuttgart central rail stations for the entire point-to-point journey. The service also includes integrated ticketing and schedule coordination. Currently regular ICE services travelling to Cologne, Siegburg or Stuttgart stop at FRA airport station, among other major destinations in Germany, Austria or Switzerland.
The connection of Madrid-Barajas airport to the high-speed rail network

The airport station would become part of the HSR line Cologne-Frankfurt. The final location of the HSR station within the airport complex was analysed amongst all different alternatives and determined in order to enable maximum speeds of between 160 and 200 km/h. To prove the important efficient operability of the station it is convenient to point out that the existing station had a great number of rail services, before the opening of the Cologne-Frankfurt line. The number of rail operations will increase as soon as it becomes part of the new Frankfurt-Mannheim HSR line linking both existing Cologne-Frankfurt and Mannheim-Stuttgart lines. This is due to the high population (37 million people) surrounding FRA airport hub node within a 200 km radius.

At this time, 174 high-speed long-distance trains stop at the station per day. The total traffic using the long-distance rail station reached 5.6 million passengers in 2012, a 20% of the modal access of users from any mean of transport arriving to the terminals.
2.3.2. - Düsseldorf airport (DUS)

Initially, DUS airport, 8 km apart from Düsseldorf centre, was exclusively served by regional services and it was a dead-end station. After 2002, the airport remains also connected to the HSR network in Germany incorporating a new station part of Düsseldorf-Duisburg line. The construction of the new rail station was planned 2 km far from the airport, adopted as an accidental link (Figure 2.17), although it incorporates a rail shuttle service, the Sky Train that enables a 5-minute connection to the terminals. The HSR infrastructure allows top speeds of 160-200 km/h. The airport is currently connected to different cities in the Rhine-Ruhr region in addition to others in the North Germany like Bremen, Berlin or Hamburg.

Figure 2.17 The Sky Train line map between the terminals and DUS airport rail station. Source: H-Bahn-Gesellschaft Dortmund mb, http://www.h-bahn.info/

2.3.3. - Cologne-Bonn airport (CGN)

Although CGN airport does not receive the same traffic as other major airports in Europe, the connection to the HSR network became of interest owing to the corresponding influence area related to one of the highest density of population in Central Europe. The creation of the high-speed line between Frankfurt and Cologne, opened to service in 2002, happened to be the perfect opportunity to arrange the future connections with the city of Cologne and its airport.

The new line, Köln-Rhein/Main line, was already serving FRA airport, one of the main airports in Europe and the highest in terms of flow of passengers in Germany. FRA airport is located just 200 km away from CGN airport. Despite this existing connection, the city of Cologne showed a great interest in developing a direct HSR access to the airport terminal. The interest of this connection was caused by the expected growth of the traffic flow of the airport and the possible shifting of capacities with DUS airport, holding a limited capacity of expansion.

As a result, the new high-speed line in the vicinity of CGN airport, with maximum speeds of 200 km/h, would finally result linked to the airport via a new branch line (Figure 2.18). The new project included two different alternatives routes sharing a common section with small curve alignments radius (between 475 and 800 m). The final outline was a branch double track line of 15 km, allowing average speeds of 130 km/h, including more than a third of its section in tunnel. The new section enables maximum speeds of 168 km/h once it diverts from the common section and the trains are able to approach the train station with maximum speeds of 98 km/h.
The connection of Madrid-Barajas airport to the high-speed rail network

Both the new loop line and the HSR station at the airport (Figure 2.19) were finally inaugurated in June 2004. The station architecture was constructed 18 meters underground and it is composed of a four-track underground platform. The airport would become the third one in Germany with a getaway to ICE trains. A crossover above the tracks allows passengers a direct access to the airport terminal.

Once this link was established, the Köln-Rhein/Main ICE line included three stations within a relative short distance: Cologne Central Station, Cologne-Deutz-Meusse terminal station and Cologne-Bonn airport (Figure 2.18). The trains with stop at the airport station operate services to Berlin, Amsterdam, Frankfurt, Brussels or Munich.

Figure 2.18 Cologne–Frankfurt HSR line in Cologne city and the loop line at CGN airport. Source: Adaptation from http://de.wikipedia.org/wiki/Schnellfahrstrecke_K%C3%B6ln%E2%80%93RheinMain & RTR

Figure 2.19 High-speed line at CGN airport. Source: UCL, New ICE Cologne–Rhine/Main line
2.3.4. Future plans: Berlin Brandenburg (BER) and Stuttgart (STR) airports

TXL airport in Berlin does not incorporate a direct access to the Berlin-Hannover HSR line, because the actual line starts a few kilometres away from Berlin metropolitan area. BER airport, which will substitute the current SXF airport, is expected to be integrated in the European HSR network (Figure 2.20) when the airport opens the doors in the near future, after a few disagreements about the opening date. The new terminals already contain an underground station for suburban and regional trains (S-Bahn) which is also fully adapted to incorporate a long-distance (ICE) support. The plan is to hold an ICE service every 2 hours for each direction, in the route relation Rostock -Berlin-Görlitz / Breslau (Wrocław) via BER airport. Direct long-distance connections will be held to Hamburg, Hannover, Krakow and AMS airport.

![Figure 2.20 Future rail diagram of Berlin urban area and the connection of BER airport. Source: http://www.stadtentwicklung.berlin.de/verkehr/politik_planung/epnp/download/plan_anbindung_flughafen.pdf](http://www.stadtentwicklung.berlin.de/verkehr/politik_planung/epnp/download/plan_anbindung_flughafen.pdf)

A major project, called Stuttgart 21, is planning to connect STR airport to the HSR network in Germany. The reason behind is the development of a major infrastructure and urban development plan which includes the project and construction of the new HSR route between Stuttgart and Ulm. The connection layout would be a loop line derived from the main HSR line, allowing top speeds of 250 km/h, including an approximately 3 km tunnelled section (Figure 2.21). The new HSR intermodal station would be composed of 2 rail tracks with a 400 m platform length. The new remodelling planning strategy would also include a complete renovation of the existing rail station for S-Bahn services and a 2 km underground loop interconnection of the conventional rail infrastructure with the new HSR line.

![Figure 2.21 Projected HSR link at STR airport. Source: DB ProjektBau GmbH, 2013](http://www.stadtentwicklung.berlin.de/verkehr/politik_planung/epnp/download/plan_anbindung_flughafen.pdf)
2.4. Belgium & the Netherlands

The first line to introduce HSR in the Benelux was the connection of the entry of Brussels to the French border, inaugurated in 1997. In 2002, the HSR route between Leuven and Liege was functionally opened to commercial services. Consequently, cities like Antwerp or the German and Dutch borders were connected to the rest of HSR network. Today the high-speed network consists of 3 major axes connecting the country’s borders to the capital, Brussels (Figure 2.22). It includes many different sections for diverse speed limitations depending on the route. Maximum speeds of 300 km/h, for instance, are accomplished on trains operating at the route between Liege and Leuven or at the newly constructed high-speed line connecting to France.

The Netherlands connected the first HSR line to the Belgium border, known as the HSL-ZUID, in 2009. The trains connect Brussels and Amsterdam, via AMS airport, Rotterdam or Breda (Figure 2.23). The Dutch line is a dedicated double track infrastructure and it enables maximum speeds of 300 km/h in most sections of the route. There are some other planned HSR extensions like the HSL-Oost, connecting two economically dynamic and dense urban areas, the Randstad region in the Netherlands and the Rhine-Ruhr area in Germany.
2.4.1. - Amsterdam-Schiphol airport (AMS)

AMS airport was not connected with HSR services until 2006, after a long process of planning and development starting in the 1960s. The airport is located 12 km on the south direction from the centre of Amsterdam and the terminal incorporated a conventional rail link in 1980. The new opening was due to the construction of the new rail line between Leiden and Amsterdam-RAI, this last one emplaced in the suburbs of the capital (Figure 2.25). This adverse location was due to technical and economic difficulties in the construction and the city centre had to be reached from Amsterdam-RAI by a tramway line. The original railway station was served by standard rail services and it became an underground station in 1981.

From 1986, the airport route remains connected to Amsterdam Central station, via the western branch diverting from Sloterdijk station. Since then, AMS airport was integrated to the long distance rail network. The high-speed services started operating at the airport in 2006 and the trains can reach speeds up to 160-200 km/h at the main section of the line (Figure 2.24).

Currently, the high-speed line crossing AMS airport connects Brussels and Amsterdam and other Dutch cities. It has become one of the main train stations in the Netherlands and it is connected to other European cities like Paris or London through Thalys, TGV or Eurostar trains. In addition, ICE International rail services allow you to travel to Germany, to cities like Cologne, Düsseldorf or Frankfurt, where HSR connections are already established. The percentage of transfer passengers reaches 40% of the total becoming one of the main hub nodes in Europe.

2.4.2. - Brussels – Zaventem airport (BRU)

The new high-speed line station at BRU airport was aiming to replace the old dead-end railway station served by local and regional services. The airport accessibility limitations caused by this
sort of stations was the main reason of adaption and integration into the European HSR network. The *Diabola Project* objective was constructing an adapted HSR infrastructure and thus, providing full accessibility and intermodal HSR interchange to the terminals (Figure 2.26). The new station, on the basement level -1, would provide not only connections with the capital, but also the improvement of direct connections with central Europe and more choices of travel within Belgium. The new adapted high-speed train terminal was inaugurated in 1998, but the HSR services were not operative until mid-2012. The new interchange station has three 425 m long platforms enabling the operation of international HSR services.

The new station, on the basement level -1, would provide not only connections with the capital, but also the improvement of direct connections with central Europe and more choices of travel within Belgium. The new adapted high-speed train terminal was inaugurated in 1998, but the HSR services were not operative until mid-2012. The new interchange station has three 425 m long platforms enabling the operation of international HSR services.

The new infrastructure planning program was reconverting the old line sections into new rail tracks adapted for enabling maximum speeds of 160-200 km/h and improving the existing stations in order to adapt them for the HSR services. The process also included the construction of new infrastructure sections ready for the operation of high-speed trains. The project includes a new underground rail link containing a double-track platform under the central reservation of the E19 motorway. The link connects it to the existing northern line directed to the Dutch border. At the same time, it allows the link Louvain and Liège via the Nossengem curve enclosing a 4-track infrastructure until Louvain.

The renovation of the existing lines and numerous stations represented a completely modernization and adjustment of the Belgium rail network into the HSR services. For this reason, the connections between the capital and the bordering countries contributed considerably in the reduction of the travel times and the readressing of the isolation of the airport. The result also contributed to fulfil its priorities of optimisation of the safety, improvement of train traffic punctuality and enhancement of the capacity of the rail network.

At the moment, there are *Thalys* services, departing from the airport and providing high-speed access to Brussels-Midi station, Paris, Liege, Cologne and Amsterdam.
2.5. - Italy

The frequent limitations of the network capacity and the out-dated infrastructure tracks favoured the upgrade of the existing conventional rail network. The first HSR line to open, due to preceding technical and operational problems, was the route between Rome and Florence. It was divided in three sections and fully opened in 1992, which provides potentiality for trains running up to 250 km/h. After its completion, the Italian network will establish a T-shape with a North-South axe connecting Milan, Florence, Bologna with Naples and Rome, and a West-East axe in the north, between the cities of Turin and Venice. The following openings were produced from 2006 until 2009 defining the present Italian HSR network (Figure 2.27).

![High-speed network in Italy](http://www.quotidianopiemontese.it/wp-content/uploads/2012/03/frecciarossa.png)

**Figure 2.27** High-speed network in Italy (in service, in construction and planned).


The connectivity of the HSR network to the Italian airports is non-existent at this moment. However, some projects have been developed for years with the intention of linking important airport hubs like MXP airport, which connection planning is detailed in the following section, or BLQ airport, which planning strategy takes advantage of the actual proximity of the existing Firenze-Bologna high-speed line.

LIN airport in Milan, in the same situation as BLQ airport regarding the HSR network position, is not projected to link up with the rail infrastructure because MXP airport has obtained a better potential within the Northern region of Milan. Other important main airports in Italy, like FCO in Rome, FLR in Firenze or TRN in Torino, are not expecting any connection to the rest of the HSR Italian network. The main drawback of the direct accesses to the airports corresponds to technical difficulties of connection to the existing rail infrastructure due to the opposed location and excessive distance to the air terminals. In Rome, railway lines, such as Firenze-Rome or Rome-Naples, are located on the other side of both city airports and it would not obtain any benefit from the creation of an air-train connection. At NAP airport, the air-rail link project includes a train station close enough to the airport, within the actual Rome-Naples line combining HSR and short distance services.
2.5.1. - Milan – Malpensa airport (MXP)

The initial military airport was renovated in 1998 due to the increasing capacity limitations in the other airport near the city, LIN airport, 7 km east from the city. MXP airport is centrally located in the northern region, 50 km off the city centre. The long distance in between the capital and the airport was the main reason of considering a convenient rail connection in order to improve the time of the journey. Also the spectacular growth in terms of passengers had the effect of potentially creating a major transport hub. The new conventional rail link was opened a few months after commercial operations started at the airport. The journey between Milan and the terminals is completed in 30 minutes reaching maximum speeds of 130 km/h.

The connection to the HSR network was discussed in 1999 in the Piano Territoriale d’Area Malpensa. The committee recommended linking the airport through the new rail line connecting Milan and Zurich (Figure 2.29). The new plan contemplates a rail underground line across the airport, connecting Terminal 1 and 2 for later continuing its way to the region of Ticino, in the North. The line would also contribute to facilitate the connections between Switzerland and the North of Italy, improving the prevailing speed limitations (up to 84 km/h) and thereby reducing the total time of the trip. The plan includes Sankt Gotthard base tunnel, the longest tunnel in Europe, under the Alps, which is expected to be opened in late 2016.

Starting in September 2010, Freciarrossa train operator offered 2 direct connections a day to MXP airport (terminal 1) from Firenze and Bologna, via Milano Central. The high-speed service was suspended in 2012 due to considerably low demands using the trains.

The possibility of constructing the airport connection through the new Torino-Milano line was declined in behalf of the long distance of the airport terminals in regards to the main rail line. The airport is approximately 15 km away from the high speed line in project. Nevertheless, it would have implied an improvement in the connections not only between Torino and Milano, but throughout all Mediterranean area and the rest of northern of Europe, including countries like Belgium, Holland or Germany.

![Figure 2.28 / Figure 2.29 Rail diagram around MXP airport / The North Italy rail access project to Switzerland. Source: Mantegazza, 2013 /Sallucci, 2011](image-url)
2.6. - Other European countries

The previous connections of the HSR network and the air transport correspond to some of the major airports in Europe. The analysed countries projected main airports to be inserted in the respective HSR network as the best option to interconnect both means of transport. On the other hand, some other countries transport system development plans are not including the option of incorporating a direct high-speed line supplying the airports, like the major hub airport LHR in London, or determining alternative solutions in order to establish a fast and convenient rail link at the airport terminals.

2.6.1. - United Kingdom

Both main airports in the United Kingdom (LHR and LGW) incorporate a conventional rail link to the terminals. In these two cases, the difficulty in implementing a rail branch from the existing high-speed line linking Paris and London (*Eurostar* services), under the Channel Tunnel, is the main reason for not selecting a direct high-speed access. The connection of the current HSR network via LHR and LGW airports is unlikely to happen due to the significant distance separating the respective infrastructures. However, both airports hold an approximately 30 minute direct connection to the capital which contributes to a successful integration of the terminals in the transport network of the region.

The British government is developing the new project of a HSR line between London and the West Midlands, known as High Speed Line 2 (HSL2). This new infrastructure plan includes two stations of enhanced connection to LHR and BHX airports (Figure 2.30). The access to LHR airport should be provided through a *Crossrail* Interchange station. The *Crossrail* line will enable an approximately 10 minute connection to the terminals from the HSL2 station. In this case, the decision was to avoid a direct connection and selecting another alternative facilitating the interconnection with the rest of Great Western and Greater London regions. At the same time, the Government has also borne in mind their potential to allow a direct connection to an at-airport station at LHR in future.

A station providing enhanced access to BHX airport for high-speed passengers would be another objective of the HSL2 project. The new Birmingham Interchange station will give access to the National Exhibition Centre and the Birmingham International station for conventional railway services. In order to develop this rail link, the station will connect the terminals in 5 minutes with a possible rapid transit link.

![Figure 2.30 New scheme of the HSR network in the UK and the connection to LHR and BHX airports. Source: Department for Transport, 2010](image-url)
2.6.2. - Switzerland

Switzerland is one of the countries in Europe without an actual HSR network due to the reduced size and the difficult topography of the regions. The only high-speed line is the one connecting Frutigen and Lötschberg base tunnel opened in 2007. In the future, the Alptransit HSR line will connect Zurich and the north of Italy underneath the Alps. However, the government is executing a new modernisation of the rail network through the plan ‘Rail 2000’ that will allow maximum speeds of 200 km/h at certain sections of the rail network.

Meanwhile ZRH airport, 9.6 km from the centre of the city, has been connected to the Swiss rail network since 1980 via a branch line (Figure 2.31). The airport also holds conventional long distance services enabling the accessibility to surrounding countries.

2.6.3. - Scandinavian countries

In Scandinavian countries, the HSR is not developed as such, most of the lines are limited to maximum speeds of 200 km/h, which is not classified as HSR services. The only operative HSR line is the route between Stockholm and Malmö/Göteborg allowing top speeds of 300 km/h. The rest of the rail network is gradually being upgraded to allow HSR circulations in the future. The rail-air connections at the Scandinavian airports are mostly an infrastructure providing a point to point service, not reflecting the natural sense of an integrated rail network.

CPH airport is currently connected to the 200 km/h rail network of Denmark and Sweden, permitting trips to Copenhagen and Stockholm. The link was originated with the decision of constructing the Öresund Bridge across the strait between both countries. The new HSR service is planned to be upgraded in the future to allow maximum speeds of 250 km/h.

In the city of Stockholm, ARN airport started operating the Arlanda Express rail services in 1999 with trains running at maximum speeds of 200 km/h. The service connects the centre of the city with the passenger terminals.

In 1998 OSL airport, the main airport in Norway, inaugurated the first dedicated “high-speed” link service in the country. The rail line was used as a link between the capital, Oslo, and its airport, 66 km off the Central Station in Oslo. The train reaches a top speed of 210 km/h. The service is now run by Flytoget- the Airport Express Train line, including departures every 10 minutes from each of the ends of the route.
2.7. - Summary of the situation in Europe

In light of the analysis of the different airport connections to the HSR network in Europe and the singularities, the main points to be evaluated, concerning the performance of the airport link, are whether the airport is connected or not to the existing HSR network and if so, what type of connection has been implemented, a main line or a loop line. Once determining the reason why the connection is operative, it is interesting to extract the factors that determine a successful mode of intermodality of both means of transportations and the actual physical integration of the rail station within the airport complex. The service integration aspects of the intermodality are also significant to reflect, as seen in CDG or FRA airports which can be considered as clear examples of the efficient implementation of an intermodality product.

The practical evaluation of each case in regards to projecting a HSR-air connection to the airport includes all the airports located in the same high-speed line quadrant. In all these cases it is considered the centre of the axes at the actual city whose airport is being analysed. The analysis, accomplished in López Pita, A. (2003), concludes that the HSR connection to the airport is operative or projected in those cases in where the location of the terminal is in the same quadrant as the HSR line, except for the case of MRS airport (Group A in Figure 2.32). The rest of examples, where the airport position is not in the same quadrant as the HSR line, were not effective in connecting both infrastructures, like in London or Rome airports (Group B).

![The relative position of high-speed lines with respect to the main airports in Europe](image)

*Figure 2.32 The relative position of high-speed lines with respect to the main airports in Europe.
Source: López Pita, 2007*
The choice for the scheme to perform the HSR-air connection is generally favouring a direct access through a main high-speed line crossing the airport or its immediate vicinity. Airports like Paris-CDG, FRA, AMS, BRU (Brussels-Cologne line) or LYS hold this frequently used airport link. The branch or loop line solution was decided to be the optimal in MXP, BRU (Brussels-Amsterdam line) or CGN airports. The difference between the first option and the second one is generally due to higher maximum speeds of trains in a main line compared to lower speeds allowed in a branch line. However, this option is characteristic to each airport circumstances and requires specific analysis in order to evaluate the optimal solution in regards to each situation. Other solutions, like a dead-end station at the airport through a spur line, are not applied for any airport link operative in this moment.

Analysing the total number of high-speed services of each connection, it can be observed that a major number of daily trains can operate through the airport adopting a main line solution. This is the case of CDG, FRA or AMS airports with high regularity of services per day, more than 50 in all cases, enhancing a more integrated intermodal scenario. With the exception of LYS airport, with not many daily connections, the rest of main line connections present an adequate number of connections per day. It can be highlighted that a high frequency of trains per day is normally associated to an important volume of passengers’ traffic at the corresponding airport, especially regarding the number of international destinations.

As observed, the impact of a HSR line connecting the airport supports the development of the airport as a major hub, the improvement of the connectivity and productivity of the transport network producing a considerable economic impact for the region. The transfer passengers find an incentive for using the HSR transportation mode, which is associated to trip of 500-800 km distance (from 1 to 3 hour travel time). In this case the supply of both modes, air and rail services, has to be understood from a complementation point of view instead of a competition scenario. In some successful experiences, the rail station has direct access to the air terminal where the airport main airline is based, for CDG airport, Air France on Terminal 2, for FRA airport, Lufthansa on Terminal 1, or for AMS airport, KLM on the same terminal as the rail access. The intermodality has to be also interpreted as a complete combination of all customer, operator, strategic and social points of views, so all the factors influencing the connection are arranged and assessed in order to create a functional interchange node.
3. - High-speed rail network in Spain

3.1. - The development and the future of the HSR network

Spain has been one of the countries in Europe to promptly develop and extend the national HSR network. The first UIC international (with standard gauge of 1,435 mm) route between Madrid-Seville opened in April 1992, operating a new high-tech train under the name of AVE (Alta Velocidad Española – Spanish High Speed). The most recent route of high-speed train in Spain was inaugurated in June 2013, connecting the city of Alicante to the rest of the HSR network, through Albacete. After this last inclusion, Spain contributes with more than 3,000 km to the European HSR network (Figure 3.1), which corresponds to 13% of the global network. It is the first country in terms ok kilometres of high-speed train in operation in Europe, and the second in the world, after the HSR network in China. The first position of average speeds in the network corresponds also to Spain, with an average speed of 222 km/h, advancing countries like Japan or France. These factors reflect the planning tendency of Spain in regards to create a dense HSR network, with one of the most technologically and strategic advanced rail systems in Europe.

![Figure 3.1](http://commons.wikimedia.org/wiki/File:Red_espa%C3%B1ola_alta_velocidad.png)

It is important to consider the great difference in time, over a decade, between the first and the second routes were opened. After 2003, and in the same period of time, the development of the total length of the HSR lines was 6 times higher in relation to the previous one. So the second decade of extension was far more constructive than the first one (Figure 3.2), leading Spain to be positioned in the most experienced and developed level amongst all the HSR systems in the world. The network is still expected to extend its length, planning and projecting new lines all over the Spanish geography. At this stage, over 1,500 km of HSR lines
The connection of Madrid-Barajas airport to the high-speed rail network

are being constructed in Spain and more than 3,500 km are in project or planning assessment. The main objective of this network is to economically and socially invigorate the country and its regions, as well to promote the equally connectivity among all the parts of the territory.

![Figure 3.2](image)

**Figure 3.2** Evolution of the length (in km) of the HSR network in Spain (1992-2011).

Source: *High speed atlas in Spain, 2012*

The Spanish HSR network currently connects 80 cities and their trains carry near 23 million passengers per year. The network also includes a total of 31 stations in 21 different provinces out of 50, supplying service to a population of more than 28 million people. Furthermore, it is willing to interconnect Spain with the bordering countries, France and Portugal. The complete construction of the most important line between Madrid, Barcelona and Perpignan (France) was concluded in January 2013. The operation of a direct route, without transfers, between Barcelona and Paris opened at the end of 2013. To accomplish this direct connection it is relevant expanding the liberalization of the European rail operators for all the countries and also implementing the technical and technological advances (ERTMS) towards the interoperability to enable the efficient movement of all the train operators in the EU within the entire HSR network. With the recommended requirements achieved, the complete interoperability of the train operational systems will allow travelling with an improved operability, reliability and punctuality from one country to another.

Today, the network in Spain is based on four main corridors: the first one connecting Madrid to some southern cities, like Sevilla or Málaga; the second one related to the corridor Madrid-Zaragoza-Barcelona-France border; the third one linking the capital, Madrid, with the city of Valladolid; and finally the route between Madrid and the Mediterranean regions, such as Valencia or Alicante. One of the main singularities of the HSR implementation is the construction of intermediate stations in cities with a wide range of population, between 30,000 or 80,000 inhabitants, or bigger cities, like Zaragoza or Camp de Tarragona influence area. The network includes many extension programmes to connect Madrid and the north of Spain, to Galicia, Castilla y León or the Basque Country. Simultaneously it is being constructed the enlargement of the southern and eastern corridors, providing AVE services to cities like Murcia or Granada. The new development plan of infrastructures and transport in Spain for the long-term period 2012-2024 (PITVI) contemplates a future connection of all the capitals of province in the country to the high-speed network, as indicated in Figure 3.3.
In addition to AVE trains (non-stopping services), AVANT trains (regional stopping services) stop at some other intermediate stations in high mobility municipalities, as previously explained. They offer a differentiated pricing structure, with travel times lower than 1.5 hours and high frequencies. The services, in direct competition with the car, reach a 52% of the market share positioning the country as a pioneer in provision of HSR regional services. Moreover, there are other trains (ALARIS, EUROMED, ALTARIA) serving long distance routes which are not considered high-speed due to maximum speeds of 200 km/h. Another rail service known as ALVIA with speeds of up to 250 km/h uses both high performance international-gauge tracks and the conventional network. The regular network in Spain is designed with Iberian gauge (1,668 mm), a different gauge to the HSR network that is constructed using the standard universal gauge (UIC international gauge). ALVIA rail services are able to swiftly from one gauge to the other, which provides the interoperability within the Spanish railway network. Thanks to this variable gauge mechanism, the reduction of the travel time is effective and beneficial for the users allowing the use of high-speed tracks in the majority of the journey, especially in cities where the HSR lines are still in construction.

3.2. - First plans of connection of Spanish airports to the HSR network

The inclusion of links to the HSR network at the main airports in Spain, like MAD and BCN, is not materialised yet, even though the planning of the airport link at BCN airport has been discussed in several occasions, starting in 1999 with the development plan of the airport the ‘Plan Director del aeropuerto de Barcelona-El Prat’. In the same year, the ‘Plan Director del aeropuerto de Madrid-Barajas’ was exclusively considering both suburban and metro connections to the future terminals, and just mentioning an enhancement of a connection to the HSR network in the long term.
The main purpose justifying the original plan of connection of BCN airport to the HSR network was the actual improvement of the current rail connection with several restrictions in operational capacity, due to the common section with the Mediterranean corridor, as well as really obsolete infrastructures. The airport master plan developed numerous rail link alternatives for the new HSR corridor between Madrid and Barcelona, establishing a main intermodal station for regional and high-speed services operating from the new terminal (current T1). It was clearly featured the importance of achieving a completely integration of the station in the terminal hall, in order to facilitate the interchange for the passengers moving from one transport mode to the other. The interest of connecting both new infrastructures was originated by the proximity of the planned Madrid-Barcelona HSR corridor (Figure 3.4), which layout through Barcelona metropolitan area was being discussed. An extra interest was also the rearrangement of the oversaturated rail section, which at that time integrated all different rail services including regional and long distance services, and also freight rail transport. The final decision rejected a new rail section providing direct access to the airport, in favour of a new intermodal station in el Prat, the closest town to the airport. The project of this air-rail connection has been currently abandoned for possibly taking it up again in the future with a most financially feasible alternative (loop line).

Some other projects in Spain discussed the opportunity of connecting GRO and REU airports (regional airports with a high seasonal tourism activity) to the HSR network taking advantage of the proximity of the HSR lines in construction in relation to the airports. In the case of GRO airport, the station would be constructed in the closest section of the HSR line between Barcelona and the French border. The distance of 1 km between the air terminal and the rail station would be covered with frequent shuttle buses. REU airport would be connected to the HSR Mediterranean corridor with Tarragona Central station once Madrid-Barcelona high-speed line connects to the rest of the Mediterranean corridor. At present, both projects have been left behind due to the adversity of the current economic situation.
4. - Madrid: the centre of the high-speed network

4.1. - Demographic and geographic pattern

Madrid is ideally located in the centre of the Iberian Peninsula and it is the capital of Spain. The population of Madrid is 3,215,633 inhabitants (Padrón Municipal 2013) and it is the most populated city in the country. Considering the suburbs and the metropolitan area, it comprises a total population of 6.4 million people (Eurostat, 2012). Compared to the rest of Europe, Madrid becomes the third major urban area in the European Union, after London (13.1 million) and Paris (11.8 million). However, the density area is not really spread in the territory compared to other urban areas in Europe, like Rhine-Ruhr, Ile-de-France or Greater London. The regions surrounding Comunidad de Madrid have really low population density compared to the actual city, with a density of 5,337.8 inhabitants/km² (Figure 4.2).

![Figure 4.1 Main urban agglomerations in Spain and their respective natural distances. (Left picture). Source: Gómez Comino, 2010](http://www.targetmap.com/ThumbnailsReports/2888_THUMB_IPAD.jpg)

![Figure 4.2 The demography of Spain, in terms of density of population. (Right picture). Source: http://www.targetmap.com/ThumbnailsReports/2888_THUMB_IPAD.jpg](http://www.targetmap.com/ThumbnailsReports/2888_THUMB_IPAD.jpg)

Additionally, most of transversal distances between Madrid and the rest of main cities in Spain reach distances of approximately between 500 or 600 km, as shown in Figure 4.1 and Table 4.1. These distance relations approach areas of high population density in the Atlantic-north, the Mediterranean and the Southern regions. The geographical shape of Spain is a perfect condition to perform HSR services from the capital, in the centre of the country, to the rest of regions. The distances to perform can be covered within maximum travel times of 2.5 hours, thus it presents a perfect opportunity to compete with the air domestic flights departing from MAD airport.
The connection of Madrid-Barajas airport to the high-speed rail network

<table>
<thead>
<tr>
<th>MADRID to:</th>
<th>Shortest Distance (km)</th>
<th>HSR Line Distance (km)</th>
<th>MADRID to:</th>
<th>Shortest Distance (km)</th>
<th>HSR Line Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALBACETE</td>
<td>221.8</td>
<td>314.0</td>
<td>MÁLAGA</td>
<td>393.0</td>
<td>512.9</td>
</tr>
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<td>ALICANTE</td>
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<td>483.0</td>
<td>SEGOVIA</td>
<td>63.0</td>
<td>68.3</td>
</tr>
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<td>BARCELONA</td>
<td>502.3</td>
<td>621.0</td>
<td>SEVILLA</td>
<td>387.0</td>
<td>470.5</td>
</tr>
<tr>
<td>CIUDAD REAL</td>
<td>150.0</td>
<td>173.0</td>
<td>TARRAGONA</td>
<td>410.0</td>
<td>521.0</td>
</tr>
<tr>
<td>CÓRDOBA</td>
<td>277.0</td>
<td>343.0</td>
<td>TOLEDO</td>
<td>66.2</td>
<td>75.2</td>
</tr>
<tr>
<td>CUENCA</td>
<td>130.0</td>
<td>188.1</td>
<td>VALENCIA</td>
<td>301.2</td>
<td>390.8</td>
</tr>
<tr>
<td>HUESCA</td>
<td>320.0</td>
<td>392.0</td>
<td>VALLADOLID</td>
<td>153.0</td>
<td>179.2</td>
</tr>
<tr>
<td>LLEIDA</td>
<td>370.0</td>
<td>442.0</td>
<td>ZARAGOZA</td>
<td>260.0</td>
<td>306.7</td>
</tr>
</tbody>
</table>


Examining the geometrical pattern of the HSR system in Spain is noticed a radial composition of the transport network with centre in Madrid. The capital is the heart of both rail and road domestic networks (hub & spoke), as identified in Figure 4.3. So accordingly to the transport configuration, the capital is one of the cities in Spain presenting a favourable accessibility and connectivity in relation to the rest of Spanish areas. The current Master Plan for Transport Infrastructures (PITVI) is expected to complete the connections of Madrid to the rest of cities in Spain in the mid-term (2012-2024).

4.2. - Main high-speed rail corridors from Madrid

The HSR lines in Spain can be combined producing 5 main radial corridors and one transversal along the Mediterranean coast (Figure 4.3). Concerning the corridors that converge at Madrid, four of them are already in service, although further extensions are programmed in the short-term. Currently, there are network developments on the North (& Northwest) and the South (Andalucía) corridors. None of the sections of the West corridor, connecting to Portugal, are opened yet, although the construction works are expected to finish in 2015. Once the entire extension of the network is completed, Spain will be territorially articulated from a cohesive point of view with a high-speed station at every province.

Figure 4.3 The final distribution of the high-speed corridors in Spain.

Source: Benito, 2010
4.2.1. - **South Corridor: Madrid – Andalucía (Sevilla – Málaga)**

The South Corridor connects the centre of Spain with the southern regions of Spain, Castilla - la Mancha and Andalucía. The first section was opened in 1992, and it was the first construction of a high-speed line in Spain. In certain sections of the line, the trains can reach maximum speeds of 300 km/h. Firstly, the route provided access to different regions and cities through stations in Ciudad Real, Puertollano, Córdoba or Seville.

The spur line diverting from la Sagra (Castilla-la Mancha) to Toledo opened in 2005. The construction of a new 20.5 km section was required in order to connect the old station in Toledo to rest of the line. The trains using the infrastructure run at top speeds of 270 km/h.

In late 2007, the opening of a new development of the corridor linked the station of Córdoba to Málaga - María Zambrano terminal. The new connection implied 155 km of new infrastructure and incorporated three new stations to the corridor: Puente Genil-Herrera, Antequera – Santa Ana and Málaga. The section, exclusively dedicated to passenger services, enables speeds up to 350 km/h.

The HSR South Corridor provided the railway sector in Spain with the first opportunity to demonstrate the efficiency of high-performance services within the country. The project was accomplished as a consequence of problems of the conventional rail line, including topographical, speed and lack of capacity difficulties. At the same time, the growth in competitiveness of the new rail connections originated a new pattern favouring the modal split in Spain, from the air transport to the train, for domestic journeys. After the opening in 1992, the high-speed train between Madrid and Seville extended the market share up to 80% versus the air, compared to an equilibrium point of 30% corresponding to the original railway.

4.2.2. - **Northeast Corridor: Madrid – Zaragoza – Barcelona – France**

The length of the Northeast Corridor is 804 km and it is one of the high-speed routes in Europe with more traffic. The line was gradually opened, starting with the first section in 2003, connecting Madrid - Puerta de Atocha to Guadalajara, Calatayud, Zaragoza and the city of Lleida. Afterwards, in late 2006, the line was extended up to Camp de Tarragona, in the south of Catalunya, to finally link to the city of Barcelona in 2008. In 2013, the line was finally extended to Figueres, in the province of the Girona, serving as well a station in the capital of the province. After Figueres, the infrastructure continues under the Pyrenees mountain chain towards France (Perpignan) delivering direct accessibility to the rest of the European HSR network.

Most of the infrastructure sections were designed so the trains can travel at speeds of 350 km/h. Therefore, the main route between Madrid and Barcelona can be completed in over 2 hours and 30 minutes. The travel time for the rail trip is now able to compete with the travel time using the air transport. This fact was one of the main reasons to produce a complete transformation of the market share of all transportation modes within this corridor. The continuous optimisation of the travel time combined with a reduction of the fares, high frequency services and significant reliability in terms of punctuality, provided the HSR line with all the factors to compete with the air transport.
4.2.3. - Eastern Mediterranean Corridor: Madrid – Levante (Valencia – Alicante)

The entire corridor can be divided in one common section departing from Madrid and arriving to Cuenca and afterwards there is a branch off: one reaching the city of Valencia and the other one directs to Albacete and Alicante. In the future, other sections that are part of the Mediterranean corridor will also be used as a direct connection to Madrid with some urban areas in Castellon or Murcia, along the Mediterranean coast.

The first part of the infrastructure to be opened in 2010 was the route Madrid-Valencia and Madrid-Albacete with a common intermediate station in Cuenca. The final extension between Albacete and Alicante was postponed until 2013.

4.2.4. - North corridor: Madrid – Galicia – Castilla – Basque Country

The first section of the line was opened in 2007 and it currently presents a small proportion of the future North and Northwest corridors, linking all northern regions: the Basque Country, Cantabria, Asturias, Castilla y León and Galicia. At the present, the route is just in service between Madrid and Valladolid with an intermediate station in Segovia-Guiomar. The high-speed line allows trains to reach speeds of up to 350 km/h and once it is fully completed, the corridor will interconnect around the 30% of the population in Spain.

There is another reduced section of the corridor, already in service within the region of Galicia, between Orense, Santiago and la Coruña. This part of the line, which comprises a total length of 150 km, was opened in 2011. In the future, it will belong to the Madrid-Galicia line and it will be also used as a connection of the North corridor and the Atlantic corridor, part of Portugal HSR network.

4.2.5. - West corridor: Madrid – Extremadura - Portugal

A new infrastructure of 164 km of the corridor is almost completed between Plasencia and Badajoz, linking intermediate agglomerations in Cáceres and Mérida, in Extremadura. In the long term the corridor will imply connecting Extremadura with the centre of the country on the North side, and the Portuguese border, on the other extreme.

4.3. - Madrid in relation to the high-speed network

Madrid presents two main dead-end railway stations providing all HSR services, both long distance (AVE) and middle distance (AVANT). Both stations are the departure points of all corridors previously explained, as shown in Figure 4.4. Madrid - Puerta de Atocha and Chamartín stations, located respectively in the southern and the northern part of the city, guarantee the function of commuting to other rail services, including regional, suburban or underground local. Therefore, the absolute local accessibility to the rest of Madrid urban area is perfectly provided by these two main rail terminals. Puerta de Atocha rail station is currently serving the Southern, Northeast and Eastern Mediterranean HSR corridors, whereas Chamartín station is used as a terminal, exclusively for the North-Northeast corridor. At present, the national interconnectivity between all HSR corridors is not in provided so far.
The table below (Table 4.2) reflects the main domestic HSR destinations (present and future) accessible from Madrid Atocha (in white) and Chamartín (in blue) stations and the respective minimum journey time between the two points (direct AVE or AVANT service). It is important to point out that the maximum travel time corresponds to the city of Girona, 3:32 hours journey, and Cadiz (in the future), completing a 3:45 hours journey. The rest of routes are mostly covered in less than 2.5 hours, which offers a favourable market positioning for the HSR mode in a competitive scenario for domestic journeys.

<table>
<thead>
<tr>
<th>Current destinations</th>
<th>Current time (hours:min)</th>
<th>Future destinations</th>
<th>Final future time (hours:min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALBACETE</td>
<td>1:19</td>
<td>A CORUÑA</td>
<td>3:15</td>
</tr>
<tr>
<td>ALICANTE</td>
<td>2:20</td>
<td>BADAJOZ</td>
<td>2:30</td>
</tr>
<tr>
<td>BARCELONA</td>
<td>2:30</td>
<td>BILBAO</td>
<td>2:30</td>
</tr>
<tr>
<td>CIUDAD REAL</td>
<td>0:59</td>
<td>BURGOS</td>
<td>1:35</td>
</tr>
<tr>
<td>CÓRDOBA</td>
<td>1:42</td>
<td>CÁCERES</td>
<td>1:45</td>
</tr>
<tr>
<td>CUENCA</td>
<td>0:51</td>
<td>CÁDIZ</td>
<td>3:45</td>
</tr>
<tr>
<td>GIRONA</td>
<td>3:32</td>
<td>CARTAGENA</td>
<td>2:50</td>
</tr>
<tr>
<td>GUADALAJARA</td>
<td>0:23</td>
<td>GRANADA</td>
<td>2:45</td>
</tr>
<tr>
<td>HUESCA</td>
<td>2:05</td>
<td>LEÓN</td>
<td>1:45</td>
</tr>
<tr>
<td>LLEIDA</td>
<td>1:59</td>
<td>MURCIA</td>
<td>2:25</td>
</tr>
<tr>
<td>MÁLAGA</td>
<td>2:25</td>
<td>OURENSE</td>
<td>2:15</td>
</tr>
<tr>
<td>SEGOVIA</td>
<td>0:26</td>
<td>OVIEDO</td>
<td>2:30</td>
</tr>
<tr>
<td>SEVILLA</td>
<td>2:20</td>
<td>SALAMANCA</td>
<td>1:11</td>
</tr>
<tr>
<td>TARRAGONA</td>
<td>2:33</td>
<td>SAN SEBASTIÁN</td>
<td>2:45</td>
</tr>
<tr>
<td>TOLEDO</td>
<td>0:33</td>
<td>VIGO</td>
<td>3:15</td>
</tr>
<tr>
<td>VALENCIA</td>
<td>1:38</td>
<td>VITORIA</td>
<td>2:30</td>
</tr>
<tr>
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<td>ZAMORA</td>
<td>1:10</td>
</tr>
<tr>
<td>ZARAGOZA</td>
<td>1:15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 Shortest travel time from Madrid and some current and future HSR destinations (in white destinations from Madrid Puerta de Atocha and in blue from Madrid Chamartín). Source: Compiled by author from ADIF, 2013b
At present, both rail stations are exclusively linked by metropolitan and suburban rail services (Cercanías) provided two tunnel sections crossing the centre of the city (in light blue Figure 4.5). The rail sections incorporate Iberian gauge tracks, thus exclusively enabling conventional trains running along the tunnel. However, the current construction to interconnect both terminal stations with a new 7.3 km tunnel, including a double set of international-gauge (1,435 mm) tracks, will allow high-speed trains to run at top speeds of 120 km/h (in red dots Figure 4.5). In the near future (presumably in 2015) the new HSR connection across the city centre of Madrid will allow the continuity of the South, North and Eastern Mediterranean corridors arriving to Atocha to Chamartín stations.

Figure 4.5 The project of the new HSR tunnel between Puerta de Atocha and Chamartin stations. Source: el País

After the completion of the tunnel, the Ministerio de Fomento (Ministry of Transports) forecasts more than 35 million HSR passengers traversing the centre of Madrid, instead of nearly 16 million users in 2011. Figure 4.6 reproduces the evolution of long-distance passengers using both terminal stations in Madrid from 2004 to 2011. The rising tendency is a direct effect caused by the constant opening of new HSR lines. Particularly, the growth is especially pronounced in 2007, the year when the city linked up to Barcelona.

Figure 4.6 Diagram of the evolution of long-distance rail users in Madrid Puerta de Atocha and Chamartin railway terminals. Source: Data extracted from High speed atlas in Spain, 2012
Additionally, the project for 2015 includes the expansion and reorganisation of both terminal stations in order to increase their capacity and the construction of both a third and fourth new international-gauge tracks of the HSR lines arriving to Puerta de Atocha station and coming from the south of the city. The actuation is aiming to segregate the circulation of those trains coming from the South and Eastern Mediterranean Corridors and also allowing a new end of the Eastern Mediterranean Corridor in Chamartin, contributing to freeing the platforms of Puerta de Atocha rail station. The total length of the new actuation will include the execution of nearly 35 new kilometres of infrastructure, including the railway tunnel across the centre of Madrid Figure 4.7). Furthermore, in the long term, the project incorporates the connection of the South and Eastern Mediterranean corridor, plus the new Western Corridor (to Extremadura and Portugal) and finally enabling trains of the Northeast corridor to use the HSR tunnel between Puerta de Atocha and Chamartin. The planning development will promote a fully interconnection for all the corridors providing a significantly better integration of the network and avoiding the entrance in the city for detour passengers.

Figure 4.7 Rail diagram of the projected HSR layout in Madrid urban area. Source: ADIF
5. - The airport of Madrid Barajas (MAD)

5.1. - General overview

Madrid-Barajas (MAD) airport (Figure 5.1) is currently the leading airport in Spain in terms of traffic exceeding the number of 45 million passengers in 2012. Additionally, the airport is the 5th in terms of traffic considering all European airports (Table 2.1). At this time, MAD airport is providing 155 destinations, 62% of which are continental flights operated within Europe and Spain. As a result of the intercontinental potential influence area, MAD airport can be considered as one of the major international hubs in the South of Europe, capable of attracting a considerable chance of economic benefits for the country and the region.

The airport complex and the runways are situated within the borough of Barajas (Madrid) and the municipalities of Alcobendas, Paracuellos del Jarama and San Sebastián de los Reyes, all in the Northeast of the metropolitan area (Figure 5.2). The old terminals (T1, T2 and T3) are located 2 km from the new terminal complex, comprised of the terminal T4 and its satellite terminal T4-S, which is linked with a 2 km long underground ‘Automatic People Mover’ (APM). The terminal buildings are located between 12 and 14 km northeast of Madrid city center.

Figure 5.2 Location of Madrid airport within the metropolitan area.
MAD airport consists of 5 terminal buildings (T1, T2, T3, T4 and T4-S). The terminals are specifically integrated for different airlines and thus offering different destinations clustered by domestic or international flights (Schengen area or intercontinental connections). The old terminals 1, 2 and 3 are hosted mainly by Star Alliance, SkyTeam and Air Europa airlines. The terminal T-4, inaugurated in 2006, is the principal airport building with an extension of nearly 500,000 m² and is able to handle more than 35 million passengers a year. The new terminal likewise operates the majority of destinations from the airport. The main airlines operating in this terminal are part of IBERIA and all others Oneworld partnership companies. As a consequence of this expansion the airport currently allows a maximum capacity of 70 million passengers per year.

The new expansion also incorporated 2 new runways, each of which are parallel to the existing ones. This major development plan enabled to increase the traffic operability of the airport, allowing a maximum of 98 operations per hour. There is a project to expand the capacity until 120 departures and arrivals per hour, in the future.

5.2. - The catchment area of the airport

One point to be outlined in the analysis is the potential demand of MAD airport, which can be reflected in the hinterland area of the airport. Generally the consideration of the catchment area would be explained in terms of the distance. The area of influence of the airport, considering the sort of national and international destinations departing from it, would include all the population within a radius of 400-500 km from the capital. This radius is considered by means of the idea of potential population able to connect to MAD airport by means of the long-distance railway network, inland public transportation modes or private vehicle. As observed in preceding sections, most of Spanish urban agglomerations are included within a 500 km radius with centre point in Madrid, as a consequence of the geographical structure of the country (Figure 5.3). Hence, the catchment area would be almost the complete IBERIAN Peninsula, partially excluding some extend urban areas like Barcelona, Girona, Santiago de Compostela or la Coruña.

**Figure 5.3** The catchment area of Madrid within a 500 km radius.

Source: Benito, 2010
The specific characteristic of MAD airport as an air transport hub also generates a more complex and spread configuration of the catchment area. The total population covered within a 400 km influence radius from the airport in 2009 exceeded the quantity of 28.3 million people (AEROAVE, 2010). The HSR potential effect derived from its fundamental characteristics will transform the vision of considering the distance as the variable decision of the catchment area; it will turn to be more proficient the use of time units.

5.4. - MAD airport as a hub node: Analysis of the traffic of passengers

The traffic evolution per year diagram (Figure 5.4) reflects the successive growth of total passengers in the last decade, until 2012. In 2007, there was an inflection point for both international and national traffic reaching maximum values and it represented a top traffic event for the airport with nearly 52 million passengers. The international traffic continued its moderate expansion until 2011, whereas all domestic routes suffer a deep decline of nearly 10 million passengers in just 5 years. After 2007, and due to severe structural circumstances of the economy in Spain and in Madrid, the airport reduced the traffic, especially last year (2012) matching an interannual variation of -9.0 %. The rise of landing taxes; the crisis of the main Spanish airline, IBERIA, based in MAD airport; the poor economic situation, affecting the national tourism; or the growing competition of the HSR network are reasons that can be associated with the phenomenon of the change in the tendency.

In Figure 5.5 is representing the composition of passengers (2012) at MAD airport regarding the sort of origin/destination. More than 68% of the total passengers correspond to international flights, whereas a smaller part belongs to domestic traffic. The international routes are mainly European destinations contributing with approximately 45% of the total traffic.
Chapter 5

After analysing last graphic, it is confirmed the interest of MAD airport regarding the volume of international connections which is going to be studied now. Particularly, it will be adequate emphasizing the intercontinental traffic (Figure 5.6), non-European, as it comprises the potential operability of MAD airport as an international hub, which relates to the Latin American connections market.

In the preceding table (Table 5.1) are considered the 25 major international routes in terms of traffic, operating from MAD airport in 2012, as well as the total international traffic flow produced in 2012, which is just below 30.7 million passengers. The most part of international routes correspond to European connections, as it can be deduced from the previous Figure 5.5. Besides the register of European routes, it is clearly emphasized the scale of traffic developed in American, and especially South American, routes, such as Buenos Aires or New York, matching a total number of 10 itineraries within the top 25.
The connection of Madrid-Barajas airport to the high-speed rail network

It is notably pronounced the influence of MAD airport in relation to the intercontinental capacity inside Europe reaching a ratio of 6.3% of the total. The airport has become the number 5, within the top European airports taking into account all intercontinental operations.

Madrid holds a 51% of the entire Spanish intercontinental traffic and thus, it becomes the main direct link to the American continent, especially to Latin and South America. At the same time, MAD is the main hub of the indirect Spanish traffic, with nearly an 18% of the total. Madrid dominates the indirect traffic from other Spanish airports (except BCN airport), 48% of which stops in Madrid. This fact accentuates the importance of the airport as a connector between all Spain and the rest of continents, as most passengers travel first to Madrid in order to link with the flight that will take them to their final destination. The character of MAD airport as a hub is consequently confirmed and it turns into a clear market leader for the Spain – South America traffic segment.

New Asian markets, like China, India or Japan, are slowly emerging in the Spanish traffic and MAD airport is leading some of the main changes. China and South Korea are taking place of some of the main intercontinental demand served either with direct or indirect routes. MAD airport shows a high potential with China, as well as an interesting capability in the route Madrid-Seoul (South Korea). Some other routes mainly North Africa and Middle East routes also belong to the extended influence market of MAD hub airport.

On the other hand, Table 5.2 displays the 25 main domestic routes in terms of total traffic from MAD airport and the total amount of passengers using domestic routes in 2012, nearly 14.5 passengers. The first route concerning the total number of passengers is the connection between Barcelona, known as Puente Aéreo, and it carries a significant traffic volume difference in relation to the second busiest domestic route (Palma de Mallorca). Madrid-Barcelona is one of the air routes in Europe with a highest demand of traffic. The traffic data clearly states that the major domestic routes correspond to connections with the areas of a

Figure 5.6 Map of the main intercontinental destinations from MAD airport. Source: http://www.ac-nice.fr/lycee-beaussier/site/attachments/article/266/1e%20BCB%20G2%20Site.pdf
high density of population, for instance, areas along the Mediterranean coast, the northern regions of Spain or, exceptionally, connections to both Balearic and Canary Islands.

5.4. - Congestion and delays at the airport

Although MAD airport capacity has been recently expanded as a result of the construction of the new terminal T4 and a pair of new runways, the airport still experiences occasional peak congestion through the day. The demand only exceeds the capacity of the airport in certain parts of the day, around 6 hours during the daytime period. In 2010, the demand for slots was close to capacity, but overall, at the moment, there is enough capacity to meet the demand request. In the following years, it is expected to experience the same limitations for some hours during the day, from 6 to 12 hours during the daytime period. At this stage, the improvements in air traffic management will allow to increase the capacity of operations from the current 98 (48 arrivals and 50 departures) until the 120 operations per hour in 2020. In this case, the capacity constraints are caused by the operational limitations of the runways.

The DIGEST report in 2012 about delays to air transport in Europe (Eurocontrol, 2012) positioned MAD airport in the 9th place of affected departures airports and the 3rd on affected arrival airports. A total of 44.5% of the total flights were delayed on departure and a 48.9% on arrival. In comparison to 2011, the airport experienced delays fall by 30% in departures and 32% in arrivals. The main reasons behind the delay situation are airline related causes, due to passengers, baggage handling, flight operations or crew issues; and reactionary delay caused by late arrival of aircraft or crew from previous journeys.

In the last few years the capacity enlargement produced by the opening of the new terminals and runways in 2006 mainly readdressed the initial congestion limitations at the airport. The growing modal split favouring the HSR in point-to-point routes also liberated some of the slots at the airport, and reducing the congestion limitations and improving delay issues occurring in the precedent years.

<table>
<thead>
<tr>
<th>25 MAIN DOMESTIC ROUTES IN TERMS TRAFFIC (2012)</th>
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<tbody>
<tr>
<td>BARCELONA-EL PRAT</td>
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<tr>
<td>PALMA DE MALLORCA</td>
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<tr>
<td>GRAN CANARIA</td>
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<tr>
<td>TENERIFE NORTE/ LOS RODEOS</td>
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<td>BILBAO</td>
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<td>SANTIAGO</td>
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<td>A CORUÑA</td>
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<td>ALICANTE-ELCHE</td>
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<td>LANZAROTE</td>
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<td>MALAGA-COSTA DEL SOL</td>
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Table 5.2 Major domestic destinations at MAD airport in terms of passengers traffic in 2012. Source: Data from AENA
5.5. - The reduction of domestic air traffic and the modal split

Recently the economic circumstances have led to a reduction of the domestic traffic in Spain, except the passenger flow between the Peninsula and both Balearic and Canary Islands. There are many reasons justifying the change of tendency. One of the main ones is the relation between the evolution of the air traffic in a country (general mobility patterns) and the GPD ratio. Due to the economic crisis in Spain and the reduction of its GPD, the mobility of passengers within the country has continued the same tendency as the economy. The cutback in the domestic traffic has been especially severe in the air transport demand, whereas high-speed trains carried more passengers. Most of HSR routes within Spain can be completed in less than 2.5 hours (from Madrid), which gives the HSR a significant competitive level of the travel time, against the rigidity and nuisance of the complex and long air transport procedures. The high level of comfort, an exceptional punctuality in nearly 99% of trains, the implantation of reduced pricing strategies in 2013 or the increase of frequencies in most of AVE routes are amplifying the users of high-speed trains, especially the point-to-point demand. On the other hand, a flight journey requires a high number of operations mainly as a consequence of safety reasons. The air travel time may include long waiting times, before the flight departure, time to complete the check-in and the airport protocol, as well as higher access times between the airport and the city centre, which involves a significant fraction of the total travel time in a short-haul flight. Thus, an extended development of the HSR network will be in favour of a modal split of passengers in the domestic market shifting from the airplane to the high-speed train. To quantify the possible resulting consequences, it is going to be analysed the modal split for the main domestic HSR-air pair routes in Spain, concerning the evolution of the rail and air demand for a certain period of time. The analysis will evaluate the demand consequences for the current four main point-to-point relations departing from Madrid.

Madrid-Sevilla

This route was the first high-speed service to compete in similar conditions with the respective air route and from the beginning, in 1992; it absorbed half of the total traffic between Madrid and Seville. From the year after and producing a direct effect, the HSR market immediately absorbed more than the 80% of the total demand (Figure 5.7). The total demand grows throughout the years until 2008, the year of the burst of the economic recession. Direct trains complete the route in 2 hours and 20 minutes at a cruise speed of around 200 km/h. The effect of the HSR was immediate in the market share of this route becoming a perfect example of the consequences of the rail implementation in the domestic market.

![Figure 5.7](image)

**Figure 5.7** Modal split for rail and air transport in Madrid-Sevilla route. Source: Data from AENA and Ministerio de Fomento, 2012a
**Madrid-Málaga**

In the case of Madrid-Málaga point-to-point relation, the effect produced by the introduction of the HSR in the route transport market was similar to the previous description. The HSR, with 12 daily services each direction, acquires market share against the air transport, but smoothly increasing from 2007, the year of completion of the HSR corridor. The modal split becomes favourable for the high-speed train in the succeeding years achieving nearly 80% of the demand quote (Figure 5.8). However, the total demand of the route experiences a 34% contraction of passengers (counting both modes of transport) from 2008 to 2012.

![Figure 5.8 Modal split for rail and air transport in Madrid-Málaga route. Source: Data from AENA and Ministerio de Fomento, 2012a](image)

**Madrid-Barcelona**

The line was fully opened in 2008, completing the section between Madrid and Barcelona. In this route, of approximately 600 km long, the penetration of the HSR from 2008 is moderate compared to the ones previously analysed, reaching an equilibrium point of around the 50% of the market share (Figure 5.9). The route still corresponds to the busiest point-to-point connection in Europe with 61.5 flights per day, accounting both directions, and 27 rail services each direction in 2012. A longer journey time for the high-speed train, similar HSR and air frequencies as well as the nuisance of the air procedures plus its access time and, are some reasons of the accentuate competition in this route between the HSR and the air mode.

![Figure 5.9 Modal split for rail and air transport in Madrid-Barcelona route. Source: Data from AENA and Ministerio de Fomento, 2012a](image)
Madrid-Valencia

The following route is one more example of enhancement of the HSR mode in Spain after the opening of a new corridor. Figure 5.10 shows the progression of passengers between Madrid and Valencia considering just train and air customers from 1999 to 2012. Before the release of the new line in 2010, the airplane was the first choice with more than 50% of the total demand. From 2011, the modal split is changed favouring the high-speed train and obtaining percentage rates of more than 80% of the passengers using the rail corridor.

Figure 5.10 Modal split for rail and air transport in Madrid-Valencia route. Source: Data from AENA and Ministerio de Fomento, 2012a
6. - The rail connections in MAD airport

6.1. - Current metro and rail connections

6.1.1. - Metro (line 8)

The first rail connection serving the airport in Madrid was provided by the line 8 (pink line) of the Metro underground network in Madrid. The new airport link line was included in the metropolitan network Extension Plan (Plan de Ampliación del Metro 1995-1999) and it was inaugurated in June 1999. This underground line delivers full accessibility from the business center of Madrid (Nuevos Ministerios) and the Madrid exhibition center (IFEMA), to the airport terminal buildings T1, T2 and T3. The rail station was designed as a terminus station in order to proceed with the future extension when the new terminal (T4) would be constructed. The station is accessible from a walkway in level 1 in the terminal T2.

When the new terminal buildings T4 and T4S were opened in 2006, it was necessary to connect the new airport wings with the metro line. In 2007, the consequent extension of the line 8 was operating a new service reaching the new terminal T4. The new metro station in the terminal building is completely integrated in the interconnection node and providing direct access from level -1 (Figure 6.1).

The rail service runs as often as a metro service and it connects the capital with the airport in 12-15 minutes (for the T4) with an average frequency of 5 minutes in peak hour weekdays. The train enables maximum speeds of up to 105 km/h.

Figure 6.1 Metro line 8 within MAD airport terminals. Source: http://www.espormadrid.es/2013/10/transpo rte-al-aeropuerto-de-madrid.html
In this new Extension Plan of the metro network in Madrid, the new station of Nuevos Ministerios in the business center was established to be the main interchange station in the area and to offer a functional and quick connection with the rest of the rail network in Madrid. For this reason, the station opened in 2002 a baggage check-in facility for passengers travelling to MAD airport previous the access to the metro platform and boarding the train (Figure 6.2). This facility was a first strategy of IBERIA, and a few more airlines, to motivate the use of the rail connection presenting the first air-rail integration and intermodality product in Spain. However, there were insufficient advantages in terms of a great advance check-in time or increasing the passengers’ convenience, as it was not offered in any other network metro station. Since 2006, all the 34 check-in desks remain closed probably because the lack of demand (according to IBERIA by much less than a 5% of their passengers, over 200 passengers a day) and the opening of the new T4 used by IBERIA did not offer a metro connection yet.

6.1.2. - Cercanías (suburban rail services)

The connection of the suburban rail services (Cercanías) to the airport was opened in October 2011. The new line, C1, links the station Aeropuerto T4 with numerous transport transfer points in the center of Madrid, like Chamartín and Atocha, both also terminal stations of HSR services. It also connects other important stations like Nuevos Ministerios or Príncipe Pío, interchangers including other regional rail services. The travel time from the airport to the city varies from 38 minutes (to Príncipe Pío station) to 11 minutes (to Chamartín station). The service includes CIVIA trains operated by RENFE every 30 minutes per each direction (Figure 6.3).

The length of the new rail infrastructure is 8.8 km. There is a first section departing from Chamartín and finishing in the crossing point of the M-40 highway. This part of the route is formed by 4 rail tracks and the rail platform is on surface. The second part is composed of 2 ballastless rail tracks and it is executed as a 4.7 km tunnel section. The dead end station at the airport (Aeropuerto T4) is located beside the metro underground station (line 8), with a central 250 m platform including one track on each side.
It is important to emphasize the fact that Ministerio de Fomento decided to adapt the conventional gauge, Iberian gauge (1,668 mm), used in this line to standard UIC gauge (1,435 mm) to enable high-speed trains running on the line. For this function, the rail infrastructure integrates a pair of 3-rail dual-gauge gauge tracks, allowing suburban, long-distance as well as interoperable high-speed rail services to operate in the line. As a result of this infrastructure design, in the future it would possible to access to the airport via HSR services, enabling a direct connection to Chamartín transfer station.

6.2. - Future plans for a HSR connection

The PITVI transport plan, published in 2012, contemplates the necessity of connection of MAD airport to the rest of the HSR network. The only formulated strategy to perform the connection at this time would be the reconversion of the existing Cercanías line (C1) into the HSR airport link (Figure 6.5). MAD airport would be served by AVE trains through a spur line terminating at the intermodal rail station at terminal T4. The line would have direct access from Chamartín station and from there it would link up to the rest of HSR corridors. Part of the existing rail infrastructure, the tunneled section, is already prepared to operate HSR trains. From Chamartin to Hortaleza technical assistance station, it is planned the construction of a single UIC gauge track in order to complete the implementation of HSR services to the airport. However the connection would only be consisted once the city UIC tunnel, commented in chapter 4, is fully operative. In any other case, the line would merely be a simple shuttle HSR service between Chamartin and the airport. The electrification of the tunnel and a few more adaptions would allow connecting the airport to both Southern and Eastern HSR corridors.

The spur line airport link (Figure 6.4), the implication of which will be developed in the following section, produces some immediate advantages concerning a considerably economical and fast execution of the infrastructure. The lack of efficiency, though, as a result of the low frequencies on a single track, in addition to the absence of a wide connectivity vision are some of the downsides of the alternative.
The connection of Madrid-Barajas airport to the high-speed rail network

Figure 6.4 / Figure 6.5 Future project of the layout of the high-speed lines within Madrid city / The plan of restructuration of the existent Cercanías line from Chamartín to MAD airport T4 for high-speed reconversion.  
Source: ADIF and Ministerio de Fomento
7. - The interest of a high-speed link at MAD airport

The aim of this section is presenting the background notions concerning the main reasons of MAD airport to be integrated in the HSR network and thus promoting the interconnection infrastructure needed to accomplish the intermodality. The particular application of some of the aspects developed in previous sections confirms the beneficial potential of constructing a HSR line connecting MAD airport to the rest of the Spanish rail network. Furthermore, and comparing the rest of European examples previously detailed, the possibility of an efficient service, combining the actual terminal facilities with the modal change interconnection, can reveal a general interest in order to provide a fast and well-organized integration of the HSR and the air mode and vice versa. The following four principal subjects summarize the geographical/spatial and strategic argumentations that meet the presumed interest in order to provide a new direct HSR access to MAD airport terminals.

7.1. - The rail infrastructure connection

Concerning the practical conclusion extracted from López Pita, A. (2003), it can be relevant to analyse whether the HSR lines in the metropolitan area of Madrid are located in the same quadrant as MAD airport. Figure 7.1 performs the schematic layout of the current four HSR corridors connecting to Madrid. The city centre (Districto Centro) is considered the centre of the reference axes and the airport is located in the first quadrant of the space. Part of the Northeast corridor (Madrid-Barcelona line) shares the same quadrant with MAD airport. At the same time, the North corridor (Madrid-Valladolid line) traverses the diagram just on the vertical axe bordering the same quadrant. Following the pattern of the rest of HSR connections to European airports, the verification of the feasibility of constructing a rail link to MAD airport turns to be affirmative. This confirmation is the first phase to prove the interest in constructing a HSR transfer node at the airport terminals.

Figure 7.1 Schematic diagram of the HSR network in Madrid relative to MAD airport location.
The connection of Madrid-Barajas airport to the high-speed rail network

The high-speed line would provide service to the new terminal T4 (and its satellite T4S) with a capacity of 35 million passengers per year (and 15 million passengers for its satellite terminal) and where an intermodal underground rail station is already operative. This decision is contemplated because the intermodality with others modes of transport will be strengthened if the HSR connection is produced on that terminal, as it holds metro and suburban rail stations, as well as other collective and individual means of transportation.

The next phase will be analysing the distance between the closest HSR corridors and the terminal building T4. The two HSR corridors to be considered are the ones located in the same quadrant as the airport, the North corridor and the Northeast corridor. The approximate minimum distance from the airport terminal T4 to the considered HSR corridors, as shown in Figure 7.2, is the following:

- Distance to the North corridor: 7 km.
- Distance to the Northeast corridor: 11.5 km.

![Figure 7.2 Map of the distance between Terminal T4 and the different HSR corridors.](image)

The results of minimum distances to the main corridors demonstrate a greater proximity to the North corridor. At first sight, in terms of constructed infrastructure, the connection to the North corridor would be more likely executed due to the shorter distance. What is more, the urban areas to cross will be the districts of Barajas and Hortaleza (Valdebebas and Valdefuentes), in some cases with areas still under urban development. At the same time, the existing suburban rail services (Cercanías) can be beneficial because the infrastructure platform can be used as the support for the new track bed and thus, minimizing the impact of the new constructions.

Another additional interest would be connecting the North and the Northeast corridors without the necessity of crossing the city of Madrid (through Puerta de Atocha or Chamartín stations). Even though the actual connection will be possible once the HSR tunnel across the city connects both stations, the aspiration is providing a more direct route through a by-pass like for other existent corridors. The connection through the airport, then, could create a great
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chance of linking the North / North-West regions of Spain with the Northeast. The new HSR line would create a new East-West rail corridor axe across the centre of the Peninsula. In addition, the rail infrastructure should be planned in order increment the accessibility of the airport and thus expanding its catchment area. For this reason, the airport HSR station should directly serve the traffic derived from the rest of the corridors (South, Eastern Mediterranean and West corridors). The application of this decision producing the enlargement and reinforcement of the airport influence area will produce a greater benefit of the intermodality and also the domestic railway connectivity.

The proposed solution of reconversion of the current suburban rail line C1 into a high-speed spur line does not provide a total integration with the rest of the HSR network. In addition, it presents a great number of limitations in capacity (frequency of services) and operability of the distribution of the passengers with the rest of the Spanish territory. The HSR interconnection main objective is to provide an efficient link to the rest of the country from the airport, as the airport hub would serve almost all the sizeable cities that are currently or will be connected to long-distance (AVE) or middle distance (AVANT) HSR services.

All mentioned discussion has to be accounted in order to design the most appropriate rail infrastructure, continuously taking into consideration the existing constraints, but always meeting the demand requirements and the stimulating potential benefits derived from the construction of the airport link.

7.2. - Potential advantages for both HSR and air transport supply from Madrid

The geographical location of MAD airport entails an extra favourable point to promote the link to the high-speed network. The considerable proximity of the airport in relation to the North metropolitan ring municipalities also implies an extra significance of the airport link line with a through station, providing direct service to the North and Northeast parts of the metropolitan area. Given the current intermodality scenario of the airport with other transport modes, like metro, suburban rail, bus and other individual transit modes, the new high-speed transit link would positively impact in the implementation of a major transport node station beyond just the metropolitan region, and also in the rest of the province.

MAD airport has some similar characteristics to other major European airports, such as FRA or CDG airports, where the intermodal connection between the airport and the high-speed network is currently successfully operative. The airport is the main air transport infrastructure in Spain in terms of passenger movements. As described in previous chapters, MAD holds a great number of destinations, mainly international (with a 68% of the total traffic), and the airport has become a major transport hub for Spain regarding the volume of intercontinental flights to Central and South America and slowly emerging to other Asian markets. The last extension of the airport in 2006 provided a great capacity of the terminals which gives sufficient potential of operation and volume of passengers. The multiple capacity constraints and the lack of expansion space in most of European airports assign a convenient prospect to MAD airport. All these facts exemplify the developing potential of MAD as an interconnection
The connection of Madrid-Barajas airport to the high-speed rail network

modal node between the HSR services and the air transport in order to maximise the capacity of the hub.

The airport has experienced a reduction of the traffic in the last few years, mainly as a result of the adversity of the economic situation, the transfer of passengers from domestic routes to other means of transport (mainly due to the HSR competition scenario), and also the lack of an efficient strategy of airlines (IBERIA) to stimulate its great capacity as an international hub. These consequences are leading today to an attenuation of the competitiveness of the airport as an international hub. The interest of this situation lies in taking advantage of the opportunity of the reduction of domestic flights and thus liberalisation of some air slots to replace them with an intensification of the existing intercontinental destinations or the creation of new ones. The excellent situation of MAD as a Latin American air hub has to be reinforced with new destinations and the increment of frequencies, and regaining the dynamism of the traffic of the airport. For that purpose, the national routes can be substituted by HSR services, promoting a further gain of accessibility of the airport for increasing the number and frequency of long haul flights and thus enlarging its catchment area serving a greater population. A correct synchronisation and intermodality of the air transport with the rail services will guide to an establishment of the HSR as a rail feeder service for the airport. The rail network will also generate new demands enlarging the influence of the airport activity and attracting more efficient mobility combinations. These circumstances will contribute in the renovation of the transport system model and the improvement of both the air and rail traffic, if the terminal integration for both modes is effectively operating. Hence, the profitability of MAD airport will be positively affected by the connection of the HSR network.

The immense capital investment provided for the development of the Spanish high-speed network and its particular pattern gives an extra value to arise the connections with Madrid. The majority of current and planned HSR corridors have the origin at Madrid, giving a fully coverage of connections with the rest of the country. The radial shape of the network contributes to substitute the decaying domestic flights with HSR services. As shown in previous chapters, the rail is winning market share against the airplane in routes covered in no more than 2 or 2.5 hours, like to Barcelona, Seville or Valencia. The competitive travel times of the HSR routes and the reliability, comfort and a recent reduction of the prices give a valuable point for attracting the demand in national routes. Following this tendency and given the high degree of implementation of the HSR network in Spain in the future, it is especially forthcoming evaluating the possibilities of intermodality and cooperation with the air mode. This resulting opportunity is beneficial to the rail transport providing a surplus in rail passenger traffic volumes and revenues without having to provide supply with extra capacity. At the same time, it would be positive to achieve a higher occupancy of the trains and establishing a new strategy of adaptation matching the demand to the supply and resulting in a more proficient operation of the trains for the operator.

The existence of two main transport operators for each mode, the airline IBERIA and the rail operator RENFE facilitates the chances of cooperation and simplifies the establishment of service integration agreements. IBERIA operates all its flights from the T4 terminal, with more than 90 destinations in 37 different countries. The operators’ cooperation is a key factor for
the intermodal product success. The existence of various operators for each mode implies difficulties in the coordination of the intermodality. Nevertheless, the alliance between airlines, like Oneworld alliance, can enlarge the chances of connections with flights served by 13 airlines and its affiliates, like British Airways, American Airlines or Air Berlin. In FRA or CDG airports, both considered as examples of intermodal efficiency, the operators agreements are mainly encouraged by one main operator for each mode.

At the same time, there is an emergence of low-cost airlines, which are winning market in domestic flights, whereas IBERIA has suffered a drastic reduction of the carried passengers. The main competitive ambit for the airline is in the short-medium haul routes. The low cost airlines and the HSR produce a competition scenario difficult to overcome. The unviability of the short-medium distance flights, due to the hard competition, is also affecting the long haul routes which contribute with more than 65% of the transit. Nevertheless, the privilege situation of IBERIA at MAD airport, with a 47.4% of the traffic in the terminal T4 in 2012, and the continuous loss in profitability for the domestic influence area is a great opportunity to expand the influence area to international markets, particularly intensify European destinations and Latin America or Asia. The cooperation scenario will support then to supply the entire traffic demand and will also promote a renovated strategy for the airline.

7.3. - Connection infrastructure & intermodal station at terminal T4

The best scenario to enhance the intermodality between the air transport and HSR services is the direct connection and integration of the airport rail station within the airport complex or even more appropriate, inside one of the terminal buildings, arranged and designed to allow a continuous transfer of passengers. This solution of intermodality will facilitate a seamless journey between both means of transportation and it will important not only to reduce the transfer time between the airplane and the train, but to give a higher level of comfort to the passengers.

As some of the successful intermodal European experiences demonstrate, the integration of the train station inside the terminal contributes to reach minimum access times. Particularly for MAD airport, the underground and rail station already constructed in level -2 of the new terminal T4 enhances the interconnection passengers to use the service with an optimal transfer time below 5 minutes. Furthermore, it will carry out fewer difficulties in the luggage transport operation and also will provide a more comfortable service to all customers, due to the complete adaptation for people with reduced or limited mobility. The new HSR would complement the rest of existing landside modes in the terminal improving a further accessibility and completing the rail transport hierarchy (local, regional and domestic services). The access to the road and highway network, the collective transportation system (Metro, Cercanías, urban and other nationwide bus services), in addition to the current great parking facilities and rental of cars are examples of the considerable density of transport at T4 terminal. The T4 infrastructure disposition is a perfect occasion to develop an intermodal interface and support an integrated airport link solution optimal for the transfer between the HSR train and the aircraft.
At the same time, it is relevant to mention that an alternative with a shuttle connection to the rail station (outer terminal) would increase the travel time and the lack of comfort for the users. A non-broken connection without intermediate transfers to provide simultaneous access between both means of transportation will be then the optimal solution and it can be partly achieved with the current underground station. With the intention of providing the adequate level of service to the connection, it is clear to define a strategy with the airlines in order to allocate the international and transit intercontinental flights in the same terminal as the intermodal HSR station. In this case, the new terminal T4, with enough passenger capacity, would be the best option to establish the long-haul flights to facilitate the intermodal efficiency. In case of flight allocation in the satellite terminal (T4S) a direct connection is provided through an Automated People Mover (APM) with an average trip duration of 3.5 minutes.

7.4. - The sustainability and other social benefits of the connection

From a social point of view, the intermodality between MAD airport and the HSR network would generate beneficial effects for users, operators and for the environmental impact. The reduction of external cost effects will be mainly produced by the mentioned substitution of the domestic air market with HSR services. The HSR, understood as the entire system, is a more sustainable and cleaner mean of transportation in terms of land use, energy efficiency, CO\textsubscript{2} emissions or safety, compared to private vehicles or air transport systems.

The environmental impact will be reduced by the substitution effect on domestic flights and alternative transport modes by HSR services. The reduction of tones of CO\textsubscript{2} is promoted beyond just the replacement of the air mode by the HSR, as well as the reduction of the use of other motorised vehicles, especially private cars. On the light of a recent study (AEROAVE, 2010), the air-HSR intermodal connection in MAD airport would minimise the greenhouse impact (in terms of emissions of CO\textsubscript{2}) nearly a total amount of 10% (representing 5kg per person and journey). This reduction would result as a consequence of the domestic passengers travelling to the airport by HSR services. The CO\textsubscript{2} emissions of the aircrafts in routes like Madrid-Sevilla or Madrid-Barcelona, under certain assumptions (door-to-door service, important load factors for the HSR in the routes and specified vehicles) can be 6 times higher than the produced by high-speed trains (Figure 7.3). Hence, the HSR produces a clear contribution towards a more sustainable mobility and the protection of the environment, in terms of reduction of air pollution and emissions. MAD airport would add-up the current sustainable and eco-friendly initiatives towards a ‘greener’ airport and urban region.

On the other hand, this situation of environmental emission improvements can be jeopardised in some measure by the environmental effect of the HSR in the construction phase which can be very acute. So the final saving can result in a lower value considering the emissions for construction and the beneficial effect can be improved after decades after the execution of the high-speed line. For this commitment, a high volume of passengers using the line can validate the environmental advantage and the social justification of deriving passengers to the HSR. The net effect on CO\textsubscript{2} emissions will be highly influenced by reaching a
certain position of the modal split from conventional modes in order to compensate the high environmental impact on the construction.

![CO2 emissions/pax-km and Energy consumption/pax-km graphs]

**Figures 7.3** Comparison of unitary CO2 emissions and energy consumption of different transport modes in the routes Madrid-Sevilla, Madrid-Barcelona and Madrid-Toledo (A-airplane; CR-conventional rail). Source: Sánchez Borràs, 2010

Additionally, the HSR is the mode in the domestic market (medium-distance corridors) with the lowest specific energy consumption compared to the plane (UIC and Figure 7.3), which is the highest among other alternative modes. This positive impact turns to be real assuming door-to-door services, particular load factors, and effective aerodynamic effects of the Spanish HSR technology, both infrastructure and rolling stock.

Another interest is produced by the diminution of the noise nuisance in the airport vicinity, though the real impact is difficult to establish. A study of the European Commission verifies that the implementation of HSR, replacing the same routes served by the air transport, will entail a reduction of a 10% of the area affected by the air transport acoustic impact. However, it will be proportional to the rolling stock technology, the train speed (which cannot be high in urban areas) and other aerodynamic conditions.

The increasing of international demand visiting Spain can be an extra motive encouraging the HSR-air interchange. Spain received a record amount of 60.3 million tourists in 2013, 80.4% of whom arrived in the country via the air mode. The flourishing tourism throughout the country should be promoted by the supply of numerous connections from the airports in order to distribute the visitors to different regions. Some of the regions with an enhancing tourism, apart from Balearic and Canary islands, were Catalunya, Comunidad Valenciana, Andalucía or Comunidad de Madrid, which are very well linked to the capital. The position of MAD airport with major international flow of passengers and the optimistic tourism market all over Spain could disclose an additional interest to support the airport link.

Additionally, some other cross effects and social advantages of the interconnection could include: the high level of safety and comfort related to the HSR mode, the relief of road traffic congestion, and further economic impacts with a direct effect on the population of all the catchment area, such as the expansion of the markets or location effects, especially for regeneration of central locations (de Rus, 2011).
8. - Feasibility of the planning and construction of the HSR connection

8.1. - Planning of the new corridor: discussion of alternatives

In the first instance, the vision of planning and constructing a new HSR line through an existing airport is a complex mission to elaborate. The existence of physical constraints, geographical restrictions and other construction limitations demands several comprises within the planning phase. Consequently, the awareness of the local context is a decisive part to identify the feasible chances of connection. Particularly at MAD airport, the entire airport development, the high-dense urbanised areas and other territorial and environmental constraints will be taken into account for the project of the HSR corridor (Figure 8.1). The objective is designing an outline to provide a new airport link and the existing rail and air infrastructure will influence the several scenarios of executing the rail line. To this end, the new airport HSR line will allow an improvement of connectivity of MAD airport, through the connection to the HSR network, and the potentiation of a new intermodal centre in the air infrastructure.

![Figure 8.1 Topographical map of the HSR network in Madrid relative to MAD airport location. Source: Adaptation from Google Maps and Topographical map Madrid, http://www.madrid.org](image_url)

The next phase corresponds to the determination of the possible options to perform the rail connection in MAD airport: a branch/loop line diverging from one of the HSR main lines, the inclusion of the airport in a new main HSR line and a spur line terminating at the airport. The three suggested types of airport links can define 4 different alternatives in order to execute the connection of the airport terminal (Figure 8.2). The options are determined...
concerning the geographical situation of the airport in relation with the closest HSR lines, the Northeast corridor heading to Barcelona and the North corridor that ends in Valladolid.

Alternative 1 – Main line

Alternative 2 – Branch line A

Alternative 3 – Branch line B

Alternative 4 – Spur line

Figure 8.2 Schematic diagrams of the different alternatives to connect MAD airport to the HSR.

Alternative 1 creates a by-pass line avoiding the entrance in the city, and connecting the North and the Northeast corridors. Alternative 2 and 3 are two different branch or loop line solutions connecting the airport to the Northeast corridor and the North corridor, respectively. Alternative 4 reflects an adaptation of the current suburban rail infrastructure to a HSR line adapting the form of a spur line. The last alternative is the link projected by Ministerio de Fomento readapting the conventional rail infrastructure with dual gauge tracks.

The 4 different alternatives correspond to the classification of conventional airport links for HSR services. Another kind of airport connection would be the so-called accidental link (Duarte Costa, 2012) reasonable when the airport is close enough to the rail infrastructure to have a station built, but not necessarily on the terminals. Normally this solution, established in DUS airport, presents a convenience of the airport’s location in relation to the rail line. In MAD airport, the determination of this design is not feasible due to the excessive minimum distance to the closest rail infrastructure, which is slightly longer than 5 km.

Particularly, it is important to point out that the connection will be analysed considering a station via the airport terminal T4. The current reorganisation of economic resources can be applied in order to minimize the total infrastructure cost as an underground
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station is already serving the terminal (with urban and suburban rail services) as shown in Figure 8.3 and 8.4. In some way, resizing the existing rail station and using the constructed facilities will enable a faster development and reasonable use of the economic funding. The station in T4 terminal will also enhance the interchange with other transport public facilities on the landside such as buses, taxis or other individual transit systems. At the same time, it will be encouraged a door-to-door seamless journey serving the inter-terminal transit traffic, so the vertical interface of the terminal will play an important role in the promotion of the intermodality.

Figure 8.4 View of the metro platform at the T4 airport station. Source: http://www.skyscrapercity.com/showthread.php?t=22718&page=188
8.2. - Analysis of the corridor area

In order to deliver a clearer analysis, the physical influence area is going to be divided in two different parts. Area 1 affects the analysis of the sections connecting to the North Corridor and Area 2 concerns to the study of the airport link to the Northeast Corridor (Figure 8.5). Each corridor alternative will be evaluated according to the respective areas.

The territorial frames can be defined by the civil infrastructure in the region of the metropolitan area. The first frame (Area 1) is delimited by the highways R2 and M40 on the North, on the South by the highway M-11, on the East by terminal T4 and the airport runways and on the West by the HSR line Madrid-Valladolid (North Corridor). Area 2 is delimited by terminal T4 and the highway R2 on the North, on the South by the HSR line Madrid-Barcelona-Figueres (North corridor), on the East by the highways M45 and M50 and by the Jarama riverbed, and on the West by the highway M40.

8.2.1. - Territorial and geographical feasibility

The geographical frame is associated, on the South, to the Jarama and Henares river valleys within the general domain of the Tajo river depression. The valley areas are the principal conductors of the main transportation infrastructure in the metropolitan area. The rest of the area is mainly flat on certain height (650 m on average) on la Meseta Central (the plateau) starting to get steep on the North due to the transition towards la Sierra (mountain range) (Figure 8.6). This particular situation can be generally beneficial for the implementation of a HSR line as a cause of low slopes (in most of the area between 0 - 3% grades, as shown in Figure 8.7). In this urban frame, the high level of urbanisation and the existing infrastructure constraints will be more restrictive than the geographical and topographical conditions. In consequence a major part of the HSR infrastructure will entail the construction of tunnelled sections, which means a higher cost of the line.
The area in study is located in the East and North-East side of the second metropolitan ring of Madrid, included in the region Comunidad de Madrid in Spain (Figure 8.8). The metropolitan area gathers more than 90% of the population in Comunidad de Madrid. The North-East side, the so-called Corredor del Henares, is the second most populated area in Madrid, including high dense cities, like Coslada, Torrejón de Ardoz or San Fernando de Henares (Table 8.1), and corresponds to a heavily industrialised area. The field of action affects various municipalities of different kind, mainly large urbanised areas with generally high density agglomerations and a high level of development of infrastructures, principally highways, roads, railways and urban infrastructure.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcobendas (Area 1)</td>
<td>112,196 inhabitants</td>
<td>2,423.35 inhab/km²</td>
</tr>
<tr>
<td>Coslada (Area 2)</td>
<td>91,425 inhabitants</td>
<td>7,635.99 inhab/km²</td>
</tr>
<tr>
<td>Madrid (Area 1 &amp; 2)</td>
<td>3,207,247 inhabitants</td>
<td>5,396.94 inhab/km²</td>
</tr>
<tr>
<td>Barajas (district of Madrid)</td>
<td>46,089 inhabitants</td>
<td>1,038 inhab/km²</td>
</tr>
<tr>
<td>Hortaleza (district of Madrid)</td>
<td>173,966 inhabitants</td>
<td>6,023 inhab/km²</td>
</tr>
<tr>
<td>Mejorada del Campo (Area 2)</td>
<td>23,048 inhabitants</td>
<td>1,263.34 inhab/km²</td>
</tr>
<tr>
<td>Paracuellos del Jarama (Area 2)</td>
<td>21,128 inhabitants</td>
<td>421.87 inhab/km²</td>
</tr>
<tr>
<td>San Fernando de Henares (Area 2)</td>
<td>41,226 inhabitants</td>
<td>1,064.57 inhab/km²</td>
</tr>
<tr>
<td>Torrejón de Ardoz (Area 2)</td>
<td>123,761 inhabitants</td>
<td>3,784.78 inhab/km²</td>
</tr>
</tbody>
</table>

Table 8.1 Population and density of the municipalities affected by the planning of the airport HSR link to MAD airport. Source: Comunidad de Madrid, 2013 Register of inhabitants
8.2.2. - Geological and geotechnical feasibility

A general view of the geological characterisation of the area will support the general analysis of implementation of the new HSR line (Figure 8.9). In Area 1 the geology presents a quite homogeneous sedimentary stratum from the Miocene (Neogene) based on sandstone, clay and silt materials. There are some polygenetic terrace gravel materials from the close Jarama river valley. The composition of Area 2, placed on the Jarama riverbed basin and its surroundings, is constituted of heterogenic mixture of sedimentary materials mainly from the Quaternary. The granulometry is composed of sands and sandy silts on the river bed and gravel on the terraces. On the South of this subarea, there is a wider variety of materials with some intrusion of green clays, micaceous sands, dolomites and silex, as well as some gypsum, marl and clays.
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The geotechnical analysis is an important phase for the prevention of high risk areas of instability of the soils, especially in very high-dense urban areas. The identification and prevention of geotechnical dangers will facilitate the execution of underground sections, thus it will reduce the total cost and stability issues. In general, the zone in study is formed by low consolidated superficial formations nearby the Jarama alluvial deposits (San Fernando de Henares, Madrid and Paracuellos del Jarama) in behalf of its heterogenic lithology (Figure 8.10). The rest of the metropolitan area, except the river valleys, is distinguished for other soft rock formations (Tertiary) with a superior carrying capacity. The study concerning the expansive clay risk zones (in Figure 8.11) will be a key factor for the construction of the rail infrastructure. Area 1 and a significant part of Area 2 reveal a moderate risk of presence of expansive clays. Whereas, on the South part of Area 2 near Coslada, San Fernando de Henares and Mejorada del Campo exists a very high risk or even potentially instable zones or some recognised specific risks.

Figure 8.10 Map of geotechnical zones in Madrid metropolitan area. Source: Adaptation from IGME

Figure 8.11 Risk of expansive clays map in Madrid metropolitan area. Source: Adaptation from IGME
The planning of the HSR corridor layout should prevent the approximation to all high risk area for geotechnical issues or in any other case the special treatment of the rail structure, tunnel or viaduct with reinforcements and adequate geotechnical techniques. The general methods of execution allow a great adaptation to any kind of soil, although conducting the layout through stable zones will enable a more sustainable execution.

8.2.3. - Environmental and ecological feasibility

The following procedure will carry out a preliminary study of the natural & biodiversity corridors and other environmentally protected sites designed by Natura 2000 network or by the Regional Authorities. The objective is protecting the most threatened species and habitats in Europe in order to assure the long-term survival. This European Directive comprises the Special Areas of Conservation (SCI) designated under the Habitats Directive and the Special Protected Areas (SPA), which were designated under the Birds Directive (Figure 8.12).

Area 1 is almost out of any environmental constraint, excepting the Northern corner with Parque Regional de la Cuenca Alta del Manzanares which is assigned as a Special Area of Conservation. By contrast, Area 2 is affected by both Directives. On one side, the Special Area of Conservation (in pink) starts on the North edge following the Jarama riverbed and directing south reaching Parque Regional en torno a los ejes de los cursos bajos de los ríos Manzanares y Jarama (Parque Regional del Sureste). The Birds Directive Site is present at Parque Regional del Sureste as well. There are other minor protected areas, of less biodiversity importance, under the name of Habitats, mainly around the SCIs and SPAs and also in other small zones.

Both main natural areas, denominated as Parques, are part of Espacios Naturales Protegidos de España (Natural Protected Places of Spain). Parque Regional de la Cuenca Alta del Manzanares is an extension of the Monte del Pardo (Pardo Mountain) and its vegetation is a mixed of pine and holm oak forests, as well as pasture and meadows. Parque Regional en torno a los ejes de los cursos bajos de los ríos Manzanares y Jarama (Parque Regional del
The connection of Madrid-Barajas airport to the high-speed rail network is extended along the Jarama riverbed and its tributary Manzanares river. It contains a very rich riverbank vegetation and important species of aquatic birds (Figure 8.13).

Figure 8.13 The protected Natural Areas in Comunidad de Madrid. Source: http://ies.victoriakent.fuenlabrada.educa.madrid.org/Departamentos/GeografiaHistoria/geoespana/ComunidadMadrid/Geofisica.htm
8.3. - Analysis of alternatives

This part is developed pursuing not only a better connection with Madrid and its surroundings, but an improvement of connectivity and accessibility all over the country. For that purpose, the willingness of enabling direct access to all the HSR corridors of the network to the airport will be the ideal. The construction of infrastructure should be judged, designed and planned on its ability to generate infrastructure capacity, economic benefits and connectivity throughout the country (London Chamber of Commerce, 2011). For that commitment, the development of the technical and functional aspects of the resulting corridor will permit a decision choice under a wider vision, affecting the passengers’ efficiency and sustainable seamless door-to-door journey.

To execute the connection to the North corridor, allocated in Area 1, we define three corridor options (Figure 8.14).

- C1 departs from the crossing point of the HSR line with M40 and M607 motorways. It follows M40 on the east direction until the junction with R2 highway. The corridor continues the path of that highway and before overpassing M12 motorway turns south to access the airport terminal T4. The rail line will be overground from the beginning until crossing Puerta Norte road junction in a tunnel, and then it becomes underground again once it follows R2 highway from la Moraleja golf course prior and entering the airport terminal from the north.

- D1 leaves the North corridor near the A1 highway (Manoteras road junction) and it continues between the M11 motorway and the conventional rail tracks after crossing M40 motorway (Hortaleza node) where the tunnel starts underneath Valdebebas district until reaching the airport station from the south. This solution corresponds to the same layout as the current line of Cercanías. The routes could include a total conversion of the line or the construction of a complete new parallel section segregated from the suburban railway.

- D2 is similar to D1, although from Hortaleza junction it continues north direction following M40 motorway and then turning when crossing R2 radial highway. From this point it heads towards the airport following the same tunnel path as alternative C1.

Figure 8.14 Corridor variants for Area 1 connecting to the HSR North Corridor.
To the same end, there are for 4 alternatives in Area 2 to perform the airport link to the HSR line Barcelona-Madrid (Figure 8.15)

- A1 derives from the main HSR line in the vicinity of the Parque Regional del Sureste and it turns north to reach M45 M50 motorway. The line continues the same way as the Jarama riverbed and the motorway until A2 highway crossing point. From this point onwards and in the proximity of the airport influence area, the tunnel starts under the lower runaways and it continues underneath T4S terminal turning towards the terminal T4 and accessing the airport from its upper section.

- A2 instead of going north from A2 highway junction, it crosses San Fernando bridge towards the city centre following A2 highway direction. In Avenida de Aragón the rail line becomes underground turning north traversing Barrio del Aeropuerto, Alameda de Osuna, el Ventorro and Cerro Buenos Aires neighbourhoods, all part of Barajas district. After that, the tunnel crosses M13 highway and enters the terminal T4 from the south.

- B1&B2 starts in the vicinity of the crossing point of R3 and M50 highways and takes the way inside the city following R3. From the classification lay-by station of Vicálvaro turns north towards the Olympic Stadium la Peineta and the crossing point of M21 and M40 highways. It starts following the M40 until Avenida de América where it becomes underground. The tunnel crosses the East of the district of Barajas - Juan Carlos I park accessing the terminal station from the lower section.

Figure 8.15 Corridor variants for Area 2 connecting to the HSR Northeast Corridor.
The logical combination of the different alternatives will determine the 4 types of connections defined at the start of the chapter. The arrangement is supposed the co-existence with the current suburban line, C1, connecting to the airport, so no overlapping layouts. However, the spur line option contemplates the analysis for that alternative of adaptation.

8.3.1. - Length analysis

The different corridor layouts can be considerably unlike concerning the sort of airport link. The length variable can be particularly remarkable in extended metropolis due to the high level of urbanisation and the consequential construction of underground sections. This fact increases considerably the cost of the infrastructure and it will important in order to discern the final solution. To this end, Table 8.2 describes a first approximation of the route and tunnel lengths (and tunnel ratio) for each of the corridors and including all defined options, so that the decision can be determined. In order to do that it has been chosen an intermediate itinerary within each corridor band.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Alternatives</th>
<th>Length (km)</th>
<th>Tunnel Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor 1 (Main line)</td>
<td>A2+C1</td>
<td>26 (15.5+10.5)</td>
<td>10 (38%)</td>
</tr>
<tr>
<td></td>
<td>B1+C1</td>
<td>25 (14.5+10.5)</td>
<td>9.5 (38%)</td>
</tr>
<tr>
<td></td>
<td>A2+D2</td>
<td>25 (15.5+9.5)</td>
<td>10.5 (42%)</td>
</tr>
<tr>
<td></td>
<td>B1+D2</td>
<td>24(14.5+9.5)</td>
<td>10 (42%)</td>
</tr>
<tr>
<td>Corridor 2 (Branch line A/ Northeast corridor)</td>
<td>A1+B2</td>
<td>33 (19+14)</td>
<td>17 (52%)</td>
</tr>
<tr>
<td>Corridor 3 (Branch line B/ North corridor)</td>
<td>D1+C1</td>
<td>19 (8.5+10.5)</td>
<td>9 (47%)</td>
</tr>
<tr>
<td>Corridor 4 (Spur line)</td>
<td>D1</td>
<td>8.5</td>
<td>4.5 (53%)</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>9.5</td>
<td>5 (53%)</td>
</tr>
</tbody>
</table>

Table 8.2 Length and tunnel length for all different combination of HSR alternatives.

The most economical solution, in terms of infrastructure cost, would be adopting a spur line link terminating at the terminal station. The difference with the longest solution, the loop line linked at the Northeast corridor, would imply more than 28% of extra infrastructure. An average length for a main line solution, Corridor 1, would result a 25 km line. Corridor 3 solution would represent a lower route distance with 19 km. The penetration of the HSR line in the urban area should be also taken into account as the infrastructure cost would diverge according to the value of the tunnel length. The tunnel ratio reveals that for every option around 40-50% of the line will be underground. Corridor 4 remains as the lowest-priced option while Corridor 2 is longest tunnel section among all alternatives.

8.3.2. - Speed analysis

The maximum speed allowed in the North and Northeast corridors is 350 km/h, even though RENFE operates the trains with maximum speeds of 310 km/h. Nevertheless, near to the city and due to urban speed constraints and the close stop at the airport railway station, the maximum speed will not reach that value in the HSR airport link in project. The trains diverting from Madrid-Valladolid line at Fuencarral run at lower speeds than on Madrid-Barcelona line side, near Torrejón de Ardoz or San Fernando de Henares. In this last part, 20 - 30 km away
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from the departure in Puerta de Atocha, the trains limit the speed up to 250 - 300 km/h according to the speed diagram in Figure 8.16. On the north side, the merging of the airport link with the North corridors takes place at 2-5 km from Chamartín station, a section limited to speeds of 100 – 110km (Ferropedia).

For speeds of 300 km/h the trains need a minimum braking distance of 3.5 – 4 km whereas for speeds of 110 km/h just 0.5 km, considering a deceleration of 1 m/s². Taking this into consideration, analysing a feasible layout of the lines (with the correspondents minimum radius) and guaranteeing the speed limitations around the urban area on both sides of the airport connection a first estimation of the speeds is displayed on Table 8.3.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Alternatives</th>
<th>Reference Speeds (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor 1 (Main line)</td>
<td>A2+C1</td>
<td>120-200</td>
</tr>
<tr>
<td></td>
<td>B1+C1</td>
<td>120-150</td>
</tr>
<tr>
<td></td>
<td>A2+D2</td>
<td>100-200</td>
</tr>
<tr>
<td></td>
<td>B1+D2</td>
<td>100-150</td>
</tr>
<tr>
<td>Corridor 2 (Branch line A/ North-East corridor)</td>
<td>A1+B2</td>
<td>150-200</td>
</tr>
<tr>
<td>Corridor 3 (Branch line B/ North corridor)</td>
<td>D1+C1</td>
<td>100-120</td>
</tr>
<tr>
<td>Corridor 4 (Spur line)</td>
<td>D1</td>
<td>100-120</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>100-120</td>
</tr>
</tbody>
</table>

Table 8.3 Estimation of the speed of the trains for all different combination of alternatives.

Concerning the analysis of the maximum speeds allowed in the mentioned alternatives, it can be demonstrated that the top speed reached in Corridor 1 will be higher than in the other alternatives. The connection through a main line generally allows longer maximum radiuses for the infrastructure and consequently an increase in the speeds of the trains in service. Corridor 2 presents similar speed values due to the connection exclusively with the Northeast corridor, which enables higher speeds nearby the junction. However, the proximity of the airport to several high-dense urban areas will constrain the cruise speed anyways. In this rail project the speed is not the strictest decision variable in order to select the most appropriate alternative.
8.3.3. - Travel and connection times’ analysis

The following part pursues comparing the different travel times from four different cities, each of which is located in a different high-speed line, to MAD airport via the four proposed alternatives and its subsequent variants. The journeys are analysed applying direct connections (non-stops and no transfer) from point to point, and the average speed for the route will be calculated from the minimum travel time of the existing routes (on Table 4.2) and applying the rail distances (from Table 4.1). For those corridors in which there is no direct connection at this stage, the travel time estimations take into consideration the future tunnel between Puerta de Atocha and Chamartín and the additional requirements to complete the continuity of corridors. In that case the average speed considered in the calculation will be estimated as 90 km/h for the tunnel section and the HSR sections in the urban area between Chamartín and MAD airport. The results are displayed in Table 8.4, highlighting in bold those connections through the project for 2015 (tunnel and duplication of tracks), detailed at the end of chapter 4.

<table>
<thead>
<tr>
<th>Times to MAD airport</th>
<th>Alternatives</th>
<th>From Zaragoza (h:min)</th>
<th>From Valladolid (h:min)</th>
<th>From Sevilla (h:min)</th>
<th>From Valencia (h:min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor 1 (Main line)</td>
<td>A2+C1</td>
<td>1:11</td>
<td>0:57</td>
<td>2:36</td>
<td>1:54</td>
</tr>
<tr>
<td></td>
<td>B1+C1</td>
<td>1:13</td>
<td>0:57</td>
<td>2:36</td>
<td>1:54</td>
</tr>
<tr>
<td></td>
<td>A2+D2</td>
<td>1:11</td>
<td>0:58</td>
<td>2:32</td>
<td>1:50</td>
</tr>
<tr>
<td></td>
<td>B1+D2</td>
<td>1:13</td>
<td>0:58</td>
<td>2:32</td>
<td>1:50</td>
</tr>
<tr>
<td>Corridor 2 (Branch line A/Northeast corridor)</td>
<td>A1+B2</td>
<td>1:12</td>
<td>1:19*</td>
<td>2:25</td>
<td>1:42</td>
</tr>
<tr>
<td>Corridor 3 (Branch line B/North corridor)</td>
<td>D1+C1</td>
<td>-</td>
<td>0:57</td>
<td>2:36</td>
<td>1:54</td>
</tr>
<tr>
<td></td>
<td>D1</td>
<td>-</td>
<td>0:58</td>
<td>2:31</td>
<td>1:49</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>-</td>
<td>0:58</td>
<td>2:32</td>
<td>1:50</td>
</tr>
</tbody>
</table>

Table 8.4 Estimation of the travel times to MAD airport from four stations within the HSR corridors.

The results demonstrate that at this stage the option of branch line, via de Northeast corridor provides direct access to the airport from 3 of the high-speed corridors, excluding the North Corridor which is highly penalised. An additional general observation is that the entrance in the city, via the tunnel, can be penalised by an extra 5 - 10 minutes, although considering no yield nor stop time.

The estimation of the length of the different corridor plus the obtainment of approximate values of the average speeds in the corridors allows a rough calculation of the time savings or growth for each alternative. To this end, the different alternatives for the airport link provide several direct interregional connections between Spanish cities, through MAD airport, which are going to be evaluated. In the first instance, this section evaluates the connections between some illustrative point-to-point relations, the travel time comparison for other intermediate destinations can be simply presumed from the resultant saving time percentages.

In the first solution through a main line (Corridor 1) is evaluated the time saving of a Valladolid-Barcelona direct connection, through the airport main line, displayed on Table 8.5. While other direct connections remain faster via other existing by-passes, the connection between the North and Northeast is the only practical to study. The comparison calibrates the
difference in time between the current fastest high-speed connection\(^1\), which corresponds to 5 hours, and the expected new journey time. The existing high-speed connection implies the interchange time needed between the arrival at Chamartín (from Valladolid) and the next departure from Puerta de Atocha to reach the final destination. Furthermore, today the trains performing this connection stop at every intermediate station for all the routes, so the average speeds considered in the analysis are lower than for a non-stopping connection. Hence, for the estimation of the new times will consider an average speed for the North Corridor (until MAD airport) of 165 km/h and for the Northeast Corridor (until MAD airport) of 196 km/h. This measure is taken in order to compare the times under similar service conditions, so providing a reasonable and moderated result. In any case, the distances can be extracted from Table 4.1 and the previous length analysis in Table 8.2 to calculate the final times.

<table>
<thead>
<tr>
<th>From Valladolid to Barcelona</th>
<th>Current Time (hours:min)</th>
<th>Alternatives</th>
<th>Connection through MAD airport (hours:min)</th>
<th>Time variation (h:min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor 1 (Main line)</td>
<td>5:00</td>
<td>A2+C1</td>
<td>4:12</td>
<td>0:48 (-16.0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1+C1</td>
<td>4:14</td>
<td>0:46 (-15.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A2+D2</td>
<td>4:13</td>
<td>0:47 (-15.7%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B1+D2</td>
<td>4:15</td>
<td>0:45 (-15.0%)</td>
</tr>
</tbody>
</table>

*Table 8.5 Estimation of the variation of time between Valladolid and Barcelona for the alternative through main line (Corridor 1)*

The next analysis follows the same procedure as in the previous case for the calculation of the travel times. In this case, airport link via a branch line from the Northeast Corridor (Corridor 2) produces a different travel time for the relations between Sevilla and Zaragoza (as an example). In this case, though, there is no need of interchange due to the present direct connection through the by-pass in Madrid, avoiding the entrance in Atocha station. The distance of the current high-speed infrastructure, between Sevilla and Zaragoza, is 757.6 kilometres. So a reasonable estimation of the average speed for the point-to-point relation is equal to 206.6 km/h, which is going to be considered as a constant value for the new travel time. The results are represented on Table 8.6.

<table>
<thead>
<tr>
<th>From Sevilla to Zaragoza</th>
<th>Current Time (hours:min)</th>
<th>Alternatives</th>
<th>Connection through MAD airport (hours:min)</th>
<th>Time variation (h:min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor 2 (Branch line A)</td>
<td>3:40</td>
<td>A1+B2</td>
<td>3:46</td>
<td>0:06 (+2.7%)</td>
</tr>
</tbody>
</table>

*Table 8.6 Estimation of the variation of time between Sevilla and Zaragoza for the alternative through branch line (Corridor 2)*

The resultant travel time, slightly higher than the original one, could be neutralized by the increase of demand for the service as a consequence of an additional stop in MAD airport. Analysing other relations would carry out the same proportion of time variation.

The next case, the airport link via a branch line from the North Corridor (Corridor 3) would not represent a difference in time connection between other two points, because at this time

\(^1\) All current travel times are extracted from the point-to-point relations offered by RENFE operator under a single ticket.
the North Corridor is not connected to any other high-speed lines. In any case, it would suppose a rise of the travel time, as it follows for the previous case.

The last alternative (Corridor 4), as a spur line, is not considered for the reason that the supply of substitute point-to-point relations is not provided, thus there is no comparison to be established.

8.3.4. - Functional analysis

The assessment of the alternatives continues with the functional consequences derived from the new infrastructure, concerning the improvement of connectivity and integration of MAD airport in the rest of the Spanish transport system. For this purpose, it is relevant considering a qualitative research of the number of daily high-speed trains stopping at the airport as well as the total of destinations supply from the station. Hence, it will be analysed the description of the benefits to encourage a successful intermodal connection at terminal T4.

**Corridor 4** (Corridor D1) corresponds to the current proposal of the Spanish Ministerio de Fomento reconverting the current suburban rail line allowing the circulation of HSR trains. The alternative could be a transitory solution concerning the present economic and financial crisis. This solution would be more economically viable than a loop line, in the short term, and it would still optimise journey times. On the other hand, the local rail service should be altered or cancelled endangering the local connectivity of the urban areas of Valdebebas or Fuente de la Mora. In any respect, the transport system has to be planned under a long term vision, promoting a sustainable transport development for users and the rest of stakeholders. A spur line with a dead-end station at the airport would suffer of low frequencies and the connectivity benefits and potential for a transport modal shift could be highly insufficient. With the actual rail configuration and after finishing the tunnel between Puerta de Atocha and Chamartín stations, the North and Northeast corridors would not obtain direct access to the airport. To face that problem, another rail line should be constructed in order to link the city tunnel with the Northeast corridor and a new by-pass coming from the North corridor to link to the airport line. The reduced size of the airport railway station, compared to terminal stations like Chamartín or Puerta de Atocha, and the need of reversing the trains is another inconvenient that restricts the operability and capacity of the airport rail terminal.

The most usual airport connections in Europe are given through a direct access from the main line, like in favourable airport links at CDG, FRA, AMS or BRU airports. This solution enhances the connectivity throughout the country and promotes a much better range of services. A through line allows services to/from the airport in both directions. As well as the cost of running services will be much less if diverting an existing AVE service through the airport instead of the inconvenience of having to reach the airport, reverse and out again on the same track. The supplementary attraction given in this case would be also the commuting service to make cross-country connections avoiding the entrance in the city. **Corridor 1** would integrate MAD airport in a bypass line linking the North and Northeast corridors (or/and the rest of HSR corridors). This alternative would be a similar solution to the TGV Interconnection line serving CDG airport in Paris since 1994, which has been a successful strategy of air-rail intermodality and interconnection of the different regions in France without crossing the capital. The wide range of possible connections with Spanish cities and with a high frequency
The connection of Madrid-Barajas airport to the high-speed rail network

service is the valuable characteristic of this alternative. The proposed variants include the connection to the Northeast corridor towards Barcelona and the connection to the North corridor, also able to divert to Chamartin station in order to link up with the future tunnel to Puerta de Atocha, and thus to the rest of HSR corridors. The by-pass structure is projected within the North Corridor due to the lack of a direct connectivity with the rest of HSR lines. Railway by-passes are already implemented or projected for the rest of corridors, so the duplication of rail infrastructures is unnecessary and redundant. Avoiding the entrance in the city (Puerta de Atocha and/or Chamartin) would certainly reduce the travel time, but the loss of demand would not justify the actuation.

The loop lines alternatives are an intermediate situation between Alternative 1 and Alternative 4. They achieve an improvement of frequencies compared to a spur line alternative. However, the connectivity between corridors would not be as effective as the first solution. **Corridor 2 and Corridor 3** would give direct access to the airport from the North or Northeast corridors, respectively. The practically completed construction of the tunnel connecting the stations of Puerta de Atocha and Chamartin will indirectly connect both corridors, but increasing the travel time derived from the entrance in the city with two intermediate extra stops. However, we are going to analyse the alternatives accepting and relating to the infrastructures already finished or in construction. Corridor 2 would result as an inaccessibility of all the regions served by the North corridor, unless a connection between the Northeast corridor and the North corridor is finally effective. In contrast, the immediate consequence of choosing alternative Corridor 3 would be the absence of a direct connection for the population served by the Northeast corridor. Furthermore, the relative location of the airport in relation to the HSR lines and the territorial condition surrounding the airport debilitates a solution as a loop line.

The functional advantages of Corridor 1 are clearly more remarkable than in any other alternative. The main line rail link will also encourage the existence of a greater number of trains stopping at MAD airport. The resultant capacity of the airport connection through a main line will be the highest among the rest of solutions, and it corresponds to the most often airport link solution established in the rest of European airports.

**8.4. - Methods of construction and integration in the urban area**

The insertion of a rail line, especially HSR, in an urban environment represents the construction of sizeable tunnels of great length and considerably affecting the context where it takes place. The safety measures are extremely high in an urban area because the proximity of urbanization and buildings, the urban service supply networks, existing transport infrastructures and other spatial limitations and important surface disturbances. Conventional stability risks and feasible settlements of a heterogenic ground are the common issues to add to the urban constraints. For all planned alternatives the underground section length ratio is around 50% and it will have a direct effect on the final choice. The current economic condition suggests the adopting new formulas and rationalising the construction of tunnels in the entrance of urban nodes.
The tunnel cross-section will be a decisive parameter in order to establish the procedure of construction of the tunnel and the land occupation. This variable directly depends on the clearance gauge required by the high-speed train due to geometric parameters, and the aerodynamic effects derived from the top speed. Particularly, in urban vicinities the speed is limited, to maximum of 150-200 km/h, not only by the constrained line layout but also by the prevention of vibration and noise issues. For this reason, the tunnel cross-section can be substantially narrower than in non-urban environments. Hence, the clearance gauge, the rolling stock, the track gage and the establishment of electrical, signal and safety systems will determine the final tunnel section. The design of the line requires a double set of international-gauge tracks for each direction, which can be in a single tunnel (Figure 8.17) or in two segregated ones. The analysis of both designs will depend on the urban impact caused by the emergency exits, not affecting the surface in case of a bitunnel solution, and the duration and cost of the work, more reasonable for a single tunnel. An example of urban tunnel for HSR lines in Madrid, which connects Chamartín and Puerta de Atocha stations, selected a monotube configuration with a pair of tracks. The adaptation to UIC gauge of the current suburban rail tunnel connecting MAD airport for HSR trains gives another example of a feasible cross-section.

![Figure 8.17](image.jpg)

*Figure 8.17 Cross-section of the tunnel for the rail connection between Chamartín and T4-Airport.*

*Source: Ministerio de Fomento*

The construction of tunnels in urban environments is one of the most restrained executions within the development of a new HSR line. The trains will run maximum depths of 20-30 metres underground and the drilling in soft and low consolidated soils, such as the ones in Madrid metropolitan area, entails strict geotechnical measures of stability in the working face and in the vault, gable and the inverted vault. Furthermore, we have to dimension the problems resulting from the urban constraints, such as settlements, in order to prevent structural building failure or the underground services above the tunnel.
The traditional method for drilling the metro tunnels in Madrid has been the so-called “Belgian Method” ensuring a better stability of the heading. The appearance of sand pockets in the geological layers is quite usual in Madrid ground. This method suggests the slowly execution of superficial tunnel faces, with reduced dirt moving, thus promotes an exhaustive control of the safety of the constructive procedure. In the construction of the conventional rail line connecting the airport the tunnel construction has followed this process, as well as the majority of tunnels in the metropolitan region. Another classical method used in Madrid for difficult and accurate drillings is the tunnel between cut-off walls and cut-and-cover process, normally used for the transition zones. The mechanical method applied for long tunnel across urban areas in Madrid is the TBM (Tunnel Boring Machine) method. This tunnelling process used an EPB (Earth Pressure Balance) machine to drill the clayey soil between Puerta de Atocha and Chamartín along the centre of the city. The tracks gage was 4 metres long and the tunnel diameter was almost 12 metres. The EPB tunnelling machine was also used to drill the 2.5 km long tunnel between Barajas – Aeropuerto T4 for the Metro line 8 in 2007 and other sections in the same area.

The route in the surface produces effects in the urban area which can be substantial and mitigation measures should be adopted. The visual and noise impacts are the first predictable effects that have to be evaluated. The open-air sections, principally the transition zones, require of special attention in order to minimise the impacts on the land, the landscape and the urban functionalities such as paths, roads, highways, etc. and then integrate the different sections of the rail line. The crossing points with existing linear infrastructure are a critical part of the project of the line. In addition, those sections right beside the building borders are potential high alteration areas, principally for lines across different activity areas. The fragmentation of urban and rustic areas, produced by the barrier effect, creates negative social and environmental consequences which alter the integration of the territory and has to be minimised.

Additionally, the route in the surface will consider the noise impact, although the speed of trains (between 100 and 200 km/h depending on the section) is not comparable to high speeds of around 300 km/h in the corridor. Nevertheless, the implementation and integration of permanent noise reduction solutions, like acoustical barriers or other walls, is preferable for susceptible sections very close to the building facades in order to apply corrective measures to provide soundproof protection. Those HSR variants in tunnel sections will contribute to minimise the noise nuisance in most of the route and deriving the routes for lower urbanised areas.
9. - Intermodality and integration of HSR services at MAD airport

9.1. - Introduction

After analysing different examples of HSR connections at different airports in Europe, there are different indicators to take into account when the intention is to succeed in the air-rail intermodality. The transfer time is the key parameter for the supply of a good level of service and the attraction of users to perform the intermodal process. The minimum time, including all processes, should fluctuate between 45-60 minutes of connection between the HSR station and the aircraft (Figure 9.1). The transfer between the HSR and the air transport could be assumed as an analogous process to the air-air users with optimal connection times. Thence, the intermodality at MAD airport will be mainly considered by the temporal integration, though the spatial and functional integration of the HSR rail station on the terminal T4 are influential features of the temporal side of the interchange. The measurement of intermodality is added up by different factors which affect to all the components to create a fast, reliable and high-capacity form of the transport performance. The European Commission (White Paper, 2001) defines three main elements that describe an intermodal integrated scenario:

- Ticket integration
- Baggage handling
- Continuity of journey

There can also be identified 4 different fields of action that influence the organisation and success of the intermodal connection and integration between the HSR and the airport (Duarte Costa, 2012). Each of those plays a different role in the performance of the transfer scenario.

The PITVI (2012) report developed by Ministerio de Fomento in Spain for the 2012-2024 period states the required actuactions to do in the airport co-modal node towards a HSR (long-distance) and air transport intermodality following the next principles:

- Connection of nodes: studying the profitability of direct connections with private funding.
- Integrated information: intermodal centre of information at the airport as well as at the railway stations.
- Coordination of services: according to the services supply of each mode and the volume of intermodal passengers
- Other measurements: particular treatment of the intermodal user at the check-in points (including baggage handling) and security screening.

The customers’ perspective of the intermodality and the previous description of factors that affect the level of integration provided will establish the standards of the implementation. Therefore, the design and construction of the rail infrastructure connecting MAD airport, discussed in the previous chapter, has to be correlative with the succeeding assessment of an
The connection of Madrid-Barajas airport to the high-speed rail network

intermodal strategy. After the strategy description, the agreement between all implicated actors and the introduction of an effective intermodal product will be the practical application in order to implement the co-modal scenario.

9.2. - Intermodal infrastructure & transport services

The integration of transport modes is mainly related with the existence of a high quality connection between the HSR station and the airport terminal(s), which has a direct influence on the journey continuity. One of the strengths of the present connection at terminal T4 is the actual interface design of the interchange point for the different modes of transport in order to minimise the walking time and length. As well it provides complete assistance and accessibility for persons with reduced or limited mobility. The access time from the airport railway station to the terminal facilities is below 5 minutes, which is assumed as optimal. In this present case, the railway platforms are perfectly integrated in the terminal building on the basement level -2. The terminal is designed in such a way that eases the vertical access to all the required facilities at the airport (Figure 9.2). On a vertical section the interchange for other modes of transport is easily designed with private vehicles and taxis for departure on level 2, buses and taxis for arrivals on level 0, metro and suburban rail services on level -2 and the APM (Automatic People Mover) connector to terminal T4S, also on level -2.

The connection to the rest of the old terminals at the airport (T1-T2-T3) is already provided with a bus service free of charge departing from level 0 and reaching the old terminals in no more than 10 minutes (Figure 9.3). Also the connection is established through the line 8 of the underground network with a journey time of 9 minutes on peak hour weekday.

Reaching the satellite T4S from the terminal T4 would imply an additional 3-minute trip once the check-in and security check processes have been completed.

Figure 9.1 Diagram of the minimum times of interchange and access between the rail and airplane and vice versa. Source: l’Hostis, 2008

Figure 9.2 Cross-section of the intermodal interface in T4 terminal (MAD airport). Source: Adaptation from IBERIA
The rail capacity of the HSR station will be evaluated by the number of passengers using the intermodal facilities. An indicator to evaluate that purpose will be the number of HSR services per day supplying the airport. An acceptable number of frequencies to create a successful intermodality will be at least one service per hour and direction. The low number of frequencies like in LYS airport reduces the chances of success in a co-modal scenario. At hub airports like CDG, 60 trains a day stop at the TGV station, or in FRA airport, with more than 160 daily trains, the intermodality between the HSR and the air transport implies effective results.

With the intention of stimulating the air-rail connection, the number of direct connections (sizeable urban agglomerations) served by the rail from the airport should be the highest possible. The interest is promoting good connection opportunities with the rest of Spain. The by-pass line through MAD airport will create a potential connection with all the cities with a travel time not exceeding 2.5 or 3 hours. Therefore, the majority of HSR routes from Madrid can be covered within that boundary. Apparently, once the Spanish HSR network is completely developed throughout the country the number of potential connections from the capital will be higher than 45. This means that Madrid will be connected to every single capital of province within the Iberian Peninsula. Particularly, the high-dense populated regions in Spain, near the Mediterranean or Atlantic coast, are the most desirable to link up. Finally, the future corridor from Madrid to Lisbon could enhance many more links with some Portuguese areas.

9.3. - Intermodality actors

The original unimodal framework of the transport in Spain derives in one of the main barriers to insert an integration operational system from a co-modal or multimodal point of view. The permanent practices and strategies of both air and rail companies have led into a specific
The connection of Madrid-Barajas airport to the high-speed rail network

The evolution of each market instead of a common perspective of transport development. Airline alliances, the abandonment of environmental limitations and a non-extensive HSR network reinforces a segregated point of view of each transport markets. A new perspective of the stakeholders involved is needed in order to cooperate with new requisites and best practices of both modes to be retained as the intermodal ones.

The number of actors and public institutions can be a barrier when addressing an intermodal agreement as it can be really high, including airlines (IBERIA or Oneworld alliance), rail operators (RENFE), airport managers (AENA), rail infrastructure operators (ADIF) and other city managers & high level policy makers. A multi-stakeholders scenario entails the responsibility to achieve cooperation and coordination of the agents, essential to promote the intermodality. Each actor’s commitment in the difficult operation process and a regulation coordinator or authority will be a key factor for the success of the air-rail intermodality (Duarte Costa, 2012).

As observed in chapter 7, the number of intermodal operators (rail and air) in MAD airport connection would be principally 2: the Madrid based airline, IBERIA, and the rail operator, RENFE. The air transport liberalisation has opened the market to a wide range of alternative companies, especially influential low cost airlines at MAD airport, like Vueling, Iberia Express, Air Europa, Ryanair or Norwegian, or other international airlines like British Airways, Air America, Air France or Aerolíneas Argentinas, good part of them part of different airline alliances, like Oneworld. Simultaneously, the future prospective for the liberalisation of operation of the rail services in Spain for different companies would enable the incoming of more operators articulating the considered intermodal product. This fact would enable the removal of major differences in infrastructure cost coverage. AENA has the aim of negotiating and garnering the links with airlines and coordinating the airport hub strategy. The Spanish rail infrastructure operator, ADIF, is responsible for the implementation and maintenance of the rail infrastructure, as well as providing the rail slots. Finally, the Spanish government, also part of the companies’ structure of the rest of actors like Iberia, RENFE, AENA or ADIF, is the authority in charge of the regulation, control and coordination of the proficiency of the transport system. Further territorial, economic and social national, regional and local authorities are involved in the process and will influence the decision makers.

The market liberalisation of railway operators, the development of interoperability of European rail networks, the establishment of an effective pricing strategy and the implementation of the information and communication technology in the transport sectors are indirect fields of action that are directly linked with the operators and the transport policy makers in order to stimulate the intermodality.

9.4. - Intermodality interface and organisation

The following part gives details about the code-sharing agreement for the rail and air operators creating a shared product, like in FRA or CDG airports with products like AIRail and TGV Air respectively. The total transfer time in MAD airport should be completed in no less than 55 minutes within the terminal T4, or 65 minutes between the T4 and its satellite T4S
The final obtaining of an intermodal product will be an important driver of the intermodal journey and, thus, a sign of the level of the service (LOS).

The existence of an integrated ticket issued by the intermodal agreement operators will contribute to the ease of transfer and the enhancement of intermodality. The use of integrated ticketing is already active for airline code share agreements and airline alliances allowing the air-air transit. The booking and purchase of a single ticket covering all legs of the journey will entail a strong agreement of the operators involved, particularly in this case, RENFE and IBERIA or other airlines. It will imply a complementarity of both modes for a particular route concerning a common time reliability in the process and a possible shared baggage handling and responsibility. The system will be additionally improved with common online ticket distribution: ticketless options, the use of electronic ticketing for electronic devices (e-ticket) or the implementation of fast ticket pick-up at the intermodal station/terminal through specific ticket machines. The strict air security protocol for passenger and baggage is not compromised by e-ticket check-in.

A common operator arrangement implies the creation of framework conditions to share marketing costs and offer discounted prices to the passengers. The commercial strategy is important in order to communicate and consolidate information for the international HSR-air customers. Providing clear and up-to-date information, a journey planner or online reservation system are strategic decisions in the attraction of new users.

The system of check-in & baggage procedure in the transfer can be determinant in the success of the intermodality as it affects the transfer time of connection between modes. Different systems for integrated airports can be defined, which are associated to the baggage security screening options either at the airport terminal or at the rail station. The high degree of security controls at the airports is clearly distinct to the system applied at the HSR sector with a minimal passenger and baggage security protocol. A time-minimising and cost-effective option will have to balance the security regulation in order to implement an optimal solution for the check-in & baggage drop-off processes. Theoretically, a stricter security system introduced in the rail would mitigate that concern. This measure would imply offering baggage screening at the rail stations, its adaptation to aviation security standards and thus providing an easier rail/air baggage handling on the same basis. Creating a new common security screening framework and regulation would be very much positive for the integration of modes.

The end-to-end check-in availability at the rail station could also provide common luggage handling for the users. According to transport intermodality surveys, intermodal passengers evaluate a common baggage handling as a high quality level of service (LOS). The establishment of check-in desks at those HSR stations receiving major passenger traffic and ticket counters at the station of origin will stimulate the efficiency of the entire process. However, the luggage acceptance process at the rail station raises future air security issues and considerable operational difficulties, which may cause delays at the train journey, and high investment and operating costs. This is because a physical separation is needed based on secure baggage carriages on the trains to convey the hold luggage, as well as an extra physical infrastructure for security checks, check-in and drop-off facilities at the origin HSR station. Main integrated products don’t offer this service unless it implies an additional cost for the
passenger. A similar check-in facility was originally incorporated by IBERIA at Nuevos Ministerios metro station in 2002, although it was eventually withdrawn due to some transfer time issues and the use of very few passengers, as commented on chapter 6.

The planning of the complete check-in process would depend on the air-rail baggage passenger requirement. At least, baggage-less and carry-on passengers should be able to check-in for the end-to-end trip at the origin point. To this end, enabling ticket counters at any rail station of the catchment area will allow shortening the interchange time between the airport rail station and the terminal. On the other hand, adopting this measure would increase the waiting time at the rail station, but it should still save time for the user compared to the long airport check-in, as it requires a reduced deadline time and there are not as many users as in the airport.

The establishment of **self-check-in and rapid baggage drop-off desks and kiosks** for customers with baggage could also invigorate the use of the air-rail interchange. The intermodal agreement could implement a sufficient number of specific counters at the airport railway station lobby towards an easier physical connection and a reduction of the waiting time. Additional information points, exclusive security screening gates and passport controls for all intermodal users could also complement the counters. One possible issue is the creation of queues subject to peak demands and it could be addressed by the use of usual check-in desks. A greater level of service would be offered with not excessive implementing cost, and representing a low security risk, higher efficacy and shortening the waiting time of the passengers.

The facilities set-up should follow the principle of short walking distance between the HSR mode and the service facility and in logical progression for the principal user group. The structure could be similar as the already implemented in T4 terminal on the route Madrid-Barcelona (*Puente Aéreo*) allowing passengers of IBERIA to show up 20 minutes before the take-off. However, the process is not equivalent to the current one as it is based for domestic flights, and the international flights, especially out of Schengen zone, require a more complex procedure with passport checking and longer waiting time.

An outline of the check-in & baggage drop-off & boarding circuit could be planned as described in Figures 9.4 and 9.5 using the present terminal interface and creating a distinctive route for intermodal passengers arriving by HSR at the airport railway station and transferring to a long-haul flight. As previously mentioned, the design of the T4 facilitates an organized track for intermodal users flow with a relative short walking time and a bit longer (around 10 minutes) in case of the need of departing from the T4S. The outline description focuses on the departure path because of the longer time of accomplishment due to multiple events, unless unexpected delays or operational issues on the inbound baggage claim. However, the arrival process would be analogous to the departure one, as shown in blue.
Figure 9.4 Cross section of the airport interface in T4 terminal (MAD airport) addressing the rail-air intermodal passengers. Source: Adaptation from Hesse, 2008

Figure 9.5 Ground plan of the intermodal interface in T4 terminal (MAD airport) for intermodal passengers. Source: Adaptation from Hesse, 2008
One of the major factors affecting the transfer time and waiting time between modes is the establishment of a **scheduling coordination** between train arrival and flight departure and vice versa. This element will contribute to the realisation of the intermodal operation as well as to the definition of the integrated transfer time. Both services will have to match their respective timetables in order to arrange the intermodal offer taking into account the entire transfer time required for the interchange (normally over an hour) and offering a competitive travel time. It is a similar case to the air-air transit facility which is normally offered as a coordinated product and the information related the timetables has to be clearly noticeable for the customers throughout the journey. In order to succeed in that fact it will be important high air and rail frequencies as well as a strict punctuality and reliability of the service.

The graphic shows the number of departures and arrivals of Iberia flights during the day. This information will enable the establishment of minimum rail frequencies in order to serve the in/out demand for different time intervals. For this purpose, it would require the consideration of the transfer time necessary to perform the entire interchange process. An example of minimum HSR frequency according this flight distribution could be the following, as shown in Figure 9.6:

- Departures from MAD airport station: 08:00; 09:00; 10:30; 12:00; 13:00; 15:30
- Arrivals to MAD airport station: 10:00; 12:00; 12:30; 14:00; 16:00; 23:00

![Figure 9.6](image_url)

*Figure 9.6 Number of Iberia arrivals (bottom graph) and departures (top graph) flights throughout a day.*

Source: Nombela, 2010

The **reliability** is one of the main transport attributes concerning the transport agreement and the assistance offered is notable in case of delay or cancellation. The provision of updated information and the commitment acquired by any intermodal operator is only possible when a high level of synchronisation is adopted by the agreement actors. The coordination between HSR and airplane has to be ensured in such a way that high frequencies are provided or a stricter control of the punctuality is guaranteed to prevent from a missed connection happening. Concerning high-speed trains in Spain, the delays were 0.37% of the total number and only 0.32% of the passengers journeys were altered by delays in 2010. Therefore, the
actual high punctuality on AVE trains will lead to reinforce air-rail connection, instead of air-air, and then a beneficial impact for air-rail intermodality. On the other hand, the scope of airport regular delays is more difficult to address due to the worldwide congestion of the air transport service and airports. In MAD airport the delays account for 11-14 minutes on average which can be increased in case of reactionary delay. In that case, the ticket flexibility and an airline agreement strategy of refunds could redirect the permanent issue.
10. - The demand and economic analysis of MAD airport link

10.1. - Investment costs

The economic cost associated to the construction of new HSR lines implies very high investment costs, and the average cost per km generally ranges from €10 to €40 million concerning all orographic circumstances and the great diversity of local elements influencing the construction (de Rus, 2012). Table 10.1 displays the total infrastructure cost of the main HSR lines in Spain and the cost per unit length (kilometre of double track platform), as well as the current airport link to the airport (not a high-speed line). As previously said, the figures are high and diverse compared to other conventional railways (non-tunnelled) due to the complexity of works and specific technical requirements for each section and route. Different elements constituting the infrastructure are related to different costs (Table 10.2), like the platform accumulating more than 60% of the total investment. If important tunnelling works are required for the infrastructure, the general cost increases as observed in Madrid-Valladolid line (North Corridor) with high mountains outlines or the line to the airport with half of its length in urban tunnel. These construction costs exclude planning, land costs and construction of stations.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Cost (€ million/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail</td>
<td>1.7-2</td>
</tr>
<tr>
<td>Platform</td>
<td>5-15</td>
</tr>
<tr>
<td>Electrification</td>
<td>0.8-1.3</td>
</tr>
<tr>
<td>Signalling</td>
<td>1.1-3.3</td>
</tr>
</tbody>
</table>

Table 10.2 Cost of elements part of a HSR line in Spain. Source: Palao, 2013

For the airport link planning, aspects like urban integration, coordination with other infrastructure, tunnel length ratio or geological characteristics of the ground are indicators which considerably modify the final cost of construction. The current planning phase assumes as much as possible the avoidance of an excessive use of the economic resources, rationalising the quantity of tunnel sections, which can be between 10 or 20 times more expensive than surface platforms, and other possible variants which can difficult the implementation of the HSR lines. In that direction, the planning promotes the use of the current rail terminal at the airport (terminal T4) underground level whose rail tracks are already adapted to allow high-speed trains. The extension of the station or the construction of a parallel rail terminal on the

2 The capital cost of the high-speed line Madrid-Sevilla makes reference to the cost required in 1992.
side could increment the total cost. To illustrate the additional cost, Table 10.3 shows some contemporary investments to construct HSR station in Spain. General middle-size station costs range from €15 to €50 million, or even higher for more complex rail developments. However, in this case the passenger interface inside the air terminal is completed.

<table>
<thead>
<tr>
<th>Station Description</th>
<th>Total cost (€million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requena – Utiel station</td>
<td>12.4</td>
</tr>
<tr>
<td>Cuenca station</td>
<td>19</td>
</tr>
<tr>
<td>Albacete station</td>
<td>48</td>
</tr>
<tr>
<td>Girona (underground station)</td>
<td>25.7</td>
</tr>
<tr>
<td>Atocha (new arrival terminals)</td>
<td>171.4</td>
</tr>
</tbody>
</table>

Table 10.3 Cost of different HSR stations in Spain. Source: Data from Palao, 2013 and ADIF, 2013b

The next feature (Table 10.4) represents an estimation of the total infrastructure cost for each variant and assuming an extra cost in case of new station or extension needed for the rail terminal. The prices are evaluated according to the cost information above applying an average cost for the specific conditions of the future line for each alternative (length of line on the surface and tunnel length). The cost of construction of the line, considering the relatively high percentage of tunnel section, will be an average value considering the HSR lines constructed in similar conditions, with costs of approximately €25 million per km. The railway station cost prediction is established in relation to the station cost data above, it will considered an average extra cost of €30 million. However, this cost exclude the costs of all intermodal facilities like baggage desks, ticketing distribution, etc.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Alternatives</th>
<th>Infrastructure Cost (€ million)</th>
<th>Cost + Station (€ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor 1 (Main line)</td>
<td>A2+C1</td>
<td>650</td>
<td>680</td>
</tr>
<tr>
<td></td>
<td>B1+C1</td>
<td>625</td>
<td>655</td>
</tr>
<tr>
<td></td>
<td>A2+D2</td>
<td>625</td>
<td>655</td>
</tr>
<tr>
<td></td>
<td>B1+D2</td>
<td>600</td>
<td>630</td>
</tr>
<tr>
<td>Corridor 2 (Branch line A / Northeast corridor)</td>
<td>A1+B2</td>
<td>825</td>
<td>855</td>
</tr>
<tr>
<td>Corridor 3 (Branch line B / North corridor)</td>
<td>D1+C1</td>
<td>475</td>
<td>505</td>
</tr>
<tr>
<td>Corridor 4 (Spur line)</td>
<td>D1</td>
<td>212.5(^3)</td>
<td>242.5</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>237.5</td>
<td>267.5</td>
</tr>
</tbody>
</table>

Table 10.4 Capital costs of the different alternatives for the airport link and possibly incorporating the price of the station.

Furthermore, the investment cost should also incorporate other costs, which can be fixed to the rail service or variable according to the traffic intensity of the line. The infrastructure maintenance costs of a high-speed line are around 100,000 € per km and year (de Rus, 2012). Rolling stock costs encloses acquisition, operation and maintenance costs and they depend on the number of trains operating on the line, hence on the total demand of the line. The operation costs of high-speed services may include signalling processes, energy supplying, management traffic systems or labour costs. The total value of operating a train can vary.

\(^3\) The real cost was equal to 218.3 million €, although today it should be added to costs of adaptation of the conventional rail infrastructure which in total adds around 40-50 million €.
significantly depending on different factors like the load factor of the trains or the particular technology used by the trains. A rough estimation of the operation costs in Spain (adding operating and maintenance costs per AVE train) assumes around 0.1712 € (value in 2002) per seat and km of line (de Rus et al., 2009).

A value of the global investment cost required for the HSR should also include possible costs of expropriations, urban and environmental integration expenses, the planning and financial cost and the cost of supplement works, extenuation of impacts and externalities or other transport networks disturbances. Alongside, the external costs for a HSR are not zero. The external cost of a high-speed line is difficult to quantify because of a balance effect between the positive environmental impact of the substitution effect on air and road traffic or the improvement of the safety; and the negative side due to the high impact during the construction period, the barrier effects, noise and visual intrusion on the landscape, as mentioned in chapter 7. Overall, the key factor in turning the external cost favourable will be a high occupancy of trains and a not excessive long distance journey, which becomes less beneficial when the final distance of the route increases. Furthermore, in this particular case a high ratio of tunnelling will contribute to mitigate the negative impacts of the externalities and the favourable modal split towards the HSR in Spain also increases the load factors of the trains.

10.2. - The transfer of passengers from the HSR network to MAD airport

The number of passengers using the intermodal station in T4 terminal is difficult to calculate in detail as a result of the lack of data and surveys. This additional traffic transported by high-speed trains to the airport can be identified as the use of the train services to accomplish intermodality. There is not methodological analysis to follow in order to obtain an accurate value of the demand, and it is shown that demand calculations can result in a deviation of more than 106 % for railway projects (de Rus et al., 2010b). At the same time, the standard deviation is high for railway projects which also results in poor levels of accuracy in demand modelling processes. An estimation of the uncertainty of the demand forecast should be included in order to reduce the high prediction errors. For this reason the present estimation will follow a first approach considering the European experience, which can illustrate the intermodal phenomenon for this case. The traffic forecast will be evaluated for the first year of operation of the intermodal connection.

10.2.1. - Air traffic: origin-destination and access modes

First of all, the last survey (published in 2012) stated that 56.3% of passengers using the terminals were Spanish and 43.7% were foreigner. The transit air-traffic in the terminal was 33.2% of the total, corresponding to 15 million passengers per year. The main destinations of the users were principally Europe (43.3%), within Spain (34.5%) and Latin America (11.4%).

Private vehicles (car) was the most used transport mode to access the airport with 32.8% of the total, followed by Metro with 26% and taxi with 24.1%. The opening of the suburban rail
link to the airport in 2011 probably altered the distribution of passengers concerning the access transport mode.

The major motive of the journey was leisure and holidays for 40.3% of the total users of the terminals. 32.3% of the survey respondents corresponded to professional and business issues and 27.3% for personal matters.

10.2.2. - Air-rail intermodal traffic

Previous analyses to determine the intermodal traffic in similar European airports, like CDG airport in Paris, enable a basic estimation of the future intermodal demand in MAD. To exemplify the intermodal performance in a major international hub we will take a look at the figures for CDG airport, one of the most integrated co-modal places in Europe. The airport started to operate TGV services in 1994 and the table above (Table 10.5) displays the intermodal figures for the 5 different surveys during the period in service.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TGV station traffic</td>
<td>1.5 millions</td>
<td>2.4 millions</td>
<td>2.7 millions</td>
<td>3.4 millions</td>
<td>3.4 millions</td>
</tr>
<tr>
<td>Part of intermodality in the TGV station traffic</td>
<td>60%</td>
<td>67%</td>
<td>67%</td>
<td>73.5%</td>
<td>81%</td>
</tr>
<tr>
<td>Intermodal passenger</td>
<td>900,000</td>
<td>1.6 millions</td>
<td>1.8 millions</td>
<td>2.5 millions</td>
<td>2.75 millions</td>
</tr>
<tr>
<td>Air traffic</td>
<td>43.4 millions</td>
<td>48.3 millions</td>
<td>53.8 millions</td>
<td>60.5 millions</td>
<td>61 millions</td>
</tr>
<tr>
<td>Part of the intermodality in the total air passengers</td>
<td>2.1%</td>
<td>3.3%</td>
<td>3.3%</td>
<td>4.1%</td>
<td>4.5%</td>
</tr>
</tbody>
</table>

Table 10.5 The figures of intermodality traffic in CDG airport from 1999 to 2011. Source: Data from Ministère de l’Ecologie, du Développement durable et de l’Énergie

The traffic of the new HSR station in MAD airport would be composed of two different demands. The HSR point-to-point passengers belong to one part and the intermodal passengers are the second part. In the point-to-point market the users would use the station as local access for the area or as an interchange of trains for other rail destinations. HSR impacts in both markets the point to point and the transit traffic. The demand will modify its behaviour, depending on the integration of services, frequency and scheduling of the high-speed trains. To quantify an approximate value of the intermodal ratio (the second part), we can provide a conservative value for the use of the HSR-air intermodality within the total air transport traffic, comparing the evolution of traffic at CDG TGV station in Paris. The interest lies on the intermodal traffic exclusively generated by the airport link. The conservative tendency for intermodality in CDG airport, 5 years after the first service, shows a first ratio around the 2% of the total passenger’s traffic (Table 10.5).

Considering a moderate value of passengers in MAD airport, we can take a reference of the traffic in 2012 of 45.2 million passengers. The estimation of intermodality results in 904,000 passengers (a 2% of the total traffic) interchanging from the HSR and the air transport. The final figure, as previously mentioned, would be extended in this case by other point-to-point relations for all alternatives stimulating a national mobility apart from the alternative Corridor 4. On the other hand, considering an optimistic value of traffic in MAD airport, which is
estimated to be above 50 million passengers in 2018, the total intermodal flow corresponds to more than 1 million passengers. So as a result of the intermodal demand the passengers range between 900,000 and 1 million passengers for the first period of operation of the airport transit link.

In relation to the point-to-point passengers using the HSR line, the alternative as a spur line (Corridor 4) is exclusively limited to the demand transferring from high-speed trains to the air transport, so in this case there is no additional demand. For the two alternatives as a branch line (Corridor 2 & 3), the point-to-point relations would not represent a remarkable enlargement of demand, due to the growth of the total travel time as a result of the diversion of trains stopping at MAD airport. For instance, passengers travelling from Sevilla to Zaragoza would be excluded of the benefits of stopping at the airport, as observed in the time analysis of chapter 8. However, the modal choice for a specific route, following a discrete choice model, uses the utility function depending not only on the travel time cost for the user but other factors like the fares, comfort and other categorical variables for the choice. The airport connection can also represent a higher occupancy of trains if the travel times from both points are still competitive, because of the possibility of supplying also direct stop in Madrid urban area. The case denoting a more beneficial result for this demand is the solution through the main line (Corridor 1) offering a direct connection from North corridor and Northeast corridor, and also contributing to enhance a better occupancy of the trains due to the stop in MAD airport, and thus allowing a provision of service for Madrid.

Nevertheless, the traffic analysis should include further demand modelling methodologies to certificate the previous estimated quantity. The modal choice theory should be based on information of users preferences obtained by direct surveys in the terminal. This study includes a very basic qualitative estimation of the demand due to the limitations to obtain revealed data of intermodality choices. One constraint to develop this point is the lack of data for the demand disclosed in this project which is produced by the new airport connection. The approach of modal split between air transport and HSR should include attributes such as the corresponding level of services, among other comfort and reliability variables. Finally, advance risk analysis of the demand values according to different elasticity in relation to the travel time, the fare or the reliability and comfort, should perform different scenarios of demand.

10.3. - The economic evaluation of the intermodality at MAD airport

The economic evaluation of the connection of the high-speed network to MAD airport is an indicator of the differences between benefits and costs accomplished by the construction of the airport link. Some general benefits have been identified along the present paper, as well as the general costs of construction and operation of the infrastructure and the high-speed service during the life of the project. Concerning the construction of a new high-speed line and the services provided, the investment costs are high and the economic effect lies on the public sector. However, the relevant issue is not the representative high cost, but whether the society is willing to pay for this investment and thus, whether the social benefits of HSR investment are worth its costs (de Rus, 2012).
The lack of information of economic profitability of the HSR in Spain and the inaccuracy of both the costs and the demand result in an additional difficulty to evaluate the economic viability of the present project. Particularly, the uncertainty of the forecast of intermodal demand for the new airport link will be one the main drawbacks for evaluating the economic feasibility of the connection through a usual cost-beneficial analysis (CBA). The justification of the HSR costs will be confirmed by high social benefits, when the opportunity cost of the actuation validates the investment. A project appraisal tool to economically and socially evaluate MAD airport connection should be applied in order to establish a rational CBA analysis considering all effects interacting with all actors/stakeholders involving the project. This CBA appraisal should be complemented by a multiple-criteria decision analysis emphasizing those quantitative aspects in order to evaluate the project. The CBA analysis reflects whether the construction of the HSR line will be beneficial for all parts of society including users, operators and the general public.

The generation of benefits described along the paper should justify the high level of costs of the high-speed line. It is confirmed that the construction of high-speed line is acceptable under a certain amount of traffic that can cover all social costs in the construction and guarantees a positive value of social profitability and thus the economic feasibility of the project. Only a high level of intensity of traffic on the corridor will be capable of neutralizing the high investment cost of construction and operation of a HSR line. An analysis of the limit value of demand for a high-speed line, under specific assumptions, demonstrates how the benefits curve presents more sensitivity than the cost line as a result of the considerable weight of the fixed costs and particularly the infrastructure costs (Ingладa, 2005). Some alternative measures will enable an enlargement of the profitability of the high speed line:

- Reduction of costs of the high-speed line, principally the infrastructure cost. In this particular case, the adaptation of under exploited infrastructures, the less rigidity of the rail layout due to the speed restrictions or the moderation of tunnelling works will contribute to minimise the expected investment cost.
- The high level of development of the high-speed network in Spain will contribute to generate complementary benefits in relation to the network effect.

Obtaining a basic value of the approximate viability of the construction of the rail line will be the last stage in the present study in order to estimate an indicator of the interest of the execution. A simple orientation of this parameter can be accomplished by the fraction obtained dividing the capital cost required for the construction of the line by the forecasted demand (part of the social benefit). The indicator is calculated as a static analysis where the investment is produced in the year 0 and both social benefits and costs are obtained in the year 1. To simplify the calculation, the traffic of the new line will be evaluated as the intermodal traffic at MAD airport station, even though the value could be higher in those variants in which the connectivity between other HSR corridors through the airport is possible. Alternatives like Corridor 1, 2 and 3 where the airport link can be used by other passengers connecting to other points of the HSR network, contribute to a growth in the demand, especially for Corridor 1 enabling direct connections between all corridors. For this reason the demand will be considered as the upper value of 1 million passengers in 2018, previously obtained. On the other hand, Corridor 4 only enables direct access from the South and Eastern
The connection of Madrid-Barajas airport to the high-speed rail network

Mediterranean corridors (and North Corridor if constructing a direct junction to Madrid-Valladolid line). So in light of these assumptions, the cost-demand rate obtained will be the minimum achieved by the construction of the airport link as shown in Table 10.6.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Alternatives</th>
<th>Cost-Demand rate (€/pax)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor 1 (Main line)</td>
<td>A2+C1</td>
<td>680</td>
</tr>
<tr>
<td></td>
<td>B1+C1</td>
<td>655</td>
</tr>
<tr>
<td></td>
<td>A2+D2</td>
<td>655</td>
</tr>
<tr>
<td></td>
<td>B1+D2</td>
<td>630</td>
</tr>
<tr>
<td>Corridor 2 (Branch line A / Northeast corridor)</td>
<td>A1+B2</td>
<td>855</td>
</tr>
<tr>
<td>Corridor 3 (Branch line B / North corridor)</td>
<td>D1+C1</td>
<td>505</td>
</tr>
<tr>
<td>Corridor 4 (Spur line)</td>
<td>D1</td>
<td>236.1</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>297.2</td>
</tr>
</tbody>
</table>

Table 10.6 The estimation of the cost – demand rate for the airport link alternatives

In France the Eastern Interconnection line through CDG airport carried a real total investment of 1,397 € million (value in 2003), 88% of which relate to the construction of new rail lines. The rate per unit length (kilometre) considered the extension of the line, which is 57 km, corresponds to 24.5 € million per km. If we analyse an estimation of the cost-demand rate according the total intermodal traffic carried in the same year (we will use available 1999 data as it is the first accounting after the opening of the line), we obtain a 1552.2 € per user and year. However, as previously mentioned, this value is firmly lower because the line is used for numerous passengers interconnecting between French regions, reaching a value of 14 million passengers in 2005.

In Spain the Northeast corridor, between Madrid and Barcelona, reached a total investment of 9,000 € million for 621 kilometres of infrastructure. The total demand for 2011 using any route within the corridor (considering that in that year it was not operative the last part between Barcelona and the French border) was 5.2 million passengers. This value gives a ratio cost-demand of 1730.77 € per passenger a very much higher number compared to the previous estimations for MAD airport link.

The comparison to other major high-speed projects grants an advantageous position to MAD airport link within other European rail developments, contrasting the demand-cost rate. The estimation of this basic economic index presumably declares the construction of the airport connection as an interesting project in relation to the potential attraction of intermodal users.

Advance economic analysis should be developed in order to include the designation of an appropriate method to sustainably finance the application of the planning phase and especially to take into account the cost of financing the execution of works. This question of interest is particularly important for a high-speed line as a result of the investment provided by the public sector, particularly in a period of time where the executive administration is focused on the financial balance of great infrastructures significantly funded by the European Union.
11. - Summary and discussion of results

The accomplishment of the present paper comprehends all different elements originating the background with regard to the interest of the HSR-air intermodality at MAD airport and its general influence with the rest of Spain. For this purpose, in this last section, the summary of the features included in the analysis and the report of the conclusions are discussed to obtain the general outlook delivered by the study.

The HSR has become a notorious alternative transport mode in the major part of European countries, specifically in Spain where it is indentified as a different transport mode and, practically a technically segregated system, relating both a dedicated infrastructure and specialized rolling stock. High-speed trains incorporate last technological advances with strict distinctions in operational procedures and organization methods with other conventional rail systems. However, different modes of exploitation are operated in different high-speed systems. The HSR in Spain combines direct services and intermediate high-speed services originating the so-called mixed conventional model (de Rus et al., 2009). The particularity of the Spanish high-speed system confers to the new mode an advantageous capacity capable of giving a considerable add value to the passenger. On the other hand, the supervision and promotion of sustainability objectives, regarding both construction and implementation of the high-speed lines, is important in order to achieve the efficiency requirements of transport systems. The generally high economic investment and the public sector support enjoyed by most of HSR undertakings should attempt to give priority to low external costs of the HSR providing a balance in regards to the improvement of safety, environmental and congestion transport patterns.

In order to summarize the analysis of the feasibility and the multiple circumstances affecting the possibility of connecting MAD airport to the HSR network, it is relevant to point out the potential of this transit link given all general attributes of the transport supply in Madrid, both for HSR and air transport. The intensive amount of capital and funds invested in the development of the high-speed network in Spain, with an explicit core in Madrid, delivers to the city a strategic transport condition, with numerous national HSR connections with the rest of Spain. The high-speed network in Spain follows a hub-spoke distribution model with centre in the capital promoting a high connectivity with the rest of the domestic territory. This favourable condition is also determined for Madrid’s geographic location, in the centre of the Iberian Peninsula, which in effect offers homogeneous access times from the majority of regions.

The recent transformations of the domestic traffic demand transferring from the air transport to the HSR mode is an immediate evidence of the changes of the transport mobility pattern within the country. Year after year the high-speed train is obtaining more users principally in the middle distance market (2.5 - 3 hours journey) emerging as one of the main causes of the important drop domestic passengers using the air transport. At the present, both HSR and air transport are slowly becoming complementary modes within the domestic market.
producing a new scenario of interaction and network hierarchy association. Furthermore, the advantageous position of the market of MAD airport in Southwest Europe appears as a great opportunity for the airport to become a major hub enhancing intercontinental connections, especially with America. To this end, the improvement of accessibility of the airport is essential in order to absorb the maximum number of passengers. This sequence of key factors, in addition to supplementary points, derives in the attraction of a HSR-air connection at MAD airport, and thus the establishment of a co-modal scenario of cooperation of both transport modes adjusting their commercial strategies into a common framework of social benefits and economic development, verified with the intermodality experience in Europe.

The definition of four general scenarios to execute the high-speed connection with terminal T4, related to the rail infrastructure, establishes: a link via a new main line connecting the North and Northeast corridors, two routes as a loop line diverted from one of each corridor and finally, a dead-end line emerging from the North corridor (the current option considered by the Spanish Ministerio de Fomento). The determination of the feasibility of the connection suggests the airport connection linking both North and/or Northeast HSR corridors as a result of the logic of their respective spatial situation in relation to the airport. The main arguments explaining the justification in favour of this solution are detailed next.

The following statements recapitulate the common characteristics of the main territorial and geographical circumstances:

− The geographical and topographical conditions are favourable to the construction of the surface HSR sections due to the favourable topography of the zone, with low slopes no steeper than 3%.
− The high level of urbanisation of Madrid and the existence of numerous infrastructures in the surrounding area, such as the M40 highway, airport runways and other service networks, result in the considerable proportion of tunnel sections for the high-speed line. This element contributes to the increase of the investment cost required, especially in the construction phase. However, the extended technical experience of tunnel drilling in this area can support its planning and construction, allowing the prevention of future issues and promoting a more efficient execution.
− The preponderant sedimentary geology of the area surrounding MAD airport is advantageous regarding the execution of the tunnels because of the low carrying capacity. This weak hardness of the material enables the implementation of cost-effective methodologies such as the traditional method or Belgian method, particularly for those zones with urban gaps or parallel to other linear infrastructures. The different variants are defined with the aim of a minimum impact on the territory, though always seeking the effectiveness of connection to the terminal. On the other hand, the high number of stability measures for the drill and a strict control of the settlements will difficult the tunnelling task. These measures will be especially important in the new tunnel constructions on the Jarama valley area with low consolidated materials and more likely to become unstable, especially those zones within the airport area.
− The establishment of urban integration measures will be necessary, in any case, for the surface sections near industries or urbanisations to avoid the expansion of the visual intrusion, noise, barrier effects and other urban fracture impacts.
Table 11.1 summarizes the resulting characteristics analysed for all different four scenarios, offering a basic report of the assessment criteria developed in all previous chapters for every subalternative considered for the intermodal connection at MAD airport (Terminal T4).

<table>
<thead>
<tr>
<th></th>
<th>Corridor 1 (Main line)</th>
<th>Corridor 2 (Branch line A)</th>
<th>Corridor 3 (Branch line B)</th>
<th>Corridor 4 (Spur line)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>26 km</td>
<td>25 km</td>
<td>24 km</td>
<td>33 km</td>
</tr>
<tr>
<td></td>
<td>25 km</td>
<td>25 km</td>
<td>19 km</td>
<td>8.5 km</td>
</tr>
<tr>
<td></td>
<td>24 km</td>
<td>100-200 km/h</td>
<td>190 km/h</td>
<td>100-120 km/h</td>
</tr>
<tr>
<td></td>
<td>33 km</td>
<td>150-200 km/h</td>
<td>100-120 km/h</td>
<td>100-120 km/h</td>
</tr>
<tr>
<td>Tunnel fraction</td>
<td>38%</td>
<td>38%</td>
<td>42%</td>
<td>52%</td>
</tr>
<tr>
<td></td>
<td>42%</td>
<td>42%</td>
<td>52%</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>38%</td>
<td></td>
<td></td>
<td>53%</td>
</tr>
<tr>
<td>Reference speeds</td>
<td>120-200 km/h</td>
<td>120-150 km/h</td>
<td>100-200 km/h</td>
<td>150-200 km/h</td>
</tr>
<tr>
<td>Functionality</td>
<td>***</td>
<td>***</td>
<td>***</td>
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<td>***</td>
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<tr>
<td>Cost (€ million)</td>
<td>650</td>
<td>625</td>
<td>625</td>
<td>825</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td></td>
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<td>475</td>
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Table 11.1 Summary of the characteristics of corridor alternatives for the HSR connection with MAD airport

The following statements reproduce different evaluations and recommendations in how to accomplish the transit link attained all aspects and attributes developed in the paper explanation.

- The functional analysis for all different variants agrees with the general European vision of connections of hub airports to their respective high-speed network. Those solutions through a direct access via the main line (Corridor 1) deliver a more optimal accessibility to the airport, a better potential for the operation of the rail supply and thus a higher sustainable use of economic resources. Moreover, in this case, the improvement of the inter-connectivity of the HSR network is essential to complete the connections of all the high-speed lines in Spain, so enabling a wider commercial strategy of establishment of routes with a relative minor cost of construction. The analysis of the connection times between stations in the North and Northeast corridors respectively, reflects the enhancement of the relations between those points producing a considerable time saving. The station at the airport, within Madrid metropolitan area, with an optimal situation of interconnection with all the transport modes, either collective or individual, induces the raise in demand for feasible routes not economically viable, but socially demanded.

- The factors concerning the rail infrastructure are not conclusive in the decision-making between all described alternatives. It is especially substantial in the assessment, the total length of the corridor and its tunnel proportion given the investment and technical difficulties of implementation in high-urbanised environment. This variable is clearly dependent on the capital cost required in the construction of the infrastructure. Apparently, the option carrying lower investment cost and easy to ascribe would be the spur line link and dead-end rail station at the airport terminal. On the other hand, if we consider the functional point of view as the top decision variable for the assessment, this solution could operate as a provisional option concerning the poor condition of attraction of demand and the lack of potential connectivity with the rest of the network.
So in this case there is less chance of enlargement of the catchment area of MAD airport and thus a weak strategic vision of infrastructure planning. Intermediate options are the variants for Corridor 1, with a smaller tunnel length ratio, and economically within the moderate investment range needed among all alternatives.

- The speed limitation within the urban area and the proximity of the airport station in a relatively short high-speed line are aspects for not considering the speed variable as strictly decisive in the choice. However, those variants with higher speed are more beneficial in the implementation of a most competitive solution for the users. The most beneficial solution would be the loop line Corridor 2 diverting from the Northeast corridor, this is caused by the highest distance of this part of the area in respect to the city centre. The solution as a branch line via the Northeast corridor (Branch line A), in this case though, entails the drilling of a tunnel all underneath the runways and the terminals. The difficulties of this operation concerning the risk control of stability and the technical considerations, suggesting the use of an EPB tunnelling machine would raise the cost of the construction operation.

- The environmental impacts of the alternatives are not excessively divergent for the area where the project is developed. The protected network Natura 2000 is not highly overlapped by the corridors area, so not generating a disproportionate impact in the natural habitats. Nevertheless, the options where the potential environmental impact is higher can be underestimated for the certain increase of the investment required in the construction in order to prevent the negative effects. A strict supervision and planning of the construction will be essential for mitigating a disproportionate increase of environmental impacts and social externalities.

- The international (European) experience of HSR connections to airports suggests a solution of direct access through a main high-speed line in case of explicit feasibility. This type of transit links enables further development of the connectivity of the network and thus higher economic benefits for the country. In these cases, the rail terminal has direct access to the air terminal of the main network airlines based on those airports. In relation to MAD airport, it would be the basement of the main hub carrier airline, IBERIA. The benchmarking strategy at European airports is clearly opting for a main through line delivering growing benefits for all airports and regions, so according to this the first alternative (Corridor 1) through a main line represents the most preferable solution.

After describing and detailing the insights of how to perform the high-speed connection to MAD airport, **the alternative very much recommended to accomplish is the Corridor 1 through a new high-speed main line linking the North and Northeast corridor. This rail line will enable a by-pass in the North corridor heading towards the North of Spain, in the direction of Valladolid, but also going to Chamartín and once the urban tunnel across the city is completed to the rest of Southern corridors. The four variants bands for the main line alternative through the airport have to be acutely defined and later discussed in the analysis of alternatives within the actual project of connection. However, this preliminary study can distinguish some primary characteristics with the purpose of discussing the suitability of each layout of the rail infrastructure for the airport connection.**
The connection to the Northeast corridor is preferable through the variant band B1 (Figure 8.15). The lower length and the advance of the route following urban gaps and other linear infrastructure are reasons of considering this variant versus A2, connecting the airport across the runways and the airport complex. A2, as well, can be problematic in respect to the environmental impacts produced in Parque Regional del Sureste, which is part of the protected Natura 2000. The variable B1 also use the gap created by other highway corridors, plus the likely adaptation of the sections in Vicálvaro rail classification lay-by station between Coslada and the east of Madrid. This section in surface could be highly recommended for the reduction of costs and the presence of a rail platform and tracks just ready to adapt into high-speed sections.

The connection to the North corridor is more diluted to determine for different factors to consider. Apparently, the best variant would be the shortest for a lower investment required corresponding to the option D2 (Figure 8.14). However, the multiple lines of suburban rail overlapped in that section merging in Hortaleza is a drawback, especially, in the construction of the high-speed line. There is a reduced space for the integration of the line and the by-pass towards Valladolid (not included in the proposal of Ministerio de Fomento). The length difference between D2 and the other option, C1 is not too wide, so in this case we can also consider the difficulties of execution. C1 option presents a more natural connection with the North corridor, in the direction of the North, but D2 is closer for the relations with the Southern corridors. The times estimation produces 4 extra minutes for C1 for relations with the South or the Eastern Mediterranean corridor. The conception of this new line determined as comparable to the Interconnection East in Paris CDG airport would guide a final decision considering C1 variant band for the vision of this new high-speed line as a corridor and carrying implications of improvement of the connectivity between the North and Northeast corridors, another decisive factor in the construction of MAD airport link.

Hence, the most reasonable concluding solution is defined through the variants C1+B1, even though a more detailed measuring scale is required to proportionate a final decision, as previously mentioned.

The economic point of view is valued within the planning phase as one of the downside points in the construction of a new high-speed line, principally as a cause of the high investment cost required for the construction and operation. In order to reduce the negative impact on society, high traffic demand using the intermodal link and station will contribute towards low opportunity costs of the project. A multiple-criteria decision analysis together with a cost benefit analysis should be the strategy to follow in order to select the most appropriate suboptimal alternative. It is important to state that in order to create a high potential intermodal terminal, it will be necessary that users are willing to pay the general cost derived from its construction and operation. A complementary risk analysis contemplating the elasticity of the demand in relation to different variables (price, travel time, level of service, scheduling coordination or comfort) should complete a more detailed economic evaluation of the intermodality at MAD airport. At the same time, it is very important the financing study focusing on the extra cost derived from the economic transactions and other economic deviations affecting the real economic feasibility of the construction of the new high-speed line. However, the object of this study does not fulfil the degree of accuracy for such a process
which has to be completed in the following stages of the design and planning of a high-speed line.

The definition of the HSR line airport link was the first willingness of the paper, but an efficient and socially profitable connection is only feasible if the intermodality factors are appropriately incorporated in the project. The attributes defining a successful performance attractive for potential users of the interchange will be described via the transport operators and stakeholder’s agreement and those actions will be decisive in the effectiveness of the connection. Attracting a large demand capacity to the intermodal connection will be manifested on high intensity of traffic and load factor of the trains in order to obtain the maximum level for social benefits for all stakeholders. Hence, the economic feasibility and profitability of the project will be strongly determined by the general characteristics of performance of the HSR-air connection. The main confirmed factor inducing an effective connection is the existence of a perfect integrated station in the terminal (in this case, T4) offering a rail-air intermodal transfer, in similar conditions as the air-air ones. In MAD airport, the underground station is already constructed with two platforms used by metro and suburban rail services. The adaptation of two platforms for the high-speed trains, given the character of the rail lines which terminate at the station, could be low-cost feasible option. The construction of two extra parallel platforms on the parking side could be another option to contemplate. The incorporation of specific facilities for the intermodality passengers, also, contributes to facilitate the connection and expand the demand of the service. The integration of the transport modes creating a fast, easy and effective intermodal interface is the main stimulus towards the supply of a competitive travel time and will be the key of the establishment of the air-rail connection.

After that spatial integration, the creation of an intermodal product resulting from the agreement between the transport operators (RENFE and IBERIA) and other agents (AENA, ADIF, etc.) will be essential for MAD airport to motivate the use of the new co-modal transport model. The intermodality product can introduce a number of suggestions stimulating the use of the service:

- Real time service information.
- Ticket integration and single check-in procedure.
- Time flexibility for co-modal users and scheduling coordination.
- Price competitiveness in relation to other modes.
- Establishment of package holiday deals especially for the airport demand with leisure and holiday purposes, which corresponds to the majority MAD airport users (40%).

Bearing in mind the preceding conclusions about the intermodality high-speed connection at MAD airport there are some additional observations and recommendations about different possibilities of performing the airport link. The following list describes some possible measures, of which feasibility is worthy considering and studying in order to enhance more social and economically sustainable of the project.

- As previously considered, the redistribution of the rail station at terminal T4 or a new adjacent construction would guide the design of the rail layout. Furthermore, the
connection, near the airport terminal, of the high-speed line with the current rail tunnels (line C1), which are already adapted to the international gauge, would create new chances of operation of the high-speed line. The so-called exploitation mixed high-speed model would allow high-speed trains running in conventional rail track sections, like the French high-speed train TGV. This measure would decrease the building cost, as both conventional and high-speed trains would use the same infrastructure and station, but it would generate an added complexity in the operational system of both rail lines.

- The chance of modifying the design of the infrastructure including, for instance, some sections adopting single track layout, or the exploitation model, allowing conventional rail services the use of the infrastructure. The proximity of the conventional rail lines to the links of the airport connections to the HSR tracks are feasible to create a mixed exploitation solution. The research for the reduction of economic costs and externalities and the rise of benefits via the enhancement of intensity of traffic on the rail line would support a more appropriate cost-effective solution.

- The possibility and study of the implementation of freight rail services on the new high-speed line at night hours or underutilized periods. Furthermore, it will be advantageous further studies about the performance and logistics of freight synergies between the high-speed rail and the air transport of goods, which market is not developed yet. The integration of airports in the rail freight network is practically today non-existent. The market segments for HSR freight transports mainly include the service one, which can be complementary to the similar services provided by a cargo terminal at airports (mail, express services, or parcels). The high-speed train could function as a feeder service of the air transport under a scenario of transport intermodality. Even though some additional infrastructure works and redesigning facilities should be developed, the benefits of transportation and the revenues potential should be studied in order to return the costs of the new line and the new air-rail terminal.
List of references

High-speed and other transport policies

[<www.uic.org/download.php/publication/521E.pdf>]

[<http://www.bepress.com/jbca/vol2/iss1/2>]


[<http://www.evaluaciondeproyectos.es/index.html>]


EUROCONTROL. (2012), *Delays to air transport in Europe. CODA DIGEST*.  

European Commission, EUROSTAT Statistics Database  
[<http://epp.eurostat.ec.europa.eu>]  

European Commission. (1997), *Intermodality and intermodal freight transport in the European Union*. Available at:  


GOURVISH, T. (2010), *The high-speed revolution: history and prospects*. HS2, Department for Transport. United Kingdom. Available at:  

List of references


International Union of Railways. (2013), High speed lines in the world, UIC High Speed Department.  
<http://www.uic.org/IMG/pdf/20131101_high_speed_lines_in_the_world.pdf>


Natura 2000, Environment, European Union  


Air-rail intermodality


IWIM - Institute for World Economics and International Management. WP84, Universität Bremen.  
<http://www.iwim.uni-bremen.de/publikationen/pdf/W034.pdf>


European Comission. (2006), Passenger intermodality from A to Z. Intermodal Passenger Transport in Europe. LINK, European Commission’s Directorate-General for Mobility and Transport DG MOVE.  

European Commission DG TREN. (2006), Air and rail competition and complementarity. Final Report  

The connection of Madrid-Barajas airport to the high-speed rail network


IARO. (1998), Air Rail Links. Guide to Best Practice. With the collaboration of ATAG, ACI.


LÓPEZ PITA, A. (2003), Airport connections of high-speed lines. Ediciones UPC (140 pages). 6th issue of “Temas de Transportes y Territorio” ISB 8483016842


VARIABLES AUTHORS. (2011), L’accessibilité terrestre aux grands aéroports européens: quelle desserte pour un bon usage des transports collectifs?. IAU Île-de-France. (182 pages) ISBN: 9782737117671


References about France

Aéroports de Lyon, <http://www.lynaeroports.com/>


Association Interconnexion Sud TGV en Ile-de-France, <http://www.interconnexionsud.org/>


List of references


MENERAULT, P. & BARRÉ, A. (2005), ‘El TGV y la reorganización de los transportes ferroviarios en la región de Nord-Pas-de-Calais’. *Ingeniería y Territorio*, 70, pp. 28-33


Réseau Ferré de France (RFF), <http://www.rff.fr/>


References about Germany

*Bahnprojekt Stuttgart – Ulm*, <http://www.bahnprojekt-stuttgart-ulm.de/>  
*Berlin Brandenburg Airport*, <http://www.berlin-airport.de/>  
*DB ProjektBau GmbH. (2013), Großprojekt Stuttgart – Ulm. Stuttgart 21 Planfeststellungsabschnitt (PFA) 1.3 Filderbereich mit Flughafenanbindung*


*Frankfurt Airport*, <http://www.frankfurt-airport.com/>  
*FRIEDRICHS, M. (2003), Bauarbeiten für die Flughafenanbindung Köln/Bonn gehen in den Endspurt. Deutsche Bahn AG, 20 May 2003. Available at: <http://www.pressrelations.de/new/standard/result_main.cfm?pflach=1&n_firmanr_=101744&sektor=pm&detail=1&r=123474&sid=&aktion=jour_pm&quelle=0>*  


The connection of Madrid-Barajas airport to the high-speed rail network

Senate Department for Urban Development and the Environment (Germany),
<http://www.stadtentwicklung.berlin.de/index_en.shtml>

UCL. New ICE Cologne–Rhine/Main line. Omega Centre, Bartlett School of Planning,
<http://www.omegacentre.bartlett.ucl.ac.uk/studies/cases/hsr-cologne_ice_2.php>

References about the Netherlands and Belgium


The Urban Mobility Portal. Available at: <http://eltis.org/index.php?id=13&study_id=3418>

Transport Review, 39, pp. 18 – 25.


Netherlands Railways (NS), <http://www.ns.nl/en/travellers/home>


References about Italy


CORRADI, M. (2012), Malpensa Airport Railway connections: state of the art and prospects. Airports as
poles of economic development. Brussels, 7th & 8th of June 2012. Available at:

MANTEGAZZA, P. and CROCE, A. (2013), Collaborazione ferro-aria. Il collegamento ferroviario al terminal
T2 dell’aeroporto di Malpensa 5ª Convegno Nazionale Sistema Tram. Ingegneria ed economia
disistema nel Trasporto Pubblico Locale a via guidata. Available at:
<http://www.asstra.it/eventi/download_allegato/690.html>

SALUCCI, F. (2011), AlpTransit 2019: un futuro ad alta velocità per il Ticino?, Relazioni e opportunità
comuni fra Milano e il Canton Ticino. Available at:
<http://www.supsi.ch/home/dms/supsi/docs/comunica/eventi/2011/Convegno-
Alptransit/Presentazioni/11_Convegno_Alptransit_240311_Salucci.pdf>

References about United Kingdom, Norway, Sweden and Denmark

Department for Transport. (2010), High Speed Rail. Presented to Parliament by the Secretary of State for
Transport. Available at:
<http://www.railwaysarchive.co.uk/documents/HMG_HighSpeedRail2010.pdf>
List of references


Flytoget Airport Train Express, <http://www.flytoget.no/eng/>

References about high-speed and air transport in Spain


Association of friends of metro de Madrid, Andén 1, <http://www.anden1.org/>


Comunidad de Madrid Regional Council, <http://www.madrid.org/>

Ferropedia, la enciclopedia colaborativa del ferrocarril, <http://www.ferropedia.es/wiki/Portada>


The connection of Madrid-Barajas airport to the high-speed rail network


IGME, Instituto Geológico y Minero de España, <http://www.igme.es/>


Madrid City Council, <http://www.madrid.es/>


List of references


