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Review Article

Air Transport versus High-Speed Rail: An Overview and Research Agenda

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The development of high-speed rail (HSR) services throughout the last decades has gradually blurred the concept of competition and cooperation with air transportation. There is a wide range of studies on this subject, with a particular focus on single lines or smaller regions. This article synthesizes and discusses recently published studies in this area, while aiming to identify commonalities and deviations among different regions throughout the world, covering services from Europe, Asia, and North America. Our meta-analysis reveals that the literature is highly controversial and the results vary substantially from one region to another, and a generalization is difficult, given route-specific characteristics, such as demand distribution, network structure, and evolution of transportation modes. As a major contribution, we propose a list of five challenges as a future research agenda on HSR/air transport competition and cooperation. Among others, we see a need for the construction of an open-source dataset for large-scale multimodal transport systems, the comprehensive assessment of new emerging transport modes, and also taking into account the resilience of multimodal transport systems under disruption.

1. Introduction

After long-lasting successes in Japan (Shinkansen), France (TGV), and Germany (ICE), HSR has seen further success stories in countries like China, Italy, Spain, and Korea; several routes are under discussion in United States and United Kingdom. While it is costly to plan, construct, operate, and maintain a HSR system, with billions of dollars, HSR has significant impacts on mobility patterns [1, 2], economic development [3, 4], energy consumption [5, 6], land use of a country [7], and overall service quality [8]. Moreover, an often advertised effect of HSR is that it will be a key technology for greener transportation and railway stations are usually built closer to city centers than airports, which gives the HSR a travel time advantage over other transportation modes between 200 km and 1,000 km [9]. In Figure 1, we highlight an example for traveling between Beijing and Shanghai in China. The travel time for both modes is almost identical, while the (ground) distance is more than 1,200 km. Accordingly, many passengers take the HSR for trips between Beijing and Shanghai, given that (a) the ticket price for HSR is roughly one-third of the air fare and (b) the level of comfort (e.g., as measured by available space) is slightly higher. This shows that the competition range between HSR and air transportation has increased significantly over the years. Naturally, this is a rather specific example for China's recent high-speed railway success story and cannot be transferred directly to other regions, as we discuss below.

The competition and cooperation between air transport and HSR in Europe and Asia have been extensively explored, based on many case studies of single routes or smaller regions. However, the results in these studies do not necessarily hold cross-regional transfers [10, 11]: since the competition and cooperation patterns between air transport and HSR are dissimilar in different markets, it is necessary to have a global overview on the developments in different regions based on cross-comparison of air transport and HSR [12]. In particular, the route structure of the HSR network in a region has substantial impacts on the passenger demand and revenues; and transferring results from one topology to another is

Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40	|	Metro Line 4
08:50	|	
09:00	Xuanwumen	
09:10	|	Metro Line 2
09:30	|	
09:40	Dongzhimen	
09:50	|	Metro Airport Line
10:00	Beijing Capital International Airport	
10:10		
...	...	
11:20		
11:30	Beijing Capital International Airport	Air China 1557
11:40	|	
11:50	|	
...	...	
13:20	|	
13:30	|	
13:40	Shanghai Hongqiao	
13:50	Pick-up luggage	

(a) Travel mode: metro + aircraft

Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40	Beijing South Railway Station	Metro Line 4
08:50		
09:00	Beijing South Railway Station	High-speed rail G1
09:10	|	
09:20	|	
09:30	|	
09:40	|	
09:50	|	
10:00	|	
...	...	
11:20	|	
11:30	|	
11:40	|	
11:50	|	
13:10	|	
13:20	|	
13:30	|	
13:40	|	
13:50	Shanghai Hongqiao	

(b) Travel mode: metro + high-speed rail

Figure 1: Comparison of air transportation and high-speed rail for a trip from Beijing Capital Times Square to Shanghai Hongqiao in China. Despite the large spatial distance of more than 1,200 km, passengers using either mode arrive approximately at the same time in Shanghai. This example highlights the substantially different competition range between both modes, compared to the standard values for other regions around the world (often 200–300 km).

often difficult [13–15]. As noted in [16], infrastructure costs in United Kingdom are particularly high and a major hurdle for HSR realization. In China, on the other hand, HSR construction costs are rather low, especially due to lower labour costs, high-volume projects with smaller amortized costs, and cheaper tunnel construction [17]. Different costs significantly affect the profitability of HSR and the competitiveness against air transport.

The first goal of this study is to provide a synthesis on the differences and similarities of the competition and cooperation effects between air transport and HSR across different regions. In recent years, much progress has been made in this research area. Therefore, in this paper, we provide a review up to 2016 on the competition and cooperation between air transport and HSR. Our study is based on ten countries, many of which are key players in high-speed rail in the last years: five countries from Europe (Spain, France, Germany, United Kingdom, and Italy), three countries from Asia (China, Japan, and South Korea), and two from North America (Canada and United States). We synthesize and discuss recently published studies regarding these ten countries, with a particular focus on (a) passenger demand, (b) travel time, (c) ticket price, (d) seats/frequencies, and (e) environment and social welfare. For many evaluation factors, we show that the existing literature is highly controversial, while it seems to be globally agreed that travel time and high passenger demand are the key drivers for the success of a HSR system. Moreover, the structure of the network and distribution of population along a line are critical factors for profitability of HSR lines in competition to air carriers. For the cooperation, on the other hand, connection time between modes is critical for the success.

As a second contribution, we propose a list of five main challenges as a future research agenda on HSR/air transport competition and cooperation. Our list mainly aims to inspire researchers rather than provide a complete list, although practitioners and policy makers could also benefit. Among others, we see a need for the construction of an open-source dataset for large-scale multimodal transport systems, which will allow researchers to perform wider comprehensive and comparable studies on the effects of competition and cooperation. Current studies are strongly biased by the availability of data for a few regions, for example, in Spain. Furthermore, a comprehensive assessment of new emerging transport modes, such as coaches and overnight HSR trains, taking into account the resilience of multimodal transport systems under disruption, is necessary as well.

The remainder of this paper is organized as follows. Section 2 provides an overview of air transport networks and HSR networks in Europe, Asia, and North America, together with the competition and cooperation effects between air

Table 1: Overview of the domestic air transport in five countries in Europe, three countries in Asia, and two countries in North America for the year 2015. Note that the busiest airport is ranked according to the number of domestic passengers. Data source: Sabre Airline Solutions (https://www.sabreairlinesolutions.com/). The abbreviation LF stands for load factor.

Continents	Country	Airport	Busiest airport	Avg. LF	Yield (Cent/km)	Departures	Total passengers
Europe	ES	45	MAD	81.63%	11.26	303,834	30,851,832
	FR	73	ORY	79.15%	20.10	52,433	23,978,266
	DE	35	MUC	73.97%	18.79	235,986	24,601,384
	UK	40	LHR	76.24%	23.47	308,476	22,613,459
	IT	41	FCO	80.20%	9.16	242,029	29,057,702
Asia	CN	152	PEK	83.09%	14.38	3,160,887	415,336,119
	JP	72	HND	77.51%	18.01	814,697	109,489,933
	KR	15	CJU	82.44%	17.70	145,738	22,839,327
North America	CA	257	YYZ	80.20%	12.79	796,976	46,253,333
	US	781	ATL	84.72%	10.26	7,925,761	697,090,531

Table 2: Overview of the HSR in five countries in Europe, three countries in Asia, and two countries in North America. Note that we use the latest data which is available. Data source: collected by hand from public accessible web pages.

Continents	Country	Stations	Length (km)	Busiest route	Busiest station	Total passengers (year)
Europe	ES	30	3,100	Madrid-Barcelona	Madrid Atocha	14,900,000 (2013)
	FR	172	2,037	Paris-London/Lille	Paris Gare du	114,450,000 (2010)
	DE	180	2,635	Frankfurt-Hannover	Frankfurt	77,200,000 (2009)
	UK	4	108	High Speed 1	London St Pancras	Not Available Yet
	IT	23	926	Milan-Rome	Rome Termini	38,900,000 (2013)
Asia	CN	514	19,449	Beijing-Shanghai	Shanghai Hongqiao	910,000,000 (2015)
	JP	104	2,765	Tokaido-Shinkansen	Tokyo	324,442,000 (2010)
	KR	45	420	Gyeongbu-Gosokseon	Seoul	54,068,370 (2014)
North America	CA	None	None	None	None	None
	US	16	734	Northeast Corridor	Pennsylvania	3,343,143 (2013)

transport and HSR. Discussions and a list of future research directions are provided in Section 3.

2. HSR and Air Transport Networks in Europe, Asia, and North America

There is a rich body of literature on HSR versus air transportation, with a focus on single lines or smaller regions. Generalizing results from one region to another is difficult, given route-specific characteristics, such as demand distribution, network structure, and evolution of transportation modes.

2.1. A Survey on High-Speed Railway versus Air Transportation. Table 1 provides an overview of the domestic air transport in these countries for the year 2015. We can observe that United States has the maximum number of airports, among which ATL (Hartsfield–Jackson Atlanta International Airport) is the busiest domestic airport in the world, followed by PEK (Beijing Capital International Airport) in China and HND (Haneda Airport) in Japan. It is interesting to note that the yield in Italy is the lowest (i.e., the airlines are probably least profitable) among the ten countries, while United Kingdom has the highest yield (i.e., the airlines are very likely to be more profitable). Table 2, on the other hand, provides an overview over the domestic HSR networks in all countries. China has the largest network, regarding the total length and also the number of stations. The busiest station in China is Shanghai Hongqiao, at the same time the largest railway station in Asia. China is also the country with the highest number of passengers per year, followed by Japan. For an overview, see [56, 57]. The air transportation networks in different regions often share highly similar topological properties [58, 59].

In general, HSR lines can be categorized into four distinct types, depending on how the infrastructure is shared [18]; see Figure 2. In the exclusive exploitation model, high-speed rails and conventional rails have a clear separation and both of them have their own infrastructure. In the mixed high-speed model, HSR can run on specially built lines and upgraded conventional lines. Conventional rails can run on both infrastructures in the mixed conventional model. Both HSR and conventional rails can run on both infrastructures in the fully mixed model.

Figure 3(a) shows the HSR networks in the five European countries (Spain, France, Germany, United Kingdom, and Italy), while Figure 3(b) shows their domestic air transport networks. Note that only domestic flights with more than 1,000 passengers per month and with distances less than 1,000 km are shown. We set the distance threshold as 1,000 km since HSR is most competitive against air transport for routes less than 1,000 km [60]. We can observe that highly developed air transport networks are still denser than newly emerged

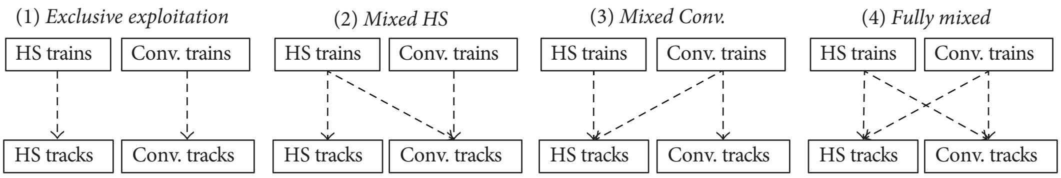
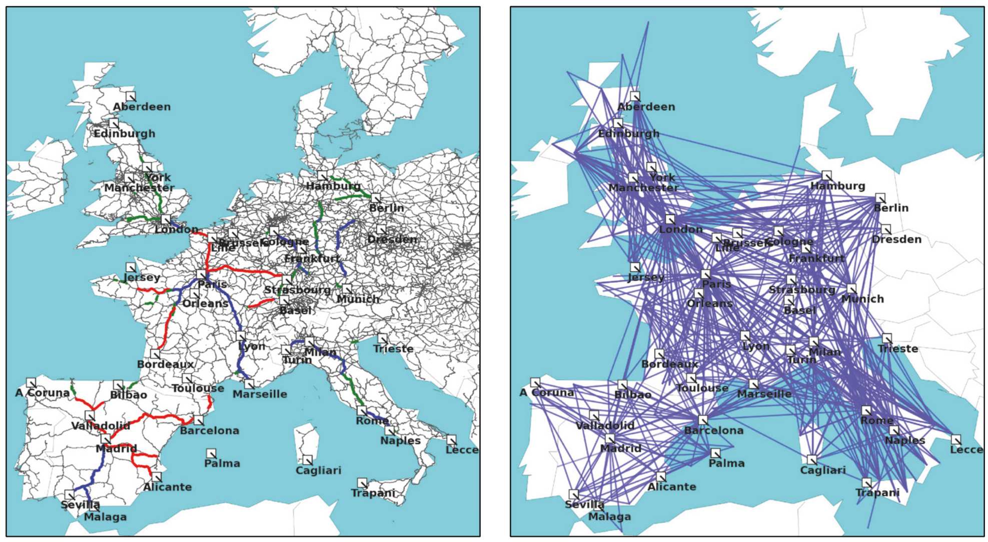


Figure 2: Four types of HSR models adapted from [18], where HS represents high-speed and Conv. represents conventional.



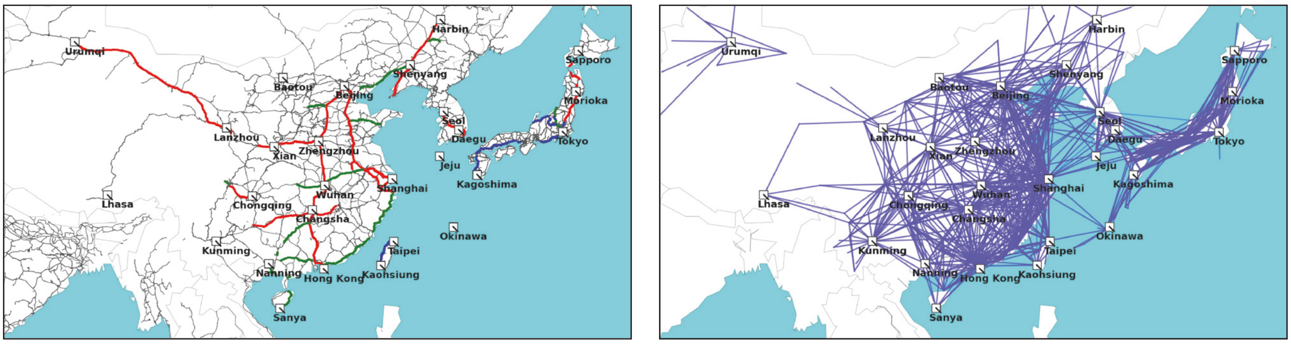
(a) HSR network (data source: OpenStreetMap)

(b) Airport network (data source: Sabre Airline Solutions)

Figure 3: Comparison of HSR networks and airport networks in five European countries (Spain, France, Germany, United Kingdom, and Italy). In the HSR networks, different colors indicate different maximum speed: green color > 200 km/h; blue color > 250 km/h; red color > 300 km/h. In the airport networks, domestic flights with passengers more than 1,000 per month and with distances less than 1,000 km are shown. It can be seen that highly developed air transport networks are still denser than newly emerged HSR networks.

HSR networks. Below, we briefly summarize HSR and air transport networks in all five European countries. The Alta Velocidad Española (AVE) in *Spain* is a mixed conventional model, with a comprehensive network of more than 3,100 km. The country disposes approx. 45 passenger airports. The busy route between Madrid and Barcelona [61] is a recurring subject of research for the competition of HSR with airlines. We believe that a major reason is that HSR operator Renfe makes many datasets available for public use. The *French* Train à Grande Vitesse (TGV) belongs to the category of mixed high-speed model and is a hybrid network of more than 2,030 km. France has around 70 passenger airports. As of 2015, the majority of the network is highly unprofitable and the number of stations has to be significantly reduced, in order to make the network more attractive [62]. The *German* Intercity Express (ICE) falls into the category of full mixed model and is best described as a hybrid network. The overall length of the network is estimated with 2,635 km. The German airport network consists of a core with about 35 active passenger airports. The HSR network of *United Kingdom* is best described as a hybrid network. The airport network in United Kingdom consists of around 40 airports with regular passenger traffic. The *Italian* HSR (operated by Trenitalia and NTV) belongs to the category of full mixed model and is best described as a corridor. The HSR network mainly consists of one line from Turin to Naples, of approx. 900 km length. The airport network in Italy consists of around 40 airports with regular passenger traffic.

Figure 4(a) shows the HSR networks in the three Asian countries: China, Japan, and Korea, while Figure 4(b) shows domestic airport networks. Note that only domestic flights with passengers more than 1,000 per month and with distances less than 1,000 km are shown. We set the distance threshold as 1,000 km since HSR is most competitive against air transport for routes less than 1,000 km [60]. Similar with European cases, highly developed air transport networks are much denser than newly emerged HSR networks in the three Asian countries. Below, we briefly summarize HSR and air transport networks in all three Asian countries. The *Chinese* HSR network is the largest worldwide and best categorized as mixed usage and hybrid network. Following its fast spreading during the recent years, the network consists of tracks summing up to over 19,000 km. Regarding the passenger usage per year, China is ranked number one in the world [63]. Almost one billion passengers have traveled with HSR transportation in the year 2014. The airport network of China consists of 193 airports with more than 1500 passengers per month in the year 2015. The Shinkansen in *Japan* belongs



(a) HSR network (data source: OpenStreetMap)

(b) Airport network (data source: Sabre Airline Solutions)

FIGURE 4: Comparison of HSR networks and airport networks in three Asian countries (China, Japan, and Korea). In the HSR networks, different colors indicate different maximum speed: green color > 200 km/h; blue color > 250 km/h; red color > 300 km/h. In the airport networks, domestic flights with passengers more than 1,000 per month and with distances less than 1,000 km are shown. Similar with the situations in Europe, highly developed air transport networks are much denser than newly emerged HSR networks.

to the category of exclusive exploitation model and is best described as a corridor. Originally opened in 1964, on time with the Summer Olympics in Tokyo, the success of Japanese HSR networks started with the Tokaido Shinkansen [64]. Currently, the networks consist of 2,765 km HSR railways, linking most major cities on the islands of Honshu and Kyushu. Japan has around 70 airports with regular passenger traffic, distributed among its islands. The *South Korea* Train eXpress (KTX) was opened in 2004 and best described as an exclusive corridor. The network mainly consists of one line from Incheon International Airport, to Daegu/Busan, passing by Seoul. The track is around 350 km long. South Korea has 15 airports with regularly scheduled passenger service. The domestic transportation in South Korea is very special, given the extraordinary air travel demand from Seoul to Jeju, but no alternatives for transportation [65]. Therefore, it is interesting to note that the KTX network outranked the Korean air travel, regarding the number of passengers, already two years after its inauguration [18].

Canada does not have any high-speed railway. Although there had been plans for HSR in *United States* since 1960s [66], there is only one HSR service in operation: Acela Express in Northeast corridor between Washington and Boston, with 14 intermediate stops including Philadelphia and New York. The North American airport network is one of the largest in the world: approximately half of the worldwide air traffic takes place in this region. Moreover, 12 of the top 30 busiest airports in the world are located in the United States. The biggest airport is Atlanta, with almost 100 million passengers per year.

Full Service Airlines versus Low-Cost Carriers. Studies in the airline industry have empirically identified significant product differentiation and cost differences between full service airlines and low-cost carriers (LCCs). Although earlier studies are mostly for Europe and US, some recent studies have been carried out for Asian markets including China, which is a major HSR market. Hereby we briefly review the key differences between full service airlines and LCCs and also how they affect the competition/cooperation between air and HSR.

There are significant differences between full service airlines and LCCs: while full service airlines are often characterized by hub-and-spoke network structures, large route networks, large fleet size with multiple types of aircraft, and differentiated products serving heterogeneous passengers, including short-medium-long haul flights, LCCs generally have point-to-point network structures, low operating costs, and decreased ticket prices and are less comfort, with focus on short and medium haul flights. With continued growth, LCCs are expanding their operations at major airports/cities as well and this triggers more direct competition between full service airlines and LCCs. While LCCs are quite popular in Europe and US, there are still a few LCCs in China; their domestic market is less than 3% [67].

Based on the 2012 data and the controlling for travel time, Dobruszkes et al. showed that the European LCCs do not compete with HSR services [11]. However, the expansion of LCCs to major airports/cities might involve tougher competition with HSR, since one of the major advantages of HSR is to transport passengers from one city center to another [68]. With different market focus, that is, LCC for short or medium haul flight passengers only, cooperation between full service airlines and LCCs might also trigger more competition for HSR customers. This cooperation model is especially attracting for passengers with connecting flights, for instance, all-pass luggage transfer and security check. We believe that air-rail cooperation would contribute towards the ultimate goal of transporting passengers or goods from their origins to destinations safely, efficiently, and environmentally friendly.

2.2. Competition and Cooperation Effects between Air Transport and HSR Networks. This section provides an overview on the competition and cooperation effects between air transport and HSR networks as reported in the literature. The overall goal of this section is to collect evidence for commonalities and deviations among study results.

Different methodologies and models have been used in the literature, such as stated preference versus revealed preference and empirical estimation versus simulation. Stated preference (SP) and revealed preference (RP) are different ways to collect information on the preferences of consumers [69]. Although the data obtained from SP and RP is not always consistent, it is believed that SP is more useful when evaluating hypothetical choice alternatives, while RP is more appropriate for existing ones [70]. Empirical estimation is mainly based on the available data, experience, and knowledge, which are collected from the past, in order to obtain some findings [25], while simulation often requires to develop a model first, representing key characteristics, behaviors, and functions of the selected real-world process or system [71]. Note that the differences in conclusions may be partly ascribed to different methodologies and models used.

We list the major findings of research studies according to the following eight main categories: passenger demand, travel time, price, seats and frequencies, environment and social welfare, value of time, elasticity/cross-elasticity, and cost ranges. For each category, we synthesize major findings for the ten countries. This section lays the foundation for our discussion on future research in this area; see Section 3.

Effects on Passenger Demand. As a new transport mode, the entry of HSR into the medium- and long-distance markets triggers strong competitions with air transport. In addition to self-induced passenger demand, HSR also directly attracts significant numbers of passengers from other transport modes. Table 5 provides an overview of the competition and cooperation effects on passenger demand, including the region and time frame under study, the competition and/or cooperation effects covered, whether the data is real-world or not, and what main results are obtained. In general, it seems to be agreed that, after the entry of HSR, the short haul market share of air transport has declined and there are modal dynamics that passengers are shifting from air transport to HSR. Significant airfare reduction could regain demands back to air transport, particularly air transport operated by low-cost carriers. In addition, HSR is able to generate passenger demands by itself. On the other hand, some analysis showed that HSR has influenced passenger demand less than expected (France) or only for local regions (Paris). Moreover, mature HSR networks may face a period of reduced demand growth, after an initial phase of excitement (Japan).

Effects on Travel Time. Travel time is critical for the competitiveness of different transport modes. An overview of the competition and cooperation effects on travel time is provided in Table 6. It can be seen that passengers tend to select HSR if the travel time is shorter than air transport; these are travelers' behaviors in most European countries. In Japan, travel time is one of the most sensitive factors for passengers' choice behavior, while price is modestly sensitive. In China, HSR is rather competitive regarding total travel time in short-medium haul market. The cooperation between HSR and air transport in the case of London Heathrow airport shows large potentials in reducing total travel time for the passengers. An important, yet often ignored, contribution to travel time is the connection time between air transport/HSR, which makes schedule coordination crucial for successful intermodality.

Effects on Price. It is also interesting to check how the competition and cooperation between HSR and air transport influence the ticket prices. Table 7 provides an overview of the competition and cooperation effects on price. Most existing research focused on the aspect of competition. It can be observed that airlines (Italy, Spain, and China) often take the reaction to reduce ticket prices under the HSR competition. On the other hand, passengers in Japan are less sensitive to the travel prices; thus reducing the prices of air tickets probably cannot attract more passengers. Taking into account the price differentiation between leisure passengers and business passengers is beneficial for the airlines. Furthermore, it is challenging to predict, whether a planned HSR project will be profitable or not. Direct transfers of obtained HSR experiences from Asia and Europe to new adopter countries (e.g., United States, Canada, and Australia) are problematic because of contextual differences. In general, constructions costs have a significant impact on the success of link-based HSR: the longer the distance, the higher the construction costs for lines, in contrast to node-based air transportation. For countries with low HSR construction and maintenance costs, for example, China, the probability of HSR being profitable is much higher than in countries with high construction costs, for example, United Kingdom and United States. Yet, there are some countries, for example, Japan and Korea, which have relatively high construction costs, but highly profitable HSR transportation. Notably, the HSR networks of these (island) countries are all best categorized as exclusive corridors. Construction and maintenance costs directly influence ticket prices and profitability.

Effects on Seats and Frequencies. Table 8 provides an overview of the competition and cooperation effects on the number of seats and flight frequencies. The reactions of airlines taken under the HSR competition are not clear: reducing the number of seats (aircraft size) is one common action. Whether the entry of HSR leads to the reduction of flight frequencies is not consistent in different regions across the world. It is highly controversial whether the flight frequencies were increased or decreased and it should be evaluated based on a consistent dataset in future studies.

Effects on Environment and Social Welfare. Table 9 provides an overview of the competition and cooperation effects on the environment and social welfare. Several studies focused on at least one of the following criteria: air pollutants, noise, land use, energy, and greenhouse gas emissions [72]; when compared with air transport, one major advantage of HSR is its environmental improvement, especially on CO_2 emissions reduction. However, as shown by [9, 51, 73], decreases in one pollutant may lead to increases in another.

Most studies look at the air-HSR in Europe. Based on an empirical comparison between air and HSR on the London-Paris route, [73] showed that there is no clear advantage to one mode over the other in terms of air pollution and it is in favor of HSR regarding climate change. Reference [50] constructed a model to assess the environmental impact of different transportation modes, with application to a new construction of a HSR station at Madrid Barajas airport. Results showed that, with HSR, passengers traveling with aircraft and private car are reduced, thus leading to environmental benefits. On the other hand, increasing the travel cost of private car is picked up by air transport rather than HSR, thus leading to negative environmental impacts. Reference [16] concluded that the overall benefits of HSR in UK are mainly induced by time savings and that the environmental and wider economic impacts of HSR are relatively small. Reference [74] showed that HSR is *greener* than air transport per seat-km (or passenger-km) from both operation and life-cycle analysis perspectives, when the load factor of HSR is high enough, but load factor of air transport is lower; the freed runway capacity is not reused. Moreover, the main advantage of HSR against air transport is travel time and the integrated air-HSR could have larger environmental benefits. Reference [75] compared the environmental performance of HSR and air transport in European Union (EU) and it was shown that HSR has a better environmental performance than air transport and thus HSR should substitute air transport in order to mitigate environmental damage. Reference [53] investigated the environmental impact of CO_2 emissions for air transport and rail, taking into account the infrastructure construction stage and the service provision stage. Analysis based on panel data showed that the operation of aviation industry is socially beneficial in the observed period (1999–2007), although its CO_2 emission per passenger kilometer is higher than the one with rail. Reference [52] assessed several social and environmental effects when transforming a large airport into a multimodal transport node, where short haul flights would be substituted by HSR. With a theoretical model, [48] analyzed social welfare and environmental impacts due to the cooperation of air transport and HSR. The Madrid-Malaga route in Spain was used as an example to evaluate the proposed model. The results showed that, in both scenarios, there are gains from social and/or environmental aspects.

Although there is no HSR built in USA, yet there is a huge debate on the construction of HSR system, especially regarding environmental impacts. Reference [5] investigated the impact of HSR investments on interstate passenger transportation portfolio, fuel, and electricity consumption in USA, using a long-term investment planning model. The results showed that there are cases with significant HSR penetration; the national long-term CO_2 emissions and costs could be decreased. Reference [46] showed that the greenhouse gas emissions could be reduced in USA with HSR. In general, people are more disturbed by aircraft noise than rail noise, which, according to [76], can be attributed to acoustic factors, as well as attitudes towards the noise source. Reference [51] evaluated future automobiles, HSR, and aircraft long-distance travel using the California corridor as a case study. It is shown that the environmental benefits are most sensitive to the number of automobile trips shifted to HSR; a HSR system with current technologies would provide significant environmental benefits over existing modes, when the ridership is high.

The Japanese air-HSR environmental aspects have been studied as well. Reference [25] empirically estimated passengers' preferences and choice behaviors using an air-rail demand model for Japanese domestic market. Results showed that CO_2 emission taxation could reduce air passenger traffic and increase HSR passenger traffic in large numbers, although the relative change might be small.

It appears that the literature has not reached a consensus on the environmental and social welfare impacts of the integration between air transport and HSR. While some studies showed environmental benefits in Europe, other studies did not find a significant environmental impact (United Kingdom, Japan). Clearly, the measurement of environmental impact depends on several variables, and there is a need for a consistent way of cross-country impact assessments. Particularly, the spatial incompatibility between HSR and air transport makes the comparison of environmental assessments difficult [72]. More efforts are needed to understand the unintended trade-off in environmental impacts; that is, reduction in one environmental concern may lead to an increase or decrease in another.

Value of Time. Value of time (VoT) captures the travelers willingness to pay for the time savings and it is a fundamental concept in the transportation analysis tasks, such as travel demand modeling, social cost analysis, pricing decisions, and project evaluation [77–79]. Several studies have revealed that there are connections between the willingness to pay for time savings and several economic factors, such as time of a day, reliability preference, and activity scheduling; all of them revealed the heterogeneous VoT [77]. The most comprehensive study of UK values of time to date is provided in [80]. It was found that there is a high estimated elasticity of 0.9 between income and VoT; the ratio between walk/wait time and in-vehicle time is much lower than the commonly used value of two; there are several other important factors affecting the VoT, such as travel mode, travel purpose, and distance. Based on the idea that travelers often have different perceptions on the VoT, a varying VoT with a modal-mix model was proposed and the social profitability of three HSR lines Oslo–Stockholm (Norway and Sweden), Stockholm–Gothenburg (Sweden), and Beijing–Shanghai Hongqiao (China) was discussed [81]. Based on the Madrid-Barcelona corridor, it was shown that savings of waiting time are more valued than access time, while savings of access time are more valued than in-vehicle time [82].

Elasticity/Cross-Elasticity. Empirical studies confirmed that the time elasticity and price elasticity across different travel purposes are often different for segmented travelers. Based on the analysis of two main corridors in Spain (Madrid-Zaragoza and Madrid-Barcelona), [83] showed that the competition level that the HSR could exert over the air transport is low. The time elasticity of the HSR ranged from −0.36 to −0.59, while its cost elasticity was −0.55. Although the time and cost elasticities of HSR are quite diverse, a plausible range could be specified: time elasticity (−0.8 to −1.3) and cost elasticity (−0.5 to −0.9) [84]. Note that the above ranges did not consider the elasticities by travel purpose. The rail fare elasticities for rail (not limited to HSR) range between −0.27 and −0.61 when considering tours for long-distance travels in the UK [85]. It was also shown that there is a strong correlation between income and the frequency of long-distance travel trip making. For the Paris-Lyon HSR route in France which was opened with two stages between 1981 and 1983, the in-vehicle travel time elasticity was around −1.6 in the first stage and then reduced to −1.1 after the opening of the Northern section [86]. The in-vehicle travel time elasticity for the Madrid-Barcelona route in Spain was around −1.3 [87]. It was observed that the absolute values of direct elasticity of HSR demand with regard to travel time are significantly greater than 1; there is an inverse relationship between the elasticity values and the distance from the Italian HSR market [88]. Based on time series data models, it was shown that the time and price elasticities on the number of trips are around −0.16 [89]. It was reported that generally the elasticities of long-distance models estimated on cross-sectional data in the literature tend to be lower than the elasticities observed when new HSR lines have been opened [90]. Based on quarterly route level panel data of air passenger demand from 2010 to 2013, the effects of HSR on China's big three airlines (Air China, China Eastern Airlines, and China Southern Airlines) were analyzed; it was found that the price elasticities of air traffic demand were −1.36 to −1.50 on all routes [91].

It was shown that elasticities are context dependent and they are influenced by regional socioeconomic differences, such as value of time, fuel prices, and GDP (Gross Domestic Product), as well as market segmentation (purpose of travel, distance classes, and transportation modes) [84]. Cautions are needed when interpreting the elasticities since they are usually estimated from small changes of the systems [92]. It was pointed out that cross-elasticities are less meaningful to compare between situations since they tend to highly depend on specific market conditions [90].

Cost Ranges. The operation costs of major European HSR networks have been reviewed in [18]: the cost ranged from 0.0776 Euro per seat kilometer for French TVG to 0.1766 Euro per seat kilometer for German ICE. Specifically, the construction cost for HSR in Spain is 7.8–20 million Euro per km, and the maintenance cost is 33,457 Euro per km. The construction cost for French HSR is 4.7–23 million Euro per km, and the maintenance cost is 28,420 Euro per km (the values refer to the year 2002). The construction cost of the HSR network in Italy is 14–65.8 million Euro per km, and the maintenance cost is 12,919 Euro per km (the values refer to the year 2002). The construction cost of the HSR network in UK is around 66.2 million Euro per km. Note that the values are referring to the year 2005, if they are not explicitly explained.

It was estimated that the long-term marginal cost for the Japanese Shinkansen ranges from 9.31 to 15.80 Yen per passenger kilometer [93]. Only limited studies analyzed the costs of a few HSR routes in China: it was reported that the minimum revenue per passenger kilometer for the Beijing-Tianjin route is 0.7 RMB [94] and 0.76 RMB per passenger kilometer for Guangzhou-Wuhan route [12]. Although the cost estimations are quite different across markets, the cost of Chinese HSR is much lower than the ones for Japan and Europe [12].

3. Discussions and Future Research Directions

In the previous section, we surveyed recent literature on the competition and cooperation between air transport and HSR, covering five main categories: passenger demand, travel time, ticket price, seats and flight frequencies, and environment and social welfare. We summarize our main results as follows:

(1) It is shown that passengers are shifting from air transport to HSR and there is also newly induced demand generated by the HSR itself.

(2) Travel time is most critical in determining the competitiveness between the HSR and air transport: shorter travel time will attract more passengers.

(3) Under the HSR competition, airlines often reduce the ticket prices in order to keep passengers in European countries; the profitability of HSR is not easily predicted in different countries because of contextual differences.

(4) The reactions of airlines taken under the HSR competition are twofold: reducing the number of seats (aircraft size) is one common action, while flight frequencies being increased or decreased is highly controversial.

(5) There is no consensus on the impacts of environment and social welfare after the integration of air transport and HSR.

(6) The connections between the willingness to pay for time savings and several social-economic factors and the travelers' value of time are rather heterogeneous.

(7) Elasticities are often context dependent and they are influenced by regional social-economic differences (such as value of time, fuel prices); the interpretation of the elasticities needs more caution.

(8) Cost estimations across different markets show that the Chinese HSR is much cheaper than the Japanese HSR and European HSR.

Given these results, we discuss several lines of future research regarding intermodal transportation below and hope that more research efforts could be focused on these topics.

3.1. Creating an Open-Source Dataset for Large-Scale Multimodal Transport Systems. Research studies often use closed-source or hand-collected datasets. This makes it difficult to reproduce the results obtained in the study. Furthermore, this leads to inconsistent views on networks, being taken at different times, with different granularity and different observable variables [95]. Among European countries, the number of studies on the impacts of HSR in Spain ranks first. We believe that a major reason is that HSR operator Renfe makes many datasets available for public use. On the other hand, because of data confidential issues, only very limited research on the impact of HSR in Germany has been published. There is a strong need for an open access multimodal transportation database or, alternatively, large-scale models for multimodal transportation. According to

Table 3: An overview of the data sources for air transport.

Region	Organizations	Links
Global	OAG (Official Airline Guide)	https://www.oag.com/
	ICAO (International Civil Aviation Organization)	http://www.icao.int
	Airport Council International	http://www.airports.org
	Sarbe Airport Data Intelligence	https://www.sabreairlinesolutions.com
	Open Flights	http://openflights.org/
	Innovata Flight Schedules	http://www.innovata-llc.com
China	Transport scientific data sharing system	http://www.transdata.cn
	Civil Aviation Administration of China	http://www.caac.gov.cn/
	The major Chinese online travel agency	http://www.ctrip.com
	China Statistical Year Book	http://www.stats.gov.cn/english/
Japan	MLIT (Ministry of Land, Infrastructure, Transport and Tourism)	http://www.mlit.go.jp/index_e.html
Spain	Spanish Public Airport Authority	http://www.adif.es
	AENA	http://www.aena.es
France	Directorate General for Civil Aviation	http://www.aviation-civile.gouv.fr/
UK	Civil Aviation Authority	http://www.caa.co.uk
Europe	Eurostat (Statistical Office of the European Union)	http://www.eurostar.com

Table 4: An overview of the data sources for high-speed railway.

Region	Organizations	Links
Global	International Union of Railways (UIC)	http://www.uic.org/
China	ransport scientific data sharing system	http://www.transdata.cn.
	Chinese Railway Timetable	http://www.chinatt.org
Japan	MLIT (Ministry of Land, Infrastructure, Transport and Tourism)	http://www.mlit.go.jp/index_e.html
Korea	KORAIL	http://info.korail.com/mbs/english/
Spain	CKAN Spain railways data	http://thedatahub.org/user/jgcasta
	Ministry of Public Works	http://www.fomento.gob.es
	RENFE	http://www.renfe.com/
	Ferropedia	http://www.ferropedia.es
France	Open data initiative of SCNF	https://data.sncf.com/
Italy	Rete Ferroviaria Italiana	http://www.rfi.it/
UK	National Rail and British Rail	https://datafeeds.networkrail.co.uk
Germany	Deutsche Bahn	https://www.bahn.de/p/view/index.shtml
	ICE network	http://www.hochgeschwindigkeitszuege.com
	Zugsonar	http://download.odcdn.de/zugsonar/
Europe	Eurostat (Statistical Office of the European Union)	http://www.eurostar.com
	European Rail Timetable	http://www.europeanrailtimetable.eu
	EcoPassenger	http://ecopassenger.hafas.de

[96], such a model should combine (a) cost-benefit analysis with (b) risk assessment and (c) qualitative impacts of interest to the population.

Recently, [97] integrated timetable formation for air, rail, metro, coach, bus, and ferry in the United Kingdom for a week in October 2010, based on an open-data source (United Kingdom's National Public Transport Data Repository) and Innovata LLC (http://www.innovata-llc.com/). A weighted, directed, temporal, and multimodal transportation network could be constructed in order to analyze the characteristics of integrated public transport system, going beyond traditional views as simple networks or networks of networks [98–100]. Such efforts, on a larger scale, could improve our understanding of global transportation patterns. An overview of the data sources for air transport and HSR is provided in Tables 3 and 4, separately. We think that these data sources could serve as a starting point to build up a comprehensive open-source dataset for large-scale multimodal transport systems. Particularly, the use of Openstreetmap and alike can ease the often tedious bootstrapping process, since it contains rich content of worldwide transportation infrastructure. Integrating Openstreetmap with publicly available GTFS feeds and information about air transportation (schedules) will provide a powerful tool for performing

Table 5: The competition and cooperation effects between air transport and HSR on passenger demand.

References	Region	Time frame	Comp.	Coop.	Data type	Main results
[19]	ES	1999–2012	√		Empirical	Only 13.9% of HSR passenger demand came from air transport, indicating services provided by air transport and HSR are rather independent; HSR can generate demand by itself.
[20]	Madrid-Barcelona route	2003–2013	√	√	Empirical	Confirmed the conventional theory that HSR attracts more passengers than air transport within distances 300–500 km. The location of HSR station is shifting away from the city center, with a favored trend of an integrated airport-HSR station.
[21]	—	—	√	√	Analytical	When the OD demand between airports is significantly different, the improved connectivity could narrow the gap between airports and bring the gateway effect back to airports with lower demands, while the gateway function remains at airports with higher demands.
[22]	—	—	√	√	Analytical	The entry of HSR reduces air traffic, aircraft size, and flight frequencies but it generates new demand.
[23]	—	—		√	Analytical	The air traffic in the HSR-accessible market is reduced, while the traffic in the hub-and-spoke connecting market is increased.
[24]	FR, DE, ES, IT, UK	1995–2009	√		Empirical	The improved rail travel time has significant impacts on reducing short haul air traffic in Europe; HSR has contribution to less domestic air passenger traffic.
[25]	JP	2005	√		Empirical	Significant airfare reduction probably could stimulate new demands and shifted demands from rail to air mode; CO_2 emission taxation could reduce air passenger traffic and increase HSR passenger traffic in large numbers.
[26]	London-Paris route	2003–2009	√		Mix	HSR is rather competitive for the London-Paris market. Frequency, total travel time, and distance are the main determinants of travelers' behaviors. Passenger preferences are rather constant in the time frame.
[10]	ES	1999–2009	√		Empirical	HSR leads to the reduction of air transport operation by 17%. Although the travel demand has been increased substantially, the share of air transport in the total market has declined.
[12]	CN	1990–2011	√	√	Mix	The HSR would be competitive against air transport in terms of network connectivity, total travel time, and cost efficiency in short-medium haul market, with passengers shifting from air transport to HSR.
[27]	5 city-pairs, Europe	1991–2010	√		Empirical	The overall air traffic is still growing with the development of HSR; lower HSR travel time would lead to higher drop in air transport passengers and operations.
[28]	DE	2006-2007	√		Empirical	The entry of low-cost carriers leads to drops in rail passengers.
[29]	KR	—	√		Empirical	The improvement of accessibility could increase the demand of HSR.
[30]	Seoul-Daegu route	2004	√		Empirical	The opening of a new HSR line resulted in a significant reduction of domestic air traffic demand.
[31]	London Heathrow airport	—		√	Empirical	In addition to major benefits for airlines, the cooperation between air transport and HSR also leads to increased demand for railways.

large-scale research. Naturally, modeling worldwide transportation requires solving issues such as data heterogeneity and different modeling paradigms/elements. So there is a need for a set of modeling constructs and tools to develop a consistent and concise representation of worldwide transportation. The efforts undertaken in Openstreetmap can serve as a starting point for future developments [101].

Moreover, we need more reliable prediction methods for origin-destination demands, given different infrastructure layouts. Existing models, for example, gravity model and

Table 6: The competition and cooperation effects between air transport and HSR on travel time.

References	Region	Time frame	Comp.	Coop.	Data type	Main results
[32]	IT	2012	√		Empirical	A 10% increase in rail travel time allows airfares to be increased by a maximum 4.2%; this is true for one month before flight departure.
[33]	Madrid-Barcelona route	—	√		Mix	The access/egress time is a key factor in determining spatial competitiveness of transport modes.
[11]	161 city-pairs in Europe	—	√	√	Mix	There are more air services if the travel time of HSR is longer.
[24]	FR, DE, ES, IT, UK	1995–2009	√		Empirical	The improved rail travel time has significant impacts on reducing short haul air traffic in Europe.
[34]	Madrid Barajas airport	2010-2011		√	Empirical	Willingness to pay for different attributes of the integrated air transport and HSR from passengers can be obtained, among which "connecting time" is the main driver, and thus schedule coordination is crucial to promote intermodality.
[25]	JP	2005	√		Empirical	Japanese passengers are most sensitive to travel time and service frequencies and modestly sensitive to price.
[12]	CN	1990–2011	√	√	Mix	The HSR would be competitive against air transport in terms of network connectivity, total travel time, and cost efficiency in short-medium haul market.
[26]	London-Paris route	2003–2009	√		Mix	Frequency, total travel time, and distance are the main determinants of travelers' behaviors.
[27]	5 city-pairs in Europe	1991–2010	√		Empirical	Lower HSR travel time would lead to higher drop in air transport passengers and operations.
[35]	FR	2006	√		Empirical	Low travel time of TVG has significant impacts on domestic air transport in France; Air France tends to divert remaining flights to its hub airport when it lost competition against HSR.
[36]	JP	—	√		Empirical	The access and egress time of HSR has significant impacts on the modal competition.
[37]	SE	—	√		Empirical	HSR has lower operational costs per available seat kilometers. Travel time is the primary competition. HSR would win over some travel from airlines.
[31]	London Heathrow airport	—		√	Empirical	Main benefits for airlines include, but are not limited to, increased connectivity and catchment area and improved accessibility. These benefits have the potential to reduce the travel time.

its variants [102–104], predict the demand between city pairs based on demography and societal data, yet neglecting the available transportation options. Naturally, the ease to travel between two points increases the attractiveness for passengers. Recent work suggests that the inclusion of social network data and telecommunication data can improve the accuracy of origin-destination matrix estimation significantly [105–107].

With the improvement of the (free) available data for research, we will need further (open-source) tools for simulation of transportation at different levels of scale, from microscale to macroscale. To sum up, data and methods/implementations should not be hidden behind paywalls, but the goal should be to make research accessible to all research teams, independent of the available funding.

3.2. Analyzing Emerging Transportation Modes and New Business Models. With increased requirements of passenger mobility, new transportation modes and new business models are emerging. One successful example is the low-cost coach MeinFernbus in Germany. Starting from 2012, the low-cost coach has spread in Germany and is extending its network across Europe [108]. Because of the cheap ticket price, the new entry of MeinFernbus has attracted passengers from car users and conventional rails. The major question is how long the company can afford these cheap prices and which pricing strategy is chosen after cutting out the other competitors from the German market. In France, by learning the pricing strategies from low-cost airlines, low-cost HSR is emerging as well [109, 110]. This could lead to intramodal competition among different HSR operators [40]. Night-train HSR is another novel business model and it is shown that night-train HSR could have a cost advantage over air traffic in 2025 [111]. The effects are much similar with the entry of low-cost airlines, which was dominated by traditional full service airlines, while the entry of HSR is competitive against short haul air travel (approx. 1,000 km). Moreover, as our introductory example shows (see Figure 1),

Table 7: The competition and cooperation effects between air transport and HSR on price.

References	Region	Time frame	Comp.	Coop.	Data type	Main results
[32]	IT	60 days	√		Empirical	A 10% increase in rail travel time allows airfares to be increased by a maximum 4.2%; this is true for one month before flight departure.
[38]	IT	60 days	√		Empirical	Fares are significantly reduced by airlines when under direct competition with HSR.
[39]	CN	2011	√		Empirical	Mean airfares for the Jing-Hu HSR routes declined approx. 29% upon the launch of HSR, but rebounded by approx. 20% after the Wenzhou HSR accidents; low-cost carriers are more responsive to the HSR events than other carriers.
[40]	IT	2009–2012	√		Empirical	The on-board services have been increased; the HSR fares have been reduced by 31%.
[25]	JP	2005	√		Empirical	Japanese passengers are most sensitive to travel time and service frequencies and modestly sensitive to price.
[41]	Iberian Peninsula, Europe	—	√	√	Empirical	With a more holistic intermodal product, the benefits of intermodality can be best captured and the competitiveness of HSR decreases with the travel costs.
[42]	CN	—	√		Analytical	Airfare decreases and rail fare increases in airport access time; airfare decreases in rail speed if the marginal cost of HSR comparing with rail speed is not too large. The profit of air transport is higher with price discrimination between leisure passengers and business passengers than without it.
[26]	London-Paris route	2003–2009	√		Mix	Leisure passengers are more heterogeneous concerning average fares than business passengers.
[43]	Madrid-Barcelona route	2003	√		Empirical	Prices and service frequency are among the most important variables in the competition.
[28]	DE	2006-2007	√		Empirical	The entry of low-cost carriers put pressure on rail ticket prices.

Table 8: The competition and cooperation effects between air transport and HSR on seats and frequencies.

References	Region	Time frame	Comp.	Coop.	Data type	Main results
[44]	ES	2010	√		Empirical	The developed integrated optimization model is able to predict the airline's response to the entry of HSR, by fine-tuning schedules, fleets, and fares.
[38]	IT	60 days	√		Empirical	Intramodal competition of two HSR operators showed that capacity and frequency are strategic variables.
[45]	FR, DE, IT, ES	2002–2010	√	√	Empirical	The number of seats was reduced, but with minor influence on flight frequencies. The reduction of services is greater at hub airports. HSR can also provide feeding services to long haul flights in hub airports.
[22]	—	—	√		Analytical	The entry of HSR reduces air traffic, aircraft size, and flight frequencies.
[11]	161 city-pairs in Europe	—	√	√	Mix	There are more airline seats and number of flights if the travel time of HSR is longer.
[25]	Japan	2005	√		Empirical	Japanese passengers are most sensitive to travel time and service frequencies and modestly sensitive to price.
[43]	Madrid-Barcelona route	2003	√		Empirical	Prices and service frequency are among the most important variables in the competition.
[26]	London-Paris route	2003–2009	√		Mix	Frequency, total travel time, and distance are the main determinants of travelers' behaviors.
[31]	London Heathrow airport	—		√	Empirical	The cooperation between air transport and HSR can bring major benefits for the airlines, such as additional capacity and freed slots.

Table 9: The competition and cooperation effects between air transport and HSR on environment and social welfare.

References	Region	Time frame	Comp.	Coop.	Data type	Main results
[22]	—	—	√		Analytical	If HSR is not sufficiently greener than air transport, the introduction of HSR will increase the environmental pollution and reduce social welfare; otherwise it will increase the environmental benefit. When the increase of the emission of HSR due to the increased speed is sufficiently high, the competition would be detrimental to the environment.
[5]	US	—	√		Analytical	There are cases with significant HSR penetration; the national long-term CO_2 emissions and costs could be decreased.
[46]	US	—	√		Mix	The greenhouse gas emissions could be reduced in US with HSR.
[23]	—	—		√	Analytical	The welfare is improved with low substitutability; when the substitutability is high, the cooperation would improve the welfare if the hub airport is heavily capacity-constrained.
[47]	—	—	√	√	Analytical	The cooperation could improve the welfare of international passengers.
[48]	Madrid-Malaga route	—		√	Analytical	The welfare would be very likely to be enhanced for airports with capacity constraints. The environmental effects could be positive or negative.
[49]	Worldwide	2010		√	Empirical	Mode substitution from air to rail is likely to play a greater role in the air pollution reduction around airports.
[50]	Madrid Barajas airport	—		√	Mix	With HSR, passengers traveling with aircraft and private car are reduced, leading to environmental benefits. Increasing the travel cost of private car is picked up by air transport rather than HSR, leading to negative environmental impacts.
[51]	US	—	√		Mix	A HSR system with current technologies would provide significant environmental benefits over existing modes, when the ridership is high.
[52]	London Heathrow airport	—	√	√	Analytical	Significant savings (delays and costs) can be obtained even with rather modest substitution.
[53]	JP	1999–2007	—	—	Mix	The operation of aviation industry is socially efficient in the observed period, although its CO_2 emission per passenger kilometer is higher than the one with rail.
[54]	27 EU countries	2020 (scenarios)	√		Analytical	Development of the HSR network across Europe should be encouraged in order to maximize the overall social welfare.
[31]	London Heathrow airport	—		√	Empirical	Increased connectivity and catchment area, improved accessibility, and reduced local air pollution.
[55]	—	—		√	Simulation	The level of passengers delays would be increased with intermodal passenger movement, while social benefits can be expected at airports with large amounts of short haul flights.

the competition range can even go beyond 1,000 km in specific cases, a distance which was difficult to imagine in the last century. Furthermore, the analysis of competition between air transport and HSR has to take into account the urban transportation from areas with higher population densities. Airports tend to be built far outside city centers, mainly for concerns about noise/emission and also because of lack of space. HSR stations, on the other hand, often are closer to the people and thus have an advantage in access times. Night-train HSR would raise direct competition against air traffic on medium haul flight routes even further (approx. 2,000 km).

Therefore, a unified modeling framework for intra/intermodal competition/cooperation between existing transportation modes and new emerging ones, with the consideration of multiple competitors [23] and additional transportation modes for estimating real access times, is of significant importance in future work. Another direction is to consider risks and uncertainties in a stochastic modeling framework [54].

3.3. Passenger-Oriented Multimodal Transportation Systems. The European Commission has a goal that *90% of travelers within Europe are able to complete their journey, door-to-door within 4 hours* [112]. Multimodal transportation systems should provide maximum convenience for passengers on their door-to-door travels. Therefore, the multilayer structure of networks should be considered [113]. One aspect is to study the driving factors to simulate new passenger demand [24] and the dynamics of passenger demand shifting between different transportation modes [19]. Currently, in the field of air transport, passenger-oriented performance metrics are drawing more attention [114–116]. A future concept in Europe is the 24/7 aircraft, which can be operated 24 hours in a day and 7 days in a week, without the restriction of airport curfews [117]. The 24/7 aircraft has quiet and short take-off/landing distances and thus it allows night operations. Moreover, it uses massive flow control and it has mission adaptation capabilities [117].

We envision an adaptive multimodal transportation system where passengers buy door-to-door or region-to-region services. This would allow airlines and air navigation service providers to flexibly trade-off airport and airspace resources within a region; this would also leverage mobility of passengers within regional airport systems by using local ground and air transportation and increase the flexibility of airline flight planning and disruption management. An interesting case study from China is an integrated multimodal transportation system, as the skeleton for the cooperative development of Beijing, Tianjin, and Hebei Province (Jing-Jin-Ji) [118].

3.4. Resilience of Multimodal, Multilayered Transportation Systems. It is critical that multimodal transport systems still function well under disruptions or failures. The first fatal HSR accident which happened in China was on 23 July 2011: two high-speed trains derailed each other and four cars fell off the Ou river bridge in Wenzhou, killing 40 people and 192 injured. Reference [39] showed that the mean airfares for the routes along the Jing-hu HSR declined approx. 29% upon the launch of HSR, but rebounded by approx. 20% after the Wenzhou HSR accidents in China. Furthermore, [119, 120] explored the potential of substituting flights with ground transportation modes in order to mitigate congestion and reduce delay, when there are severe shortfalls in airport capacity or airport closure temporarily. An optimization model is proposed to determine which flights to cancel or to be replaced by ground transportation modes, with the minimization of incurred cost as the objective function. This model was applied to a representative US airport. Results showed that the real-time intermodal substitution could save around 8%–14% of the disruption cost, compared with the case without the intermodal substitution. These effects are similar to the gains with multiple airport regions in air transportation, where nearby airports can compensate with each other [121].

It is very interesting and challenging to investigate further real-time modal substitution in multimodal transport systems at a larger scale. Naturally, this directly addresses the issue of cooperation between operators in different transportation modes. This fact, together with the problem of cascading failures in multimodal, interdependent networks [122], requires much more research. Complex network-based techniques can significantly contribute to this challenge [123–126]. Particularly, modeling the system as a temporal complex network can help to better predict the resilience of the system under failures [127].

3.5. The Role of ICT in Multimodal Transportation Systems. Smartphones already play a critical role in multimodal transport systems. Reference [128] showed that the introduction of simple ICT (Information and Communication Technologies) solutions in multimodal transportation systems can noticeably improve its overall behavior. The extraordinary growth in excessive smartphone usage has led researchers to the idea of performing data mining on top of user's mobility data. Examples for such analyses are physical activity monitoring [129], regional travel demand analysis/forecasting [130, 131], and personal impact monitoring [132]. Therefore, a major goal is to motivate changes in travel behavior and more conscious use of resources, leading towards the vision of green transportation [133].

There are still many challenges regarding the determination of a precise location and travel modes on mobile phones, in particular with energy efficient methods. Moreover, position determination and mode detection should not be looked at separately: combining imprecise data from both can lead to better overall results. Such ideas have been implemented in navigation systems, which automatically snap to the next street, if the GPS does not give an accurate (or a nonsense) position. Similarly, for modality detection, if a device believes that the user is in a train, it can more accurately detect the position by snapping to train lines (if such information is available online/offline). Furthermore, it would be interesting to investigate how the usage of smartphones influences the competition/cooperation relationship in multimodal transport systems.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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