Land Use Policy 38 (2014) 290–299

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

The construction of a HSR network using a ranking methodology to prioritise corridors

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ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form
18 November 2013
Accepted 23 November 2013

Keywords:
High-speed rail line
Urban planning
Transport planning
Impacts assessment

ABSTRACT

The construction of new high-speed rail (HSR) lines, in a climate of financial instability since the onset of the global crisis of 2007–2008, has reopened the debate among the scientific community. Support for the new projects is facing serious concerns over the extremely elevated costs of high-speed and the ability of today's governments to fund or co-fund these systems. This is the main reason the assessment of methodologies to prioritise the construction of new high-speed rail (HSR) corridors has recently become an important issue for transport planners in countries like the U.S. where HSR does not exist.

The literature on ranking tools for prioritising HSR corridors is practically non-existent, even in Europe. In 2009, a new ranking methodology was developed and applied to 30,000 city pairs in the U.S. to determine their suitability for high-speed rail investment. As none of these lines has been constructed and none of them are in operation, this methodology has not been validated. The main objective of this paper is to analyse, validate and improve this ranking tool using data from a current HSR network: the Spanish one. Results show the consistency of the model as a preliminary approach to ranking pairs, mainly for the top first O–D relations; however the model fails to discriminate clearly between secondary groups of corridors. These deficiencies are chiefly due to the type of variables used by the model which ultimately, after improved, would provide policymakers with a useful tool when planning the construction of a new HSR network.

Introduction

The search for validated methodologies to prioritise the construction of new high-speed rail (HSR) lines has recently emerged as a key issue for transport planners in countries with no previous HSR systems. The U.S. is a good example of this process. In February 2009, as part of the American Recovery and Reinvestment Act (ARRA), Congress allocated 8 billion dollars to the states for intercity rail projects, prioritising projects that support the development of a high-speed intercity service. Previously, high-speed rail (HSR) in the United States was limited to Amtrak's Acela Express Service, which runs along the Northeast Corridor (from Boston to Washington DC) at speeds averaging 110 km/h for the entire distance, although briefly reaching 240 km/h at times. This ARRA was accompanied in April 2009 by the publication of the first American High-Speed Rail Strategic Plan (Federal Railroad Administration FRA, 2009), an ambitious document directly proposing ten priority HSR corridors.

There is a wide divergence between U.S. and European scenarios for the implementation of HSR. Most authors (see Button, 2012) concur as to the "controversial" nature of the definition of HSR given in the American Strategic Plan, as it refers not to a new infrastructure but to the type of service (*Express, Regional and Emerging*). Emerging and Regional lines (with speeds under 250 km/h) cannot be considered "pure HSR" under European (The Council of the European Union, 1996) standards, and the vast majority of the HSR corridors in the American Strategic Plan barely fall into this last group (Emerging). In view of the fact that only new *American HSR Express* corridors will have comparable construction and operation costs to European and Asian HSR lines, the FRA takes an interesting approach in its Strategic Plan: not all the proposed HSR corridors will require the same type of passenger rail service. This approach reveals a genuine HSR planning process, involving an analysis of the particular features of each candidate corridor before funding. Even in European countries, the construction of the first HSR lines did not follow the results of a ranking assessment within a transportation and urban planning process. This is the reason that little research has been done in Europe on methodologies based on ranking HSR corridors, while there is much more literature on demand forecasting for new HSR lines.

The initial proposal of the FRA was to develop a mechanism to assess which corridors across the nation have the greatest potential

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http://dx.doi.org/10.1016/j.landusepol.2013.11.017

demand for high-speed rail, and would thus provide the greatest transportation, economic, and social benefits; but finally no methodology was formally established. Only one subsequent document, published in 2009 (US Department of Transportation, 2009), offered an insight into how the FRA would make decisions on awarding the ARRA funding. In this document the FRA indicated that three categories of criteria would be used in the decision-making process. The first assesses the public return on investment. The second assesses project readiness and sustainability of benefits. In addition to these two categories of project-specific evaluation criteria, the FRA would employ cross-cutting selection criteria intended to balance projects against national priorities (geography, economic conditions, innovation and technology, and the existence of multi-state agreements).

This urgent need to devise a ranking methodology to prioritise future HSR corridors has coincided with a worldwide financial crisis. The construction of the first high-speed rail (HSR) lines in countries like United States and the U.K., immersed in a climate of financial instability since the onset of the 2007–2008 global crisis, has reopened the debate among the scientific community specialising in HSR. In 2012, vol. 22 of the Journal of Transport Geography included – at a very timely moment – a special section on rail transit systems and high-speed rail, featuring an in-depth discussion of the first American HSR Strategic Plan developed by the FRA. This special section contains an analysis that makes clear and constant references to the European HSR experience. Although some authors support the new projects (Johnson, 2012), opponents (Button, 2012) express grave concerns over the exorbitant cost of high-speed rail, and the ability of today's governments to fund these systems. Other authors (Givoni and Banister, 2012) focused their analysis on the integration of the transport system, arguing that experience proves that the success or failure of a new HSR line does not depend only on speed, but on door-to-door travel time, and this depends on the integration of the entire transport system. Against this economic backdrop, the prioritisation of future HSR corridors has become an indispensable tool for avoiding future financial failures.

The first attempt to develop a prioritisation tool was made by two American urban planners (Todorovich and Hagler, 2009). The model (described in detail in Section 'The ranking model approach') used twelve variables to create an index across five categories: population size, urban transit connections, origin-destination distance, economic vitality and congestion. These five categories were weighted and then added in an equation that allocated scores to 27,000 city pairs in the U.S., with New York–Washington coming top of the ranking. The top city pairs appeared to be consistent from a potential demand approach, although the model has not been validated with real data. For example, San Francisco–Los Angeles, in fifth position, is today the only *express* HSR route scheduled for construction in the U.S. as a new infrastructure that can realistically be termed "high-speed" according to European standards (CHSRA, 2012). There is therefore no real data available to check the results. The proposed methodology is based on the hypothesis that five main categories of variables determine the value of the Ranking Index (RI) to score corridors in order to evaluate their HSR potential demand.

Although demand forecast is not the only criterion for ranking corridors, it is a key factor for scoring projects. However traffic generated by a new transport infrastructure is always difficult to estimate by traditional modelling (Ortúzar and Willumsen, 2001) due to the percentage of "induced passengers": these are new passengers, new trips, that are not transferred from another previous mode of transportation in a corridor. As Ortúzar and Willumsen note, the sequential four-step model reveals a clear flaw in the generation stage in that it is viewed as virtually inflexible as regards any change in the offer of transport. This setback may be important in the evaluation of certain structural projects, such as projects that may have a significant impact on the standards of service provided in different areas, and particularly for long-term estimations. These shortcomings also have a direct impact on the induction calculation. Attempts have been made to introduce a new concept in the generation stage, such as "demand feedback to any change in the transportation network" by means of an accessibility variable. However, the experience has so far proven ineffective, at least for aggregated models, partly due to the difficulty in establishing an adequate accessibility indicator (Ortúzar et al., 2000).

As a result, demand forecast for new HSR lines in Europe (Ni et al., 1994) has been based on an ad-hoc model in which the induced traffic generated by a new infrastructure can be interpreted as a joint gravity model (which uses the generalised cost of each mode in use together with a modal split model – Logit). Thus the induced traffic is proportional to the generalised cost and dependent on the services offered in terms of fares, frequency, comfort and access to the station. Modes other than high-speed lose the traffic that "emigrates" towards the new line. This loss can also be calculated using a modal split model to compare the competing generalised costs. The French experience estimating the induced traffic caused by a new HSR line was based on this approach, and research on induced traffic in Spain (Guirao, 2000, 2006) followed the same methodology.

In conclusion, if the ranking tool is based solely on the demand approach, the literature indicates that at least the current alternative modes to high-speed should be considered in each corridor. It would be also advisable – albeit difficult – to include some type of accessibility variable in this aggregated model in order to evaluate changes in accessibility caused by the new HSR line.

If the ranking tool is based on a financial approach using profitability criteria, the complexity of the methodology increases, depending on the concept of profitability used and the type of benefits considered for the profitability calculation. HSR profitability has recently emerged as an important issue for scientific literature, due to the restrictions in public expenditure caused by the financial crisis. In 2007, de Rus and Nombela (2007) were the first to calculate the required minimum level of demand from which investment in HSR could be considered profitable from a social perspective. They used the real costs of construction, maintenance and rolling stock for currently operating European HSR lines, in addition to potential time savings, standard values of time and expected growth in demand (which is not easy to predict, as argued above). Although this approach has been generally accepted by the scientific community, it is clear that the wider economic benefits of high speed are difficult to estimate, as they are swamped by many – not inconsiderable – external factors such as territorial impacts. Social benefits can be calculated not only according to potential time savings, standard values of time or expected growth of demand. Territorial impacts may lead directly to social and economic benefits, and although they are difficult to estimate and analyse, attempts to study them have been made by some Spanish authors. Gutierrez (2001) directly measured the accessibility impacts of the future Madrid–Barcelona–French border HSR line. This estimate revealed that while the new HSR line would increase territorial inequity at the national level, the same line would reduce the disparity in accessibility at the European and corridor level (as peripheral small and medium-sized cities would gain greater accessibility benefits than large central cities). HSR impacts at different territorial levels have also be analysed (Ureña et al., 2009) and it was concluded that HSR systems helped large intermediate cities attract mid-level business and technical consultancy firms, urban tourism, and interregional conferences, in addition to increasing the regional centrality of these cities in relation to smaller cities. Ortega et al. (2012) analysed the impact of high-speed rail on territorial cohesion at different planning levels. These territorial impacts are barely taken into account in HSR profitability studies, but should not be overlooked in any ranking tool to prioritise corridors at a national level.

This paper contributes to the limited existing literature by developing the analysis of this type of ranking models and highlighting their importance in the HSR planning process. The added value of this research lies in the first assessment of a real case study using current HSR traffic data. In order to describe the research as a whole, the article has been divided into the following parts: objectives and state of the art in 'Introduction' section; description of the ranking model proposed in the U.S., terms and equation (in 'The ranking model approach' section); the modelling process using the Spanish case study with a discussion of the results ('The case study: the Spanish HSR network' section); and finally, presentation of the most important conclusions ('Conclusions' section).

The ranking model approach

The methodology proposed by Todorovich and Hagler (2009) is based on the hypothesis that five main categories of variables determine the value of a Ranking Index (RI) to score corridors in order to evaluate their HSR potential: population size, urban transit connections, origin-destination distance, economic vitality, and congestion. Population size and economic vitality tend to be the main factors affecting trip production (Ortúzar and Willumsen, 2001) together with income, vehicle ownership, household structure and family size. Factors like value of land, residential density and accessibility have generally also been considered for trip generation modelling at zonal levels. As described below, Todorovich and Hagler use car congestion and local transit connections as a type of accessibility factors affecting the use of future HSR lines. Lastly, distance between origin-destination has always been included as a variable – as an impedance function – in trip distribution models.

These five categories of variables were weighted and then added in an Eq. (1) for scoring the city pairs. Tables 1 and 2 give an explanation of each variable with its associated value. The equation was applied only to American cities of above 50,000 inhabitants, and this process included approximately 600 cities and towns. The city pairs were created using a geographic information system (GIS), connecting each city to all other cities located between 100 and 500 miles (160 km and 800 km) from the origin city. This yielded approximately 27,000 city pairs across the nation on which to base the analysis.

$$\begin{aligned} RI = {} & (CR) + 0.5(LR) + 0.5(S\_LR\_Len\_I) + 0.5(HRT) + 0.5(S\_HR\_Len\_I) \\ & + (Met\_Pop) + 10(Metro\_Main) + (City\_pop) + (Mega) + (CR\_1) \\ & + 0.5(LR\_1) + 0.5(E\_LR\_Len\_I) + 0.5(HRT\_1) + 0.5(E\_HR\_Len\_I) \\ & + (Met\_Pop\_1) + 10(Metro\_Ma\_1) + (City\_pop\_1) + (Mega\_1) \\ & + (C\_Length) + (G\_GDP\_Scal) + (TTI\_Ind) \end{aligned} \tag{1}$$

Table 1
Transit and population variables. Synthesis of choices and values according to the Todorovich and Hagler model.

Variable	Meaning	Possible choices	Value
CR	Commuter rail at origin city	Yes	1.0
		No	0.0
CR_1	Commuter rail at destination city	Yes	1.0
		No	0.0
LR	Light rail at origin city	Yes	1.0
		No	0.0
LR_1	Light rail at destination city	Yes	1.0
		No	1.0
S_LR_Len_I	Origin city light rail system mileage	0	0.0
		0–15	0.5
		15–30	1.0
		>30	1.5
E_HR_Len_I	Destination city light rail system mileage	0	0.0
		0–15	0.5
		15–30	1.0
		>30	1.5
HRT	Heavy rail transit origin city	Yes	1.0
		No	0.0
HRT_1	Heavy rail transit destination city	Yes	1.0
		No	0.0
S_HR_Len_I	Origin city heavy rail system mileage	0	0.0
		0–25	0.5
			1.0
		>100	3.0
E_HR_Len_I	Destination city heavy rail system mileage	0	0.0
		0–25	0.5
			1.0
		>100 miles	3.0
Met_Pop	Metropolitan area population of origin city	<250,000	0.0
		250,000–1,000,000	1.0
		1,000,000–2,500,000	2.0
		>2,500,000	3.0
Met_Pop_1	Metropolitan area population of destination city	<250,000	0.0
		250,000–1,000,000	1.0
		1,000,000–2,500,000	2.0
		>2,500,000	3.0
Metro_Main	Is the origin city the largest in the metropolitan area?	Yes	1.0
		No	0.0
Metro_Ma_1	Is the destination city the largest in the metropolitan area?	Yes	1.0
		No	0.0
City_pop	Population origin city	<100,000	0.0
		100,000–500,000	1.0
		500,000–1,500,000	2.0
		>1,500,000	3.0
City_pop_1	Population destination city	<100,000	0.0
		100,000–500,000	1.0
		500,000–1,500,000	2.0
		>1,500,000	3.0
Mega	Is the origin city located in a megaregion?	Yes	1.0
		No	0.0
Mega_1	Is the destination city located in a megaregion?	Yes	1.0
		No	0.0

Eq. (1) shows that the model is fairly dependent on the weight allocated to each variable. The values of the variables range from 0 to 3.0, and the authors logically give the maximum weight (10) to the variable *Metro_Main (or Metro_Ma_1)*, which reflects whether the origin city (or destination) is the largest in the metropolitan area. A metropolitan area is usually associated with an area of interactions between a core or cores (which can be defined using morphological criteria such as population or employment thresholds) and its hinterland of neighbouring municipalities showing a significant relationship with the core (usually estimated from travel-to-work commuting flows). As can be seen, the number of variables associated to the features of each city (urban structure, transit connection and population size) is greater than the combined variables associated to the corridor itself: distance, combined economic variable and combined congestion index. This approach prioritises the functional structure of the two cities over the interaction between them, and this fact will condition the modelling results. Each category of variable is presented in detail below,

Table 2
Combined variables (length, GDP Geometric Mean and congestion index). Synthesis of choices and values according to the Todorovich and Hagler model.

Variable	Meaning	Possible choices	Value
C_Length	Corridor length (miles)	<150	$\frac{Length}{100}+1$
		150–300	2.5
		300–350	$\frac{500-Length}{100}+0.5$
		>300	$\frac{500-Length}{100}$
C_GDP_Scal	Geometric mean of per capita GDP of the two metro regions (dollars)	<20,000	0.0
		20,000–30,000	0.5
		30,000–40,000	1.0
		40,000–50,000	1.5
		50,000–60,000	2
		>60,000	2.5
Variable	Meaning	Possible choices (TTI for no registered cities[a])	Value
TTI_IND	Combined TTI index of the two cities in city pair S_TTI (origin city TTI) E_TTI (destination city TTI) TTI = Texas Institute TT Travel Time Index	1.09 (150,000–500,000 inh.) 1.16 (500,000–1,000,000 inh.) 1.23 (>1,000,000 inh.)	2.5(S_TTI -1) + 2,5 (E_TTI-1)

[a] Estimated TTI for non registered cities depends on metropolitan population.

with a discussion of the main issues that may be determining when applied to a real case study.

Hagler and Todorovich omitted to provide a critical reflection on the decisions underlying their choice of variables and the use of combined variables, or on the way in which weights were assigned to these variables. Additionally, there is a clear linear dependence between the different variables in their model. We know that large populations usually enjoy a denser public transportation network, and in order to add new information to the model, they (Hagler and Todorovich) would therefore have chosen not to use transit variables related to the length of the lines but to accessibility to the new HSR station. The importance of the assigned weights can be analysed by testing the sensitivity of this model to each group of variables (population, transit variable and combined variables). We have verified that population variables (in the most favourable case) can reach up to 70% of the RI value, while transit variables and combined variables account for only 18 and 12% of the total RI respectively.

Population variables

Todorovich and Hagler's ranking model considers as trip generation factors both the city population (taken from the 2000 U.S. Census), the size of the metropolitan area affecting the city, and the role played by the city in the metropolitan area. It has been demonstrated that sufficient travel demand for HSR rail services can be ensured by locating the HSR station in major metropolitan areas. The definition of a metropolitan area is clear in the U.S., and the Federal Register (2000) has published *the Standards for Defining Metropolitan and Micropolitan Statistical Areas*, but in Europe these statistical data (the size of the main metropolitan areas) tend to be more elusive.

The ranking index also aims to take into account urban form and population density by determining whether a city is located in a *megaregion* (also called megalopolis or the megapolitan area). Megaregions, as a concept (Gottman, 1961), are defined as networks of metropolitan regions with shared economies, infrastructure and natural resource systems, stretching over distances of roughly 300 miles–600 miles in length. The megaregion concept provides cities and metropolitan regions with a context within which to cooperate across jurisdictional borders, including the coordination of policies such as transportation. In 2008, the Regional Plan Association (RPA), an American independent not-for-profit regional planning organisation founded in 1922, recognised 11 emerging megaregions (RPA, 2008) in the U.S. This term is rarely used in Europe, since the dimensions of European countries are unlike anything in the US. European countries can only be considered to function as a small megaregion when densely populated. For Todorovich and Hagler, high-speed rail systems work best as part of a network with multiple connections, as has been shown in European and Asian megaregions. Cities that are located in one of the eleven megaregions are more likely to be part of a network of interconnected cities with the appropriate density to support high-speed rail systems, rather than an isolated city pair. Most of these megaregions have population densities similar to European countries with successful high-speed rail systems.

Local transit variables

The location of the future HSR station and its connection with the local transit is a key factor for attracting new riders. Transit variables considered by the model include the existence of commuter rail, heavy rail and light rail in each metropolitan area. The length of the heavy rail and light rail transit system for each city is also considered in the ranking model (data from the Federal Transit Administration for 2004). The suggestion is that high-speed rail systems will attract greater numbers of riders if they begin and end in central locations within the metro region and tie seamlessly into existing commuter rail and transit systems. However, the model ignores urban bus transit in favour of other rail transit systems. In Europe, the bus plays a very important role in the urban transportation system in terms of market share, and although the capacity of a rail system is usually higher than a bus network, bus transportation guarantees accessibility to households and constitutes the last link of a viable and integrated transportation chain.

Another important point worth noting in regard to the transit variables considered is that this ranking model omits the data from the current interurban traffic between each origin and destination. As the literature has shown, it is important to study alternative transportation modes to high-speed in order to forecast the loss of traffic that will "emigrate" towards the new HSR line. The authors themselves admit that this is a significant drawback of this model, although they justify it by the fact that although air and interurban rail travel data are not counted in their index, there is a direct link between the economic productivity of each corridor and the intercity travel market between their major cities. Thus the potential of each corridor to attract new trips has been indirectly included in the model through an economic variable (*C_GDP_Scal*).

Economic variable

Gross domestic product (GDP) per capita is the broadest measure associated with both economic productivity and personal income. The authors argue that high-speed rail systems depend heavily on business travel to sustain ridership, and that business travel is highest in places with more productive economies; they even illustrate how economic productivity and demand for intercity travel frequently coexist. For each O–D pair, the geometric mean of per capita GDP of the two metro regions (in U.S. dollars) was calculated for use in the ranking model. The Bureau of Economic Analysis provided the 2006 per capita GDP at the metro region level.

Distance variable

The distance variable used in this ranking index is based on the European and Asian experience. The authors have established that distances below 100 miles are better suited to auto and commuter rail networks, whereas distances over 500 miles are more efficiently travelled by air. This index weighted the distance criteria such that it peaked between 200 and 300 miles and decreased to zero after 500 miles (see Table 2). The value begins at 2 for corridor lengths of 100 miles, increases linearly, and peaks at 2.5 for corridor lengths between 150–300 miles, decreases linearly to 2 at lengths of 350, then decreases to 1.5 and continues decreasing linearly to a value of 0 for lengths of 500 miles.

One important point is that this combined variable ignores the accessibility time to the HSR station in each city in the O–D pair. This accessibility time, added to the HSR travel time (dependent on speed and distance), gives the total travel time and is one of key variables that conditions HSR demand.

Road congestion variable

The argument for using a road congestion variable in a model for ranking HSR corridors is that metropolitan congestion increases intercity private car travel, making rail a more attractive option. In the U.S. this type of data is compiled by the Texas Transportation Institute (TTI) in its Urban Mobility Report, but it is not easy to come by a similar study in Europe. The Urban Mobility Report (TTI, 2005) measures average daily delays on key arterial roads during prime commuting hours. The “travel time” index is the ratio of travel time in the peak period to the travel time in free-flow conditions (TTI ranges from 1 to 1.5). For each O-D pair in the ranking model, the combined city index was created by subtracting 1 from the TTI for each city and multiplying the total by 2.5. As not all U.S. metropolitan areas in the case study have TTI indices, cities not specifically identified with a TTI were given the TTI for their size of metropolitan area, either “small” (150,000–500,000 inhabitants), “medium” (500,000–1,000,000), or “large” (1,000,000). This last scale was applied to the Spanish metropolitan areas due to the lack of congestion index data.

Table 3 shows the top city pairs obtained using this ranking methodology. The scores for the 27,000 city pairs ranked in this index ranged from 3.9 to 44.9, and the scores the authors finally listed beside the city pairs represent that city pair’s scores as a percentage of the top score. The results obtained are consistent with an intuitive a priori assessment: high-population density U.S. regions would head the ranking pairs and, as expected, the top 50 city pairs identified were primarily concentrated in the Northeast, California, and the Midwest. However there is no analysis relating the evolution of the gap between the score of each pair and the previous one. When this gap is wider, does this mean the pairs are functionally more different? Is it possible to identify different stages in the score reduction from the top pair? Is the model able to discriminate clearly between the city pairs? Is the model capable of grouping city pairs with similar features? Some changes are probably needed in the variables and the model structure to solve these drawbacks.

The authors use the results of the ranking list to design a phasing plan for HSR construction in the U.S. (shown in Fig. 1), considering more than one high-ranking city pair within a megaregion which could together serve to form a network. To design this phasing map, certain assumptions have been made relating to the current transportation system, although they are not modelled or explained in the research. Any transportation planning process should include an evaluation of the current transportation system, and the transportation alternatives (modes, prices, timetable, frequency) to HSR in the top city pair will determine the place with the greatest need in order to start construction. Once the ranking results are known, even the method used to design the layout of each HSR line is subject to debate, and certain initial criteria should be set out. For example, should urban planners opt to link two cities using the shortest possible itinerary, or should they consider a stop in cities mid-route, even though this may represent a longer itinerary and – in consequence – a greater investment? The Spanish experience is proof that the design of a HSR network is subject to a number of territorial constraints. In the following pages, the Spanish case is used to validate this methodology and discuss how this type of tool can play an important role in planning new HSR lines.

Case study: the Spanish HSR network

This section applies the equation proposed by Todorovich and Hagler to Spain in order to study a country with a HSR network, and determine the best phasing of a HSR construction plan. Spain, with more than 20 years of operating experience, has the longest HSR network in Europe (2900 km), although it has a geographic size of only 492,375 km^2 (similar to California), and operates as a single megaregion. With a total population of 37 million inhabitants, the average population densities are over 90 people per square kilometre, much higher than in U.S. states. In contrast to European countries, only 13 states in the U.S. have over 90 people per square kilometre, and just eight have over 120: Connecticut, Delaware, Florida, Maryland, Massachusetts, New Jersey, New York, and Rhode Island.

In order to use similar criteria to the U.S. model, some considerations should be taken into account. Spain is administratively divided into 17 regions and 50 provinces, and only the capitals of the province were selected for the first application of the American model (except capitals located in the islands). All these cities have over 50,000 inhabitants, and, except for two special cases, represent the highest population in the province. The first run of the model demonstrated clearly that we had overlooked two cities – not provincial capitals – whose population was greater than the capital itself: Jerez de la Frontera and Gijón. In these special cases, these cities – together with the provincial capital – were considered as one metropolitan area (Oviedo-Gijón, Cádiz-Jerez de la Frontera), and thus in the definitive model application these two cities were included in the list of selected nodes. City pairs were created by connecting each city to every other city located between 100 and 500 miles (160 km and 800 km) from the origin city. This selection process yielded 49 cities and 1176 city pairs across Spain on which the analysis was based. In view of the fact the model was not devised for use with metric units, Spanish distances were converted into miles, and the values in the GDP variable were converted into 2001 dollars.

Table 3
Top 50 city pairs in the U.S.

Rank	City pair	Score	Rank	City Pair	Score
1	New York–Washington	100.00	26	Detroit–Washington	87.27
2	Philadelphia–Washington	98.24	27	Cleveland–New York	87.25
3	Boston–New York	97.22	28	Philadelphia–Pittsburgh	87.23
4	Baltimore–New York	96.83	29	Portland–Seattle	87.19
5	Los Angeles–San Francisco	96.43	30	Pittsburgh–Washington	86.69
6	Boston–Philadelphia	96.05	31	Los Angeles–Sacramento	86.58
7	Los Angeles–San Diego	94.92	32	New York–Providence	86.58
8	Los Angeles–San Jose	94.19	33	Raleigh–Washington	86.36
9	Boston–Washington	92.79	34	Detroit–Philadelphia	86.30
10	Dallas–Houston	91.37	35	Chicago–Louisville	86.25
11	Chicago–Detroit	91.09	36	Hartford–Philadelphia	86.20
12	Baltimore–Boston	90.39	37	San Diego–San Jose	86.14
13	Chicago–Columbus	89.42	38	Hartford–Washington	86.13
14	Chicago–Saint Louis	89.25	39	Chicago–Cincinnati	86.02
15	Los Angeles–Phoenix	89.03	40	Cleveland–Philadelphia	85.99
16	Chicago–Cleveland	88.71	41	Charlotte–Philadelphia	85.60
17	Charlotte–Washington	88.39	42	Philadelphia–Raleigh	85.58
18	San Diego–San Francisco	88.32	43	Buffalo–New York	85.58
19	Columbus–Washington	88.21	44	New York–Virginia Beach	85.52
20	Cleveland–Washington	88.13	45	Austin–Dallas	85.47
21	New York–Pittsburgh	88.03	46	Manchester–New York	85.41
22	Phoenix–San Diego	87.97	47	Philadelphia–Providence	85.36
23	Las Vegas–Los Angeles	87.79	48	Bridgeport–Philadelphia	85.31
24	Detroit–New York	87.47	49	Columbus–Philadelphia	85.24
25	Chicago–Minneapolis	87.33	50	New York–Rochester	85.11

Population data

It should be noted in relation to the population variables used in the model that one of the main problems when adopting metropolitan areas as units of analysis and policy in European countries is the absence of widely-accepted standards with which to identify them. The dearth of studies in Spain identifying metropolitan areas is a serious drawback that discourages the use of metropolitan areas as units of analysis in the study of interurban transportation. The model proposed by Todorovich and Hagler uses five variables dependent on metropolitan areas (*Met_Pop*, *Met_Pop_1*, *Metro_Main*, *Metro_Ma_1*, *C_GDP_Scal* and *TTI_IND*). In view of the lack of official data, we have used the results provided by Boix and Veneri (2008) to identify Spanish metropolitan areas according to the Spanish 2001 National Census INE (Instituto Nacional de Estadística). There are five major metropolitan areas in Spain (Madrid, Barcelona, Valencia, Seville and Bilbao) which have about 35% of the national population and 38% of the employment. Only the metropolitan regions of Madrid and Barcelona have over 2.5 million inhabitants, while Valencia, Bilbao, Murcia, Malaga and Gijón-Oviedo belong to

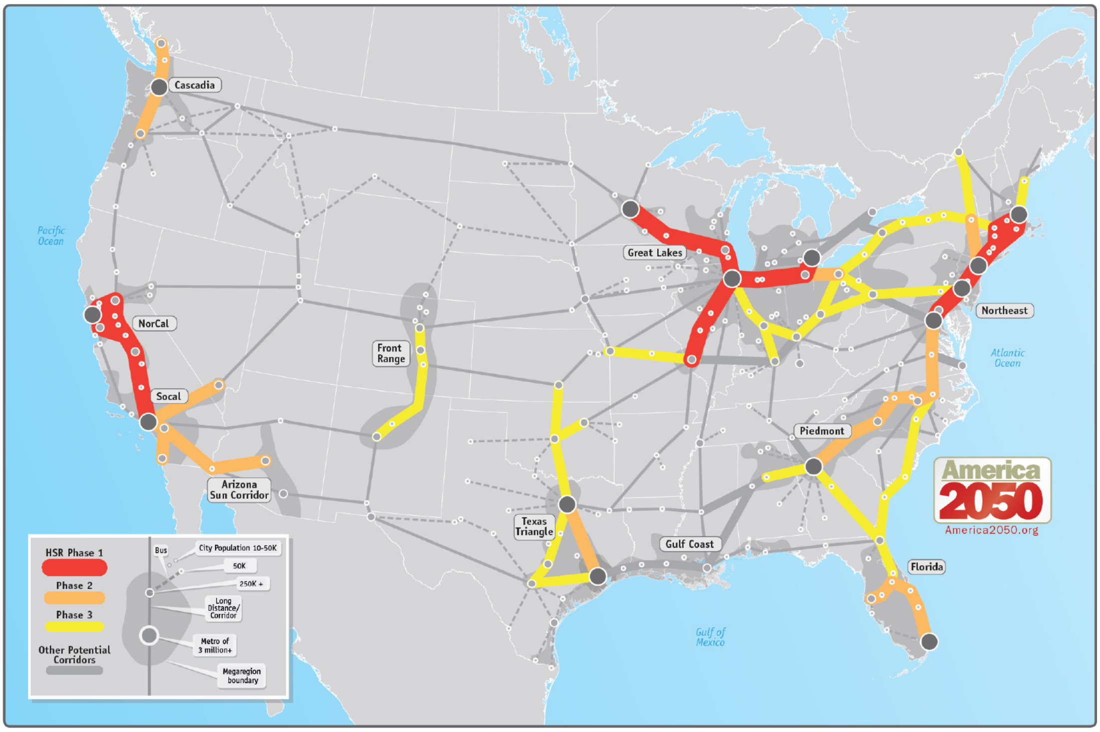

Fig. 1. U.S. HSR phasing plan.

Source: Todorovich and Hagler (2009).

the second group defined in the ranking model (between 1 million and 2.5 million inhabitants).

In relation to the U.S. concept of megaregion, we have worked on the hypothesis that all the O–D pairs in this study belong to the same megaregion, and this variable therefore did not affect the scores. However, we have maintained it in the ranking model in order to conserve the original structure.

Local transit data

Data on commuter rail, heavy rail and light rail, as well as the length of the heavy rail and light rail transit system for each Spanish city selected were also included in the ranking model. It should be noted that the market share of public transport in the urban Spanish context is higher in comparison to U.S. cities. As an example, public transport is very important in the two largest metropolitan areas, as it reaches values of the same order of magnitude as the private vehicle: 40.4% in Madrid and 31.4% in Barcelona (Gobierno de España, 2012). The role played by urban buses, although not taken into account in the ranking model, is very significant in Spain. The density of rail service supply in regard to population and surface area shows smaller ranges than the density of bus services (2000–5000 km. per 1 million inhabitants).

In addition – and in contrast with the U.S. – it should also be noted that before the construction of the new HSR network, Spain enjoyed a serviceable interurban passenger rail and road system. When HSR arrived in Spain in 1992 with the construction of the Madrid–Seville line, a new transportation infrastructure was added to the country's existing dense transportation network. The Madrid–Seville line marked the beginning of the construction of an ambitious high-speed railway network in Spain, which has been used from the start for two types of services: long-distance services and regional shuttle services, both with practically the same quality of trains and speeds. In Spain, highway and conventional rail networks have a radial structure, centred on the country's capital, Madrid. The new HSR network follows the same topology, connecting Madrid with the most populated cities (Barcelona, Valencia and Seville). The busiest Spanish domestic air routes (considering only the Iberian Peninsula) link these cities.

Economic data

As the per capita GDP in metropolitan regions in Spain is not recorded by the INE, we have used provincial data: per capita GDP at the provincial level according to the regional Accounting Base. Furthermore, due to significant differences between the value of the U.S. and Spanish GDP per capita (only two provinces had a minimum of 20,000 dollars of per capita GDP in 2001), the range of values of the *C_GDP_Scal* variable (Table 1) had to be changed. In order to differentiate corridors according to an economic variable, we have used a more realistic scale, maintaining the top value of the variable in the U.S. model. The value begins at 0 for corridor *C_GDP_Scal* under 10,000 dollars, then increases linearly and peaks at 2.5 for corridor *C_GDP_Scal* over 20,000 dollars.

Road congestion data

There is no indicator similar to the TTI index at the European level, except for the *TomTom congestion index*. This initiative, developed by the company TomTom and published in 2012 (Tom Tom International BV, 2013) is based on actual GPS measurements, and the sample size for each city is expressed in total number of kilometres measured for the period. The methodology used is similar to the TTI index. The report compares travel times during non-congested periods (free flow) with travel times in peak hours, and this difference is expressed as a percentage increase in travel time. The sole disadvantage in using these results is that only three Spanish cities were included in this study (Madrid, Barcelona and Valencia), so the estimated TTI index for non-registered cities proposed by Todorovich and Hagler (based on metropolitan population size) was used in the Spanish model.

Results

Table 4 shows the top 50 Spanish city pairs obtained by applying the model. The connections between the three most populated cities (Madrid, Barcelona and Valencia) appear in the top ten of the ranking, showing a considerable difference (up to 3.0) in their scores compared to the following city pairs (the average difference between subsequent city-pair scores is 0.41). Fig. 2a shows the current Spanish HSR lines in operation with their corresponding opening date. The present network covers the top ten city pairs with the exception of four important missing links: Barcelona–Valencia, Madrid–Bilbao, Barcelona–Bilbao and Madrid–Murcia.

First, the model was validated by comparing these results to the current HSR network, and recording the traffic in each city pair in the top 50 that benefits from a HSR link. Table 5 shows the city pairs according to their position in the modelling ranking, indicating distance, travel time and annual traffic recorded in 2011. It can be seen that traffic decreases as we go down the ranking, with Madrid–Barcelona continuing to be the top origin–destination pair with more than 2.5 million passengers. In general terms, the results can be assumed to be consistent with recorded traffic, and the proposed model, which focuses mainly on the size and transit offer of metropolitan areas, can be used as a tool in a HSR network planning process. Nevertheless, Table 5 also shows some deficiencies in the ranking list that require explanation. Madrid–Valencia is second in the ranking list, but the recorded traffic in 2011 was lower than for Madrid–Seville (position 4); this may be for two main reasons. First, the Madrid–Seville line opened in 1992, and Madrid–Valencia in 2010; this latter connection had probably not yet reached its "maturity". Furthermore, Seville has a considerable tourism attraction factor, and the model only considers (for each metropolitan region) population, transit and per capita GDP. These conclusions can be extended to another poor scoring connection, Madrid–Cordoba (ranking position 34), with 800,679 passengers. Tourism is clearly a trip attractor variable, and particularly in countries where tourism is one of the main contributions to national GDP (over 10% in Spain).

Improving accessibility to a tourist city can be made a priority in the process of planning a new HSR network. It is important to identify the predominant economic activity of a metropolitan area (not simply its per capita GDP) as a demand attractor. Tourism is a clear example in Spain, but academic centres (university campuses such as Harvard and MIT) or industrial technology areas (like Palo Alto in California) can play the same role. Toledo and Segovia (in Spain) are good examples of this tourism-based approach. Madrid–Toledo appears in position number 113 in the ranking model, due mainly to the size of the city (almost 78,000 inhabitants) and its proximity to Madrid (less than 100 km). However, HSR traffic in 2011 was 1,497,660 passengers, a higher figure than for city pairs with positions above 15 in the ranking. Toledo is a mid-sized city in central Spain, 70 km south of Madrid, and was declared a World Heritage Site by the UNESCO in 1986 for its extensive cultural and monumental heritage. However, this city pair was successful in terms of traffic not only due to its HSR link to Madrid, but also because of the service provided by the operating company. Since 2005, Toledo has had over 10 daily HSR shuttles (30 min travel time), and this fact is also favoured by the availability of monthly tickets which are economically very advantageous compared to ordinary one-way

Table 4
Top 50 HSR city pairs in Spain according to the results obtained using the model of Todorovich and Hagler.

Rank	City pair	Score	Rank	City pair	Score
1	Madrid–Barcelona	100.00	26	Valencia–Murcia	83.95
2	Barcelona–Valencia	96.73	27	Valencia–Sevilla	83.78
3	Madrid–Valencia	96.73	28	Madrid–A Coruña	82.90
4	Madrid–Bilbao	93.01	29	Salamanca–Madrid	82.82
5	Madrid–Sevilla	92.81	30	Madrid–Granada	82.51
6	Madrid–Zaragoza	90.50	31	Madrid–Almería	82.14
7	Barcelona–Bilbao	90.44	32	Barcelona–Castellón	82.14
8	Madrid–Murcia	89.81	33	Madrid–Castellón	82.14
9	Madrid–Malaga	89.53	34	Madrid–Cordoba	82.14
10	Barcelona–Zaragoza	89.44	35	Madrid–Lleida	82.14
11	Madrid–Gijón	88.21	36	Madrid–Logroño	82.14
12	Barcelona–Murcia	88.04	37	Barcelona–Santander	81.86
13	Madrid–Alicante	87.84	38	Barcelona–Burgos	81.62
14	Barcelona–Alicante	87.41	39	Madrid–Tarragona	81.46
15	Madrid–Vitoria	86.93	40	Valencia–Málaga	81.23
16	Madrid–San Sebastián	86.77	41	Madrid–Albacete	81.07
17	Barcelona–San Sebastián	86.16	42	Barcelona–Logroño	81.07
18	Madrid–Santander	85.71	43	Madrid–León	81.07
19	Barcelona–Vitoria	85.24	44	Valencia–Alicante	80.98
20	Valencia–Zaragoza	84.64	45	Barcelona–Valladolid	80.13
21	Barcelona–Pamplona	84.27	46	Madrid–Jerez de la Fontera	80.13
22	Madrid–Pamplona	84.27	47	Madrid–Badajoz	80.01
23	Valencia–Bilbao	84.23	48	Madrid–Huesca	80.01
24	Madrid–Burgos	84.21	49	Madrid–Teruel	80.01
25	Madrid–Valladolid	84.00	50	Sevilla–Malaga	79.93

tickets. This frequency, if the timetables are suitable (as is in fact the case), allows their use by commuters.

The use of this HSR technology for short distances (also called *regional HSR*) as a commuter railway is also financially debatable; however in Spain this type of corridor, which would never appear at the top of the ranking according to Hagler and Todorovich's model, is an actual fact, with high recorded traffic. These regional city pairs (commercially known as AVANT in Spain) boast high-speed shuttles to connect the city with an attracting centre (usually located at one end of the high-speed line). Other AVANT corridors (with an actual ranking position above the modelled one) are Seville–Cordoba, Barcelona–Lérida and Madrid–Valladolid, where the same arguments can be used to support the high rate of traffic recorded. For these HSR commuters, accessibility to the location of the HSR station is especially important in order to reduce the total daily travel time to work (door to door).

As can be seen, the type of service offered and not only the size of the population for an O–D pair can condition transportation demand in some specific cases of cities located within a 200 km radius from the centre of a major metropolitan area. The ranking model should be able to identify this demand factor, especially during the city selection process. In the case of regional HSR services, regional cities located within a 200 km radius from the centre of a major metropolitan area should be studied in detail in order to award higher values in the ranking result. Following the same approach, the location and accessibility of the future HSR station with regard to the city centre will also affect a city's assessment in the model. However this ranking tool is designed to be used during the planning process, when the location of the future stations has not yet been decided.

Another important variable the model fails to consider is the previous interurban transportation system in each corridor. The impacts on demand caused by the opening of a new HSR line can be expected to be greater when there is no competitive transportation alternative to HSR in terms of generalised cost. This information is not included in the model by means of a variable, and therefore some of the results in Table 4, when compared to current rail traffic, can only be explained using data from existing alternative modes. A good example is the Barcelona–Tarragona corridor which has a conventional commuter rail that is much more competitive than the regional HSR service.

Lastly, Fig. 2b shows a proposal for a theoretical phasing of construction based on the modelling results. This proposal has been compared with the real process in Fig. 2a. As can clearly be seen, the construction of the Spanish HSR network should have begun with the Madrid–Barcelona–Valencia triangle, and this is consistent with the population density of this triangle area. The phasing would

Table 5
Long-distance HSR traffic for the only top 50 city pairs currently in operation.

Origin	Destination	Ranking position	Distance (km)	Year service opened	HSR travel time (min)	Passengers 2011
Madrid	Barcelona	1	621	2008	150	2,545,907
Madrid	Valencia	2	391	2010	100	1,836,500
Madrid	Seville	4	471	1992	150	2,137,026
Madrid	Zaragoza	6	306	2003	75	1,175,053
Madrid	Malaga	9	513	2007	150	1,433,361
Barcelona	Zaragoza	10	260	2008	90	600,511
Madrid	Cordoba	34	345	1992	105	800,679
Madrid	Valladolid	25	180	2007	56	1,083,590
Madrid	Lérida	35	442	2003	125	238,754
Madrid	Tarragona	39	521	2006	150	294,702
Madrid	Albacete	41	322	2010	90	248,992
Seville	Malaga	50	270	2008	110	104,317

Source: Observatorio del Ferrocarril en España (Ministerio de Fomento, 2012).

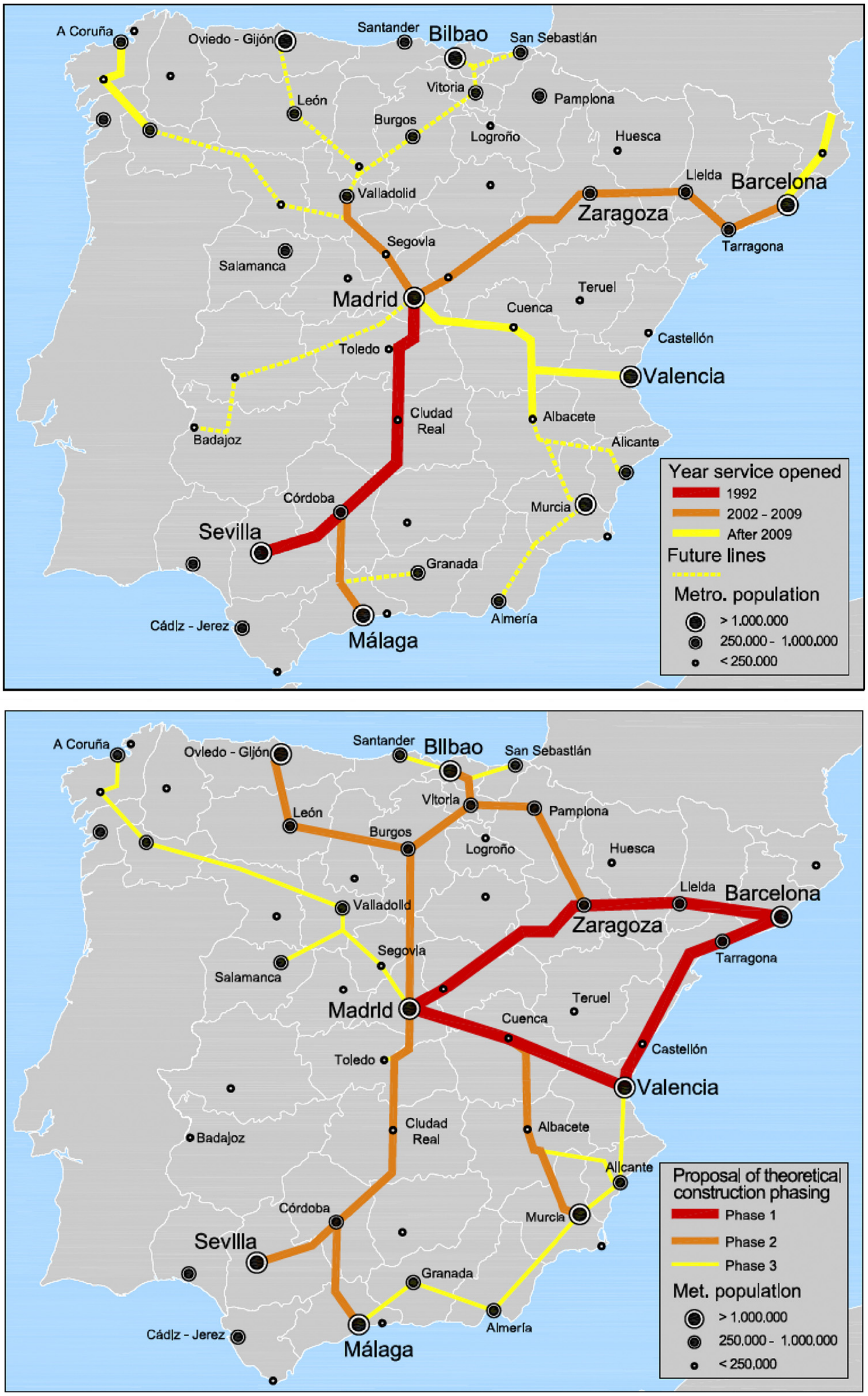

Fig. 2. Current Spanish HSR lines in operation with their year of opening (above, a). Proposal for a theoretical construction phasing based on the modelling results (below, b).

have continued with the Madrid–Bilbao and Madrid–Seville corridors, followed by other secondary connections like Madrid–Murcia and Madrid–Gijón/Oviedo. Sadly, the Madrid–Bilbao line is today far from coming into operation, and the real construction phasing has differed from the one suggested by the modelling results. The reasons for these changes can be found in the targets and priorities defined in the planning process set down by different Spanish governments during the last 20 years, not always using the same criteria.

The ranking model proposed by Hagler and Todorovich could provide authorities and policymakers with useful information for planning the construction of a new HSR network when priorities are focused on major metropolitan areas, and on improving their accessibility. But any HSR planning process at a national scale requires a broad accessibility analysis that takes into account the whole transportation system in order to achieve real territorial equity with regard to accessibility to the transportation network. Otherwise, a new HSR line could turn out to be redundant in terms of infrastructure provision, or could even cause the closure of old conventional rail lines, leaving small towns without rail accessibility. This type of secondary impact should not be overlooked throughout this planning process, after the objectives and priorities have been defined.

In terms of recommendations, the research has revealed that the direct application of the ranking methodology to the Spanish case entails several difficulties (mainly due to the considerable differences between the European and the U.S. context). In order to point to a proposal for the generalised extrapolation of the methodology to other countries, the authors present here some specific suggestions: the elimination of redundant and dependent variables (e.g.: population variables can be unified into one single one: the population of the metropolitan area) and the evaluation of a city's local transit system using a variable that actually measures accessibility to the future HSR station (not merely the existence and length of different local networks). Other recommendations include the introduction of a variable in the model to take account of current interurban alternatives to the future HSR line and the possible elimination of the city congestion variable, analysing instead the existence of congestion in the current interurban transport systems (airports, conventional rail lines or roads).

Conclusions

The lack of validated methodologies for prioritising the construction of new high-speed rail (HSR) lines has become an important issue in countries that do not yet have HSR systems. The state of the art, described in 'Introduction' section, shows how traditional literature on transport demand modelling has provided policymakers with various tools to forecast future HSR traffic; however there has so far been little research aimed at exploring a methodology to rank HSR corridors in a country. HSR demand forecast reveals difficulties when estimating induced traffic, and even HSR profitability analysis ignores the benefits related to territorial impacts. This paper contributes to the limited existing literature by developing the analysis of this type of ranking models, and emphasising their importance in the HSR planning process.

Section 'The ranking model approach' analyses the only available ranking tool, presented in 2009 by two American researchers and never validated. In the model equation, the number of variables associated to the features of each city (urban structure, transit connection and population size) prevails over the combined variables associated to the corridor itself: distance, combined economic variable and combined congestion index. Moreover, certain determinant variables are missing, such as those relating to interurban transportation and local bus transit. This approach stressed the functional structure of the two cities over the analysis of their interaction, and this conditions the modelling results. Certain of the variables used as part of the ranking model pose difficulties when applied to Europe, such as the concept of *mega-region*, *metropolitan area* and the *TTI index*. The authors present specific suggestions (at the end of 'The case study: the Spanish HSR network' section) for drafting a proposal for the generalised extrapolation of the methodology to other countries.

The application of the model to Spain described in Section 'The case study: the Spanish HSR network' required an adjusted database and was validated using current 2011 HSR traffic. In conclusion, the results are consistent with the traffic recorded, and the proposed model – focusing mainly on the size and transit offer of metropolitan areas – can be used as a tool in a HSR network planning process. Some deficiencies in the final Spanish ranking list clearly highlight the model's weaknesses. It is important to identify the predominant economic activity of a metropolitan area (not only its per capita GDP) as a demand attractor and the type of future HSR operation. A different evaluation should be given to the cities located within a 200 km radius from the centre of a major metropolitan area, especially if HSR regional services are to be offered to potential commuters. The previous alternative transportation modes to HSR for each candidate corridor are also factors capable of producing slight modifications in the final ranking results. The location and accessibility of the future HSR station from the city centre will also affect a city's assessment, although its location is not usually fixed in this initial planning stage.

Finally, recommendations for any new HSR network planning process include setting down the main targets and priorities before ranking the potential corridors; and conducting a study of the previous transportation system. Some criteria for territorial equity could help to avoid future transportation accessibility deficiencies for cities that are not part of major metropolitan areas.

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