Sustainable Development of Railway Corridors: Methods and Models for High Speed Rail (HSR) Demand Analysis

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Abstract. The realization of High Speed Rail (HSR) lines generates different type of effects that have been observed and studied in the scientific literature in last decades. The paper focuses on the travel demand models to estimate the effects of HSR on passenger mobility. The HSR travel demand may be segmented into three main components: diverted demand from other modes, or from other rail services, to HSR; induced demand, which can be direct and indirect; economy-based demand growth. The aim is to analyse and highlight the actual trend of scientific publications on the HSR demand analysis, thus identify the existing research gaps and the needs inside this trend, so the necessary future directions of research.

Keywords: High Speed Rail (HSR) · travel demand models · sustainable development · railway corridors · state-of-the-art

1 Introduction

According to the Union International des Chemins de Fer [1], there are more than 100,000 km of planned and operative High-Speed Rail (HSR) lines in the world: 52,484 km in operation, 11,960 km under construction, 11,383 km planned, and 28,586 km planned over the longer term. The largest network today is in China (35,388 km), followed by Spain (3330 km), which has overtaken Japan (3041 km) and then France (2734 km). The HSR network in Italy includes less than 1000 km in operation and about 120 km under construction.

Historically, the first HSR has been implemented in Japan with Shinkansen technology since 1975: an infrastructure characterized by the presence of slab tracks and not of ballast. Afterwards, HSR spread to Europe and almost every country developed its own technology: TGV in France since 1981, Pendolino in Italy since 1988 and AVE in Spain since 1992. In the last decades, HSR lines spread worldwide; and today China is the global leader in HSR, given his primacy in extension of railway lines.

The construction of HSR lines generate potential effects that have been studied and analysed in the scientific literature. They may be grouped into: *transportation*, such as infrastructures, services and demand; *socio-economic*, such as economic growth,

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accessibility, equity; and *environmental*, such as energy saving and decarbonization. In more general terms, HSR effects may be brought back to some of the 17 Sustainable Development Goals of United Nations [2]. Goal 9 can be recalled: "Build resilient infrastructure, promote sustainable industrialization and foster innovation". Goal 9 includes Target 9.1 "Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-beings, with a focus on affordable and equitable access for all". Hence, Goal 9 determine direct impacts on industry, innovation, and infrastructure, however, there are also indirect impacts on climate health. Goal 13: "Take urgent action to combat climate change and its impacts. Climate change is a real and undeniable threat to our entire civilization. The effects are already visible and will be catastrophic unless we act now. Through education, innovation and adherence to our climate commitments, we can make the necessary changes to protect the planet. These changes also provide huge opportunities to modernize our infrastructure which will create new jobs and promote greater prosperity across the globe." The pursuit of goal 13 is essential for sustainable development. HSR is the mode/service of transport that competes directly with air transport for passenger mobility considering the economic and social components. The existing research shows that HSR is the mode/service with the lowest carbon footprint per passenger/Kilometer, while air transport is the mode with the highest carbon footprint. Therefore, in conditions of economic and social parity, HSR allows a strong pursuit of the environmental component expressed by goal 13 [2].

The paper focuses on the travel demand models to estimate the effects of HSR on passenger mobility. In the current scientific literature, the HSR travel demand is commonly segmented into three main components: *diverted* demand from other modes, or from other rail services, to HSR; *induced* demand, which can be direct and indirect; *economy-based* demand growth. The objective of the paper concerns the review of the current scientific literature on HSR travel demand analysis and assessment, by means of existing and methods and models. Thus, the aim is the identification of the existing gaps in the state of the art, in order to identify possible future directions of research. Thereby, the remaining part of the paper is articulated as follows. Section 2 contains some HSR definitions, reported in the main reference documentation of EU and international association. Section 3 is subdivided into two parts: the first part describes the HSR demand variables and the second part describes the main papers reporting case studies of application of passenger travel demand models for HSR. Finally, the research perspectives are discussed in the last section.

This work is aimed to support transport planners and decision-makers in the evaluation of future investment in HSR lines by means of methodological and modelling tools to assess the potential travel demand.

2 HSR Definitions

This section reports the main definitions of HSR existing in the technical literature, which may be classified as definitions based on the characteristics of the railway infrastructure, such as the maximum speed, and definitions based on the characteristics of the railway services, such as the use of the railway infrastructure by the different services.

As far as concerns railway infrastructure, it is necessary to recall the four main advancements regarding the HSR definitions in EU.

EU introduced in 1996 [3] some definitions of HSR associated to the maximum speed that trains could reach while travelling on a specific track segment. According to EU, the term "High Speed Rail" indicates a system "composed of the railway infrastructures comprising lines and fixed installations, of the trans-European transport network, constructed or upgraded to be travelled on at high speeds, and rolling stock designed for travelling on those infrastructures.". The EU Directive 48/1996 established that high speed infrastructure comprises three types of lines:

- "specially built high-speed lines equipped for speeds generally equal to or greater than 250 km/h";
- "specially upgraded high-speed lines equipped for speeds of the order of 200 km/h":
- "specially upgraded high-speed lines which have special features as a result of topographical, relief or town-planning constraints, on which the speed must be adapted to each case."

European Rail Infrastructure Managers in 2008 [4] classified railway lines according to the different demand segments, and infrastructure performances (axle load). Among the identified classes, the characteristics of the following railway networks are reported below (see Table 1):

- High-Speed (HS) passenger network with speeds higher than 250 km/h;
- Conventional High-Speed (CHS) passenger network with speed up to 250 km/h;
- Heavy Freight (HF) network with 100 km/h and up to 35 tons for axle load; and
- High-Speed/Logistical Freight (HS/LF) network with speeds up to 250 km/h.

A strategic vision for the above railway networks at year 2035 has been also proposed; in particular, a maximum speed of 360 km/h was foreseen for the HS network, taking into account the business needs of potential travellers (Table 1).

Table 1. Vision for some railway networks at 2035 [4]

	Railway network	2006/2007		2035	
		Speed (km/h)	Axle load (tons)	Speed (km/h)	Axle load (tons)
Pax	H.S.(*)	300	18	360	18
	C.H.S.(**)	200	20	250	18
Freight	H.F.(−)	100	25	100	Up to 35
	H.S./H.F.(°)	160	20	Up to 250	18

(*)High Speed; (**)Conventional High Speed; (−)HF: Heavy Freight; (°)HS-HF: High Speed-Heavy Freight.

EU directive of European Parliament and of the Council of 11 May 2016 [5] integrated the criteria for identifying HSR lines introduced in [3]:

- specially built high-speed lines equipped for speeds generally equal to or greater than 250 km/h;

- specially upgraded high-speed lines equipped for speeds of the order of 200 km/h;
- specially upgraded high-speed lines which have special features as a result of topographical, relief or town planning constraints, to which the speed must be adapted in each case. This category includes interconnecting lines between high-speed and conventional networks, lines through stations, accesses to terminals, depots, etc. travelled at conventional speed by 'high-speed' rolling stock.

Finally, UIC released a directive in 2018 [1], consistent with the EU standards, where "High speed rail (HSR) encompasses a complex reality involving many technical aspects, such as infrastructure, rolling stock and operations, as well as strategic and cross-sector issues including human, financial, commercial and managerial factors". Moreover, UIC states that "HSR is still a grounded, guided and low grip transport system: it could be considered to be a railway subsystem". The most important change comes from the speed: "HSR means a jump in commercial speed and this is why UIC considers a commercial speed of 250 km/h to be the principal criterion for the definition of HSR.". A secondary criterion is admitted on "average distances without air competition, where it may not be relevant to run at 250 km/h, since a lower speed of 230 or 220 km/h or at least above 200 km/h is enough to catch as many market shares as a collective mode of transport can do."

As far as concerns railway services, Campos et. al., (2009) [6] introduced an economic definition of the HSR service, which is defined as "the relationship of HSR with existing conventional services, and the way in which the use of infrastructure is used". They identified four exploitation models:

1. *exclusive exploitation* model, when a complete separation exists between high speed and conventional services, each one with its own infrastructure (model adopted in Shinkansen technology in Japan);
2. *mixed high-speed* model, when high speed trains run either on specifically built new lines or un upgraded segments of conventional lines (model adopted in TGV technology in France);
3. *mixed conventional* model, where some conventional trains run on high speed lines (model adopted in AVE technology in Spain);
4. *fully mixed conventional* model, where both high speed and conventional services can run (at their corresponding speeds) on each type of infrastructure.

Campos et al. [5] categorized the Italian railway network as "Fully Mixed Conventional", just for the Rome-Florence line. Particular attention has been given to the study of the Southern Italy railway system, with a focus on the experimental studies about the introduction of services using the conventional and HSR networks. A model has recently been proposed in order to analyse the services, defined as "hybrid", which operate on two different networks [7], proposing the formalization of the optimal timetable project model with unchanged infrastructural resources [8].

3 Travel Demand Models

The travel demand models presented in this paper have their theoretical background in Transport Systems Models (TSMs) framework [9–13]. TSMs simulate a transport system through a process, in which transport supply and travel demand interact generating the

flows and the performances of the transport system. TSM is composed of three main elements. The transport supply model simulates the utilities of users deriving from the use of transport infrastructures and services; The travel demand model simulates user choices based on the performance of transport infrastructures and services. The supply-demand interaction model simulates the interaction between the user's choices and the performance of the infrastructures and the services.

Travel demand models may be broadly classified into two main approaches: *aggregate* models and *disaggregated* models.

Aggregated models may be segmented into three categories:

- *statistical-descriptive* models which estimate the levels of demand throughout relationships with attributes belonging to the level-of-service and socio-economic class;
- *time series* models which use historical data to forecast demand flows with given characteristics (e.g. origin-destination relationship);
- *partial-share* models, which simulates the user choice method through a procedure of partial sequential choices, or steps; the most common case is constituted by multi-stage models, including trip generation, trip distribution, time choice (arrival/departure), service choice, route/run choice.

Disaggregated models are theoretically and operationally more complex in relation to the difficulty of finding data on user choice behaviour. They can be based on the theory of discrete choice model [9, 14, 15]. The discrete choice model has been specified with different formalization of alternatives and linked perceived utility random utility [9, 14, 15], fuzzy utility [16, 17], or quantum utility [18, 19].

Generally, the random utility models differ according to the perceived utility function, which can be specified by considering different functional relationships between the levels of choice (hierarchical or factorial), different hypotheses on structure of choice set of alternatives, and different hypotheses about the distribution of random residuals. The different hypotheses about the distribution of the random residuals lead to two main categories of models:

- models with choice probabilities expressed in closed form (e.g. multimodal logit, nested logit);
- models with simulated choice probabilities (e.g. probit, mixed logit).

As far as concerns the partial share models, the models associated to the main trip choice dimensions of travellers are reported in the following, according to [9, 11, 12].

The *trip generation* model estimates the number of trips from an origin o, given the purpose and the temporal interval (sh):

$$\mathrm{d(o/sh)} = d(\mathbf{x}_\mathrm{G},\ \beta_\mathrm{G}) \tag{1}$$

where: $\mathbf{x}_\mathrm{G}$ is the vector of attributes and $\boldsymbol{\beta}_\mathbf{G}$ is the vector of generation parameters.

The *trip distribution* model estimates the percentage/probability of trips undertaken by travellers to a destination d, given the origin, the purpose and the temporal interval (osh):

$$\mathrm{p(d|osh)} = \mathrm{p}\left(\mathbf{X}_\mathrm{D},\ \boldsymbol{\beta}_\mathbf{D}\right) \tag{2}$$

where: $\mathbf{X}_{\mathrm{D}}$ is the matrix of attributes and $\boldsymbol{\beta}_{\mathbf{D}}$ is the vector of distribution parameters.

The *mode-service choice* model estimates the transport mode-service m chosen by the travellers given the origin, the purpose, the temporal interval and the destination (oshd):

$$\mathrm{d}(\mathrm{m}/\mathrm{oshd}) = \mathrm{d}\left(\mathbf{x}_{\mathrm{M}},\ \boldsymbol{\beta}_{\mathbf{M}}\right) \tag{3}$$

where: $\mathbf{x}_{\mathrm{M}}$ is the vector of attributes and $\boldsymbol{\beta}_{\mathbf{G}}$ is the vector of mode-service parameters.

The *route, or run, choice* model estimates the route, or run, r chosen by travellers given the origin, the purpose, the temporal interval, the destination and the mode-choice (oshdm):

$$\mathrm{d}(\mathrm{r}/\mathrm{oshdm}) = \mathrm{d}\left(\mathbf{x},\ \boldsymbol{\beta}_{\mathbf{R}}\right) \tag{4}$$

where $\mathbf{x}_{\mathbf{R}}$ is the vector of attributes and $\boldsymbol{\beta}_{\mathbf{R}}$ is the vector of route, or run, parameters.

4 HSR Travel Demand Variables and Models

4.1 Framework of Classes of Demand

The transport demand generated by HSR services is sub-divided in the scientific literature into three classes [20]:

- Diverted demand:
  - from other modes (e.g., car, air, and bus) to HSR, and
  - from other rail services to HSR;
- Induced demand:
  - direct (e.g., changes in trip frequency)
  - indirect (e.g., increase in mobility due to changes in lifestyle and/or land use;
- Economy-based demand growth (Table 2).

Diverted demand is a shift of demand, or diversion, towards HSR services. This diversion may occur either from other modes, as in the case of a shift from airplane/car to HSR services, or from other rail services, as in the case of shift from intercity to HSR services. The diverted demand could depend on several attributes, endogenous to the transport system, such as the location and the number of railway stations, the location of airports, the ticket price, the service frequency.

Existing studies show that entity of diverted demand towards HSR from other modes could be different in relation to HSR in-vehicle travel times. The revealed user behaviours concerning the diversion towards HSR mode-service from air mode show the following elements [1, 21]:

- when HSR travel times are less than 2.5 h, travellers' choices are oriented almost totally to HSR alternative (train is the dominant mode);

Table 2. Classification of demand generated by HSR services [20].

Diverted	From other modes	Shift from air/auto to HSR	Endogenous factor
	From other rail services	Shift from Intercity to HSR	
Induced	Direct	Changes of trip frequency, destination or related activity pattern	
	Indirect	Increase of mobility due to changes in activity patterns and land use	Exogenous factor
Economy-based		Decrease/increase of mobility due to economy trends	

- when HSR travel time is about 3.5 h, travellers' choices are equally distributed between train and air;
- when HSR travel times are higher than 5 h, travellers' prefer air mode.

Induced demand depends on [20]:

- directly on travel behaviour in terms of frequency, destination, or organization of activities, and it is characterized by factors which are endogenous to the transport system,
- indirectly on changes in land use, or in lifestyle of travellers, and it is characterized by factors which are exogenous to the transport system.

Economy-based demand is characterized by national and international economic trends, considering that higher-income users travel more. This component of demand is a function of additional attributes, such as: accessibility and regional equity, and thus of exogenous factors [20].

Some before-after studies present in the literature concern mainly the observation of the diverted demand component. There are fewer cases where the induced component has been explicitly quantified, while in any case the demand generated form the economic growth was reported separately. The studies show, in general, positive effects in the terms of diverted demand towards HSR services both from other modes and from conventional rail services [21–23]. In Italy the opening of HSR line from Turin to Salerno in 2009 generated an increment of railway traffic from 15 million of pax/year in 2009 to 43 million of pax/year in 2018 [24], of which 7 million have been diverted from conventional railway services, 19 million have been diverted from private car, buses, and air modes, and 17 million constitute the component of induced demand.

4.2 Models

This section contains a description of existing publications mainly focusing on models estimating the diverted demand towards HSR, classified according to the country of application of the model.

The selected publications, in some cases, are more general dealing with the presentation of a general framework for estimation of the HSR demand components described

in the previous paragraph. As matter of fact, it is worth to recall the study of [25], that defined a general modelling framework for the evaluation of the three components of the HSR travel demand and their reciprocal interactions. The authors further analysed the case of the entering of a new private HSR company in the Italian railway market, that generated a competition between private and public railway companies, and airline companies, on long-distance inter-city trips [26].

The modelling of the HSR diverted demand is treated in several contributions of literature concerning different countries.

In Italy, Cascetta et al., (2011) [27] presented a study of the impacts of the HSR service operating along the Italian Rome-Naples relationship. The authors analysed the diverted demand towards HSR service from other transport modes and from other rail services (e.g., Intercity, Eurostar services). They built a discrete choice model on the dimensions of mode-service-company-run for "home-based trips" and "non-home-based trips" purposes. Cascetta and Coppola (2012) [28] calibrated a discrete choice model on the dimensions of mode-service-run for different travel purposes (e.g., business, and other purposes). The specified model was a multi-level nested logit model, where the different levels were transport modes, rail services, HSR companies and service class. Cascetta E. and Coppola P. (2014) [29] analysed the effects of the entering of a single public HSR operator in the Italian railway market from 2005 to 2012; and the effects of the entering of a second private HSR operator from 2012. The authors developed an integrated modelling system to forecast the effects of competing timetables-services-prices between the HSR and air companies, auto, conventional railway mode-services. Borsati and Albalate (2020) [30] empirically studied the effects of the opening of HSR services in Italy on the total distances travelled by light vehicles along motorways during the period 2001–2017 and the entity of these effects after the opening of on-track competition between two HSR Italian companies.

As far as concerns France, Zembri (2010) [31] provided an empiric study on the rail-air competition between HSR services, called TGV, and air services in France, and on the conditions resulting in the success of HSR service in terms of demand diverted. Behrens and Pels (2012) [32] calibrated a nested (and mixed) multinomial logit models of HSR-air passenger demand traveling along the London-Paris relationship and estimated the direct elasticity of passenger demand with respect to frequency for business and leisure purposes. They considered the competition between a combination of four airports (Heathrow, Gatwick, Luton, London City) and four airline companies (Air France, British Airways, British Midland Airways, EasyJet) and the HSR service operated by Eurostar. Direct and cross elasticities are estimated with respect to travel time, frequency, and fare per each alternative, year, and trip purpose by means of a multinomial logit model.

The Spanish country was studied in some publications. Roman et al. (2009) [33] analysed the extra-urban rail demand, considering the potential competitors to the HSR service, diverted by other modes of transport (air, private car and bus). A nested logit model is specified and calibrated, and the direct and cross elasticities are estimated. Roman and Martin (2014) [34] simulate passenger choices between two transport alternatives: HSR rail and air services. Two models have been specified and calibrated: multinomial logit and mixed logit. Cross elasticity is introduced, but not calculated.

As far as concern China, Cheng (2010) [35] examined the impact of HSR on the intercity transportation market in Taiwan. When HSR entered in operation the generated traffic was mainly diverted from air mode, conventional railway, and buses. It is worth noting that air transportation almost exited the market. Li and Sheng (2016) [36] studied the diverted demand between two choice alternatives, air and HSR, along the Beijing-Guangzhou corridor (China). They conducted a stated preference survey to estimate the parameters of multinomial logit-based discrete choice models. Zhang et al. (2017) [37] used panel data of air passenger demand from 2010 to 2013 to analyse the effects of HSR on the main airlines in China. According to the authors, HSR services had relevant negative impacts on the air demand, as it became much more elastic after the introduction of competing HSR services. Ren et al. (2019) [38] analysed the impact of HSR services on intercity travel behaviour along the Chengdu-Chongqing corridor (China), with a focus on the diverted demand towards HSR services.

In Japan, Yao and Morikawa (2005) [39] specified a multi-level discrete choice model on the dimensions of mode/service/run. The alternatives considered were bus, car, airplane. Clever and Hansen (2008) [40] focused on competition between air and HSR modes in Japan, analysing the trade-offs between accessibility, frequency, and speed of the two services.

Hensher (1997) [41] specified and calibrated a discrete choice model in the dimensions of mode, service and run estimating the diverted demand to HSR from other modes in Australia. The direct and cross elasticities have been introduced and calculated.

5 Final Remarks

The paper deals with travel demand models to estimate the effects of HSR services on the passenger mobility at country level, focusing on the inter-city trips. According to the literature, the HSR travel demand may be segmented into three main components: diverted demand, induced demand, economy-based demand.

Literature studies focused mainly on the development of models for the estimation of the diverted demand towards HSR in the countries where high investments were allocated for the realizations of HSR lines. The proliferation of these publications was mainly due to the attempt of capturing the demand diversion from the air mode, which was the main macroscopic effect in the market generated by the opening of HSR lines.

Publications specifically dealing with models to estimate induced demand are less numerous in the literature. It is worth to recall the publication [29], where trip generation and trip distribution models have been specified and calibrated in order to estimate the demand induced by the activation of HSR service in Italy; and the publication [38], which reports the spatial variations of travel demand through a comparison of trip intensity indices of different origin-destination (OD) pairs in China.

The travel demand generated by the economic growth may be estimated as the result of the specification and application of Spatial Economic Transport Interaction (SETI) modelling frameworks (see [42], and the references included), as in [10], where the authors developed an integrated macro-economic and transport system of models for passenger and freight demand estimation at country level.

In general, from the literature review it emerges that it is possible to associate to each of the three HSR demand components one (or more) partial share model(s) simulating one (or more) trip choice dimension(s), presented in Sect. 3 (see Table 3).

The diverted demand may be estimated by means of mode-service-company-run choice models, presented respectively in Eqs. (3) and (4). The induced demand from changes of trip frequency and trip destination may be estimated by means of trip generation and trip destination models, presented respectively in Eqs. (1) and (2). The estimation of induced demand by the modification of passengers' activity patterns and of land use, and of the demand generated by the economy growth, implies the building of SETI modelling frameworks able to capture the two-way relationship between spatial economic and transport systems (see [42], and the references included).

Future research will concern a more comprehensive and detailed classification of literature on HSR travel demand models according to the HSR demand model characteristics in terms of specified attributes and calibrated parameters.

Table 3. HSR demand components and trip choice dimension models.

HSR demand component	Model	Type
Diverted	Mode-service/route(run)	Travel demand
Induced	Trip generation/distribution	
	Activity generation/location	SETI(*)
Economy-based	Production-consumption generation/location	

(*) Spatial Economic Transport Interaction model, [42]

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