The geography of rail transport

Published in Roger Vickerman (Eds), International Encyclopedia of Transportation, vol. 5, pp. 427-436. UK: Elsevier Ltd

http://dx.doi.org/10.1016/B978-0-08-102671-7.10462-2

(POSTPRINT)

Frédéric DOBRUSZKES
Université libre de Bruxelles (ULB)
Brussels, Belgium
frederic.dobruszkes@ulb.ac.be

Amparo MOYANO
Universidad de Castilla La Mancha (UCLM)
Ciudad Real, Spain
amparo.moyano@uclm.es

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Submitted to the International Encyclopedia of Transportation

Keywords
Rail transport geography
Railways
High-speed lines
Rail infrastructure
Rail traffic
Rail network
Transport history
Transport planning
Intermodal competition
Urban systems

Abstract
This chapter first investigates the geography of actual rail transport worldwide. In doing so, we set up a typology based upon network- and traffic-related indicators per country, with special attention paid to the distinction between passenger and freight traffic. Then the chapter covers the factors that explain the geography of infrastructures and traffic, taking into account historic factors that may have come into play a long time ago, given that many actual lines were built a considerable time ago. As the chapter elucidates, rail transport is shaped by physical geography, geo-economic factors, the shape of urban systems, intermodal competition in line with distances, railways logics, and the importance of network effects and political factors.

1. Introduction

Railways as a system began with the introduction of the steam-powered locomotive in the early 19th century and the opening of the first public inter-city railway: the Liverpool and Manchester Railway in the United Kingdom in 1830. This was the first guided transport mode that combined steel rails/steel wheels, steam engine locomotives, and a convoy. It was also the first mode of transport to be fully timetabled. Similarly, in many other countries, contemporary railways were built during the 19th century and, in specific contexts, were associated mainly with the development of different economic situations.

Surprisingly, the geography of railways systems has not been extensively investigated. In several countries, railways are part of the landscape, so scholars generally have not questioned their presence. In other countries, there are no railways anymore or only some residual rail operations, which are not considered.

In this context, the chapter presents the current overall geography of rail transport and offers an in-depth examination of the different factors that influence the construction, operation, and/or maintenance of railway systems around the world. The chapter is organized as follows: Section 2 analyzes the current situation of railway systems and their development, considering both infrastructure and use-related variables; Section 3 discusses the main factors affecting the development of railway systems; and Section 4 concludes the chapter.

2. The overall geography of rail transport

While railways are commonplace in many countries worldwide, their geography varies significantly in terms of network length, density, and utilization (traffic intensity and passengers versus freight markets). In an attempt to introduce overall railway geography, country-level statistics supplied by the International Union of Railways (UIC) have been considered to build a typology of railways systems. Four main variables have been considered: the density of rail lines (DensityLines) and the density of high-speed lines (at least 250 kph) both in km/km² (DensityHSL); passengers' traffic (Pkm_km) and freight traffic (Tkm_km), both in relation to the total length of rail lines.

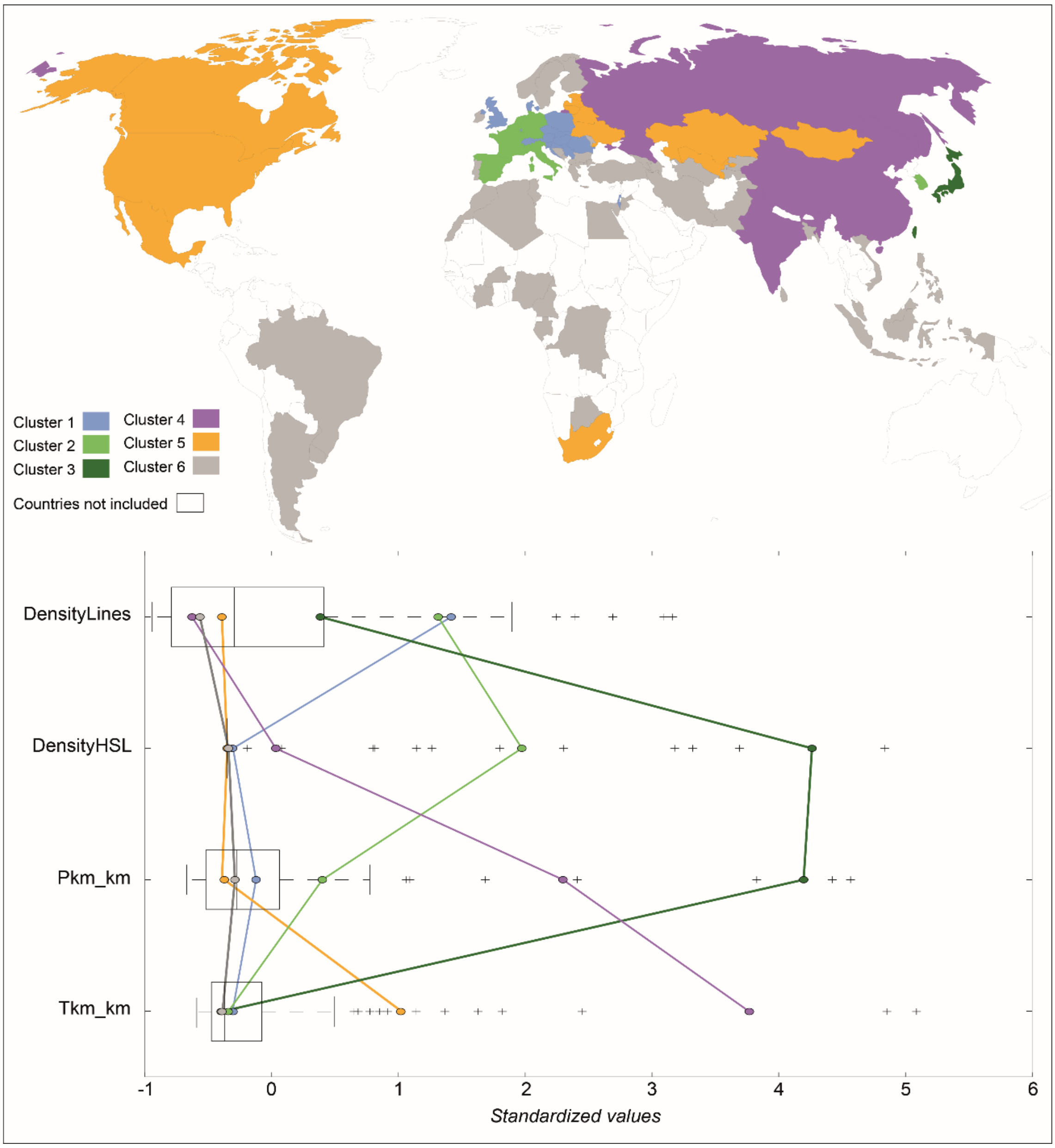

Figure 1. Classification of the world's countries: clustering and boxplot analysis (based on using the k-means clustering technique and data from UIC 2016 as a compromise between actualized data and the sample size)

This led to six main groups (Figure 1):

a) **Medium-sized countries with a high density of rail lines (cluster 1):** In this group, mainly countries in Eastern Europe and the UK are included. The density of railways is the highest of the sample and traffic per kilometer is limited, slightly over the median value (see Fig. 1: boxplot analysis).

b) **Medium-sized countries with both conventional and high-speed lines (clusters 2 and 3):** These two clusters encompass most of the countries in Western Europe and South Korea (cluster 2), in addition to Japan and Taiwan (cluster 3), where the highest density of high-speed rail networks can be found. The main difference is that those countries in cluster 3 present high population densities along major rail corridors, and the use of railways is more consolidated, which implies a higher *Pkm_km* value.

c) **Large or very large countries with high freight traffic (clusters 4 and 5):** In this case, due to the large size of the countries included in this group, the density of rail lines is very low compared to the above-mentioned countries. Of course, this does not prevent dense railways networks in densely populated areas, like Eastern China (see below). However, this group is characterized by high volumes of freight traffic (in relation to their length of rail networks). The main difference between clusters 4 and 5 is passenger traffic, which is much higher in cluster 4 (namely, Russia, China, and India) and follows similar patterns to those found in clusters 2 and 3.

d) **Large countries with reduced railway use (cluster 6):** In this group, countries present a very low density of rail infrastructure (even non-existent in some cases) and reduced use of the railway system, both for passengers and freight.

In addition to the overall geography of the world's countries, close attention must be paid to the current situation of high-speed rail systems (Fig. 2):

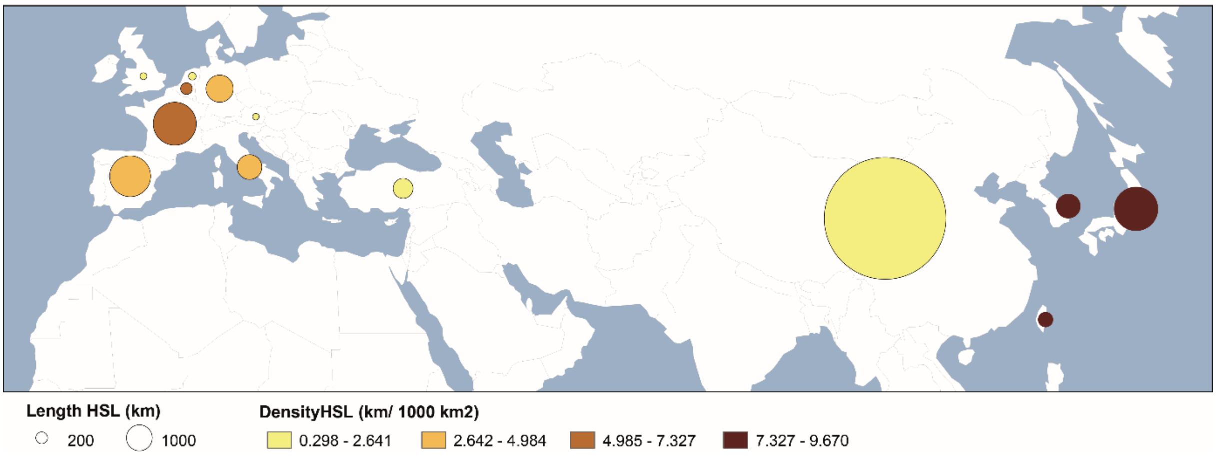

Figure 2. World's countries with high-speed rail infrastructure (at least 250km/h) in 2018. Source: UIC

Currently, there are 13 countries with high-speed rail infrastructure for speeds over 250 km/h (mostly included in clusters 2 and 3). In this sense, China is the world's leader in HSR extension (21,782 km length), followed by Japan (2,848 km), France (2,734 km), and Spain (2,482 km). However, the situation concerning the density of lines (*DensityHSL* variable) is quite different:

while Japan, South Korea, and Taiwan present the highest density values of this kind of infrastructure (over $7.327 \cdot 10^{-3}$ km/km^2), China, Turkey, Austria, The Netherlands, and the United Kingdom have less than $2.641 \cdot 10^{-3}$ km/km^2.

Of course, any analysis of the geography of rail systems depends on spatial units. This chapter is not the place to elaborate on the so-called Modifiable Areal Unit Problem (MAUP) (Arbia, 1989). But for sure, the picture one gets changes dramatically, subject to spatial units, in line with urbanization patterns that are better rendered at sub-national level. Figure 3.

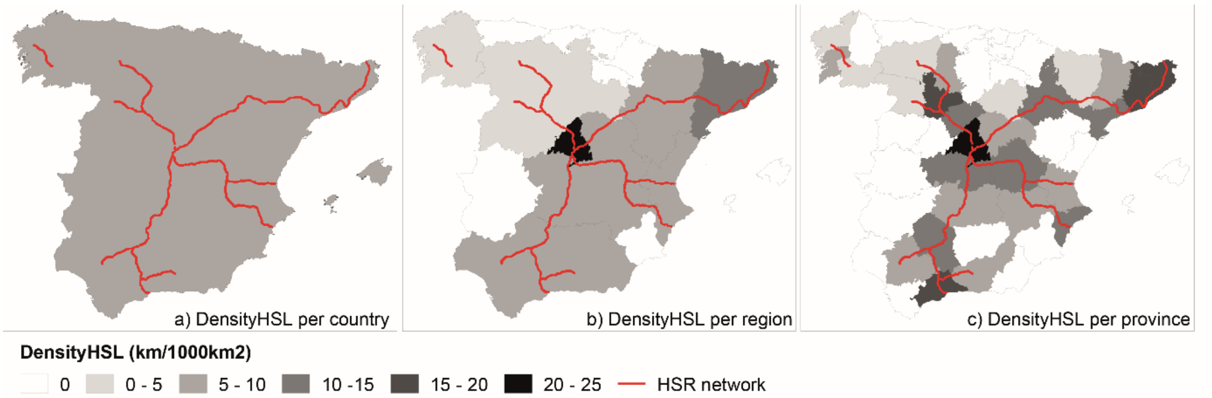

Figure 3. The impact of spatial unit on indicators: High-speed lines in Spain (at least 250km/h). Sources: Data from ADIF (Spanish Infrastructure Administrator) and FFE (Spanish Railway Foundation), 2019.

It is also worth noting that in countries with more than one single rail line, traffic density can be quite diverse within a single network. In France, typically, the lowest-density lines account for 46% of network length but only 6% of the supply. Conversely, 78% of the supply is concentrated in only 30% of the network (Table 1).

Line group	Length	Supply
Main lines (UIC 1-4 and HSLs)	30% (8,900 km)	78%
Intermediate lines (UIC 5-6)	24% (7,000 km)	16%
Thin lines (UIC 7-8)	46% (13,600 km)	6%

Table 1. Network vs. supply concentration in France

Supply is given in gross tonne-kilometers hauled (GTKM). Source: Rivier and Putallaz (2005)

3. Rail geography as a production of multiple factors

The geography of rail transport unveiled in the previous section obviously does not fall from the sky. It is the product of numerous factors that are discussed below, with a special emphasis on rail networks.

Geo-economic factors vs. economic history

It would be tempting at first to expect that countries' demographic weight and surface would favor the development of railways, notwithstanding internal heterogeneity. However, developing and operating railways is expensive. All other things being equal, economic development is thus also a key factor. Economic development would directly increase passenger and freight demand and would suggest that public authorities or private interests would have enough means to build the infrastructure.

For the subset of 82 countries considered above, we set up a multiple regression model where the length of railways is a function of population, area, and GDP/capita. Following the logarithmic transformation of all variables, the parameter estimates should be interpreted as elasticities. The first factor is population (proxy for market size); then comes GDP/capita. Once controlling also by surface area, railway length has the highest elasticity with GDP/capita (a 1-% increase in GDP/capita would increase railway length by 0.77%, all other things being equal) (Table 2).

	Model I	Model II	Model III
Intercept	-2.034*	-6.570***	-6.762***
Ln POPULATION	0.617***	0.689***	0.401***
Ln GDP/CAPITA		0.707***	0.768***
Ln AREA			0.379***
Adjusted R^2	0.498	0.692	0.794

Significant at *** 99%, ** 95% or * 90% level of confidence

Table 2. Regression models for Ln Railway Length at the country level (n=82)

However, such a multiple regression does not really make sense. Indeed, it is worth noting that many of today's rail lines were actually built a long time ago and would arguably not be built from scratch today, given the development of other transport modes in the intervening time.

Following Kondratiev's theory, the economy experiences long-term waves. Although this theory has been challenged, each cycle involves major innovations that will drive the next period of high growth (A phase). The second wave, more or less in the second part of the 19th century, was based largely on railways, which were both a major innovation and a main industrial activity and were intensively utilized by the then heavy industries. As a result, countries that took part in the industrial revolution at this time were very quickly covered by a high grid of railways, of which many are still operated today (Martí-Henneberg, 2013). A typical example is Belgium (Figure 4). The network has been built mostly over the 2nd Kondratiev wave, then consolidated over the 3rd wave, and significantly dismantled during the 4th wave, when car ownership and motorways became standard. This process was only balanced by the opening of some high-speed and freight lines over the past 25 years. Given the cost of maintaining and operating railways and intermodal competition (see below), it is likely many existing lines would not still exist if they had to be built today from scratch.

In another context, many railways in Africa were designed by the colonizer. British explorer Stanley, who was recruited by King Léopold II of Belgium to explore and acquire lands in Congo, stated that "without the railroad, the Congo is not worth a penny" (Deckard, 2019: 246). Railways were essential to overcome non-navigable parts of the Congo River. More generally, colonizers in Africa built railways to control lands and to transfer huge amounts of minerals and agricultural resources to metropolitan areas. This ensured penetration lines with low density and scarce interconnections (Taafe et al., 1963), often until today (Oliete Josa and Magrinyà, 2018). Several lines have ended (even though they are still part of local landscapes), but surviving lines mostly date back to colonial times.

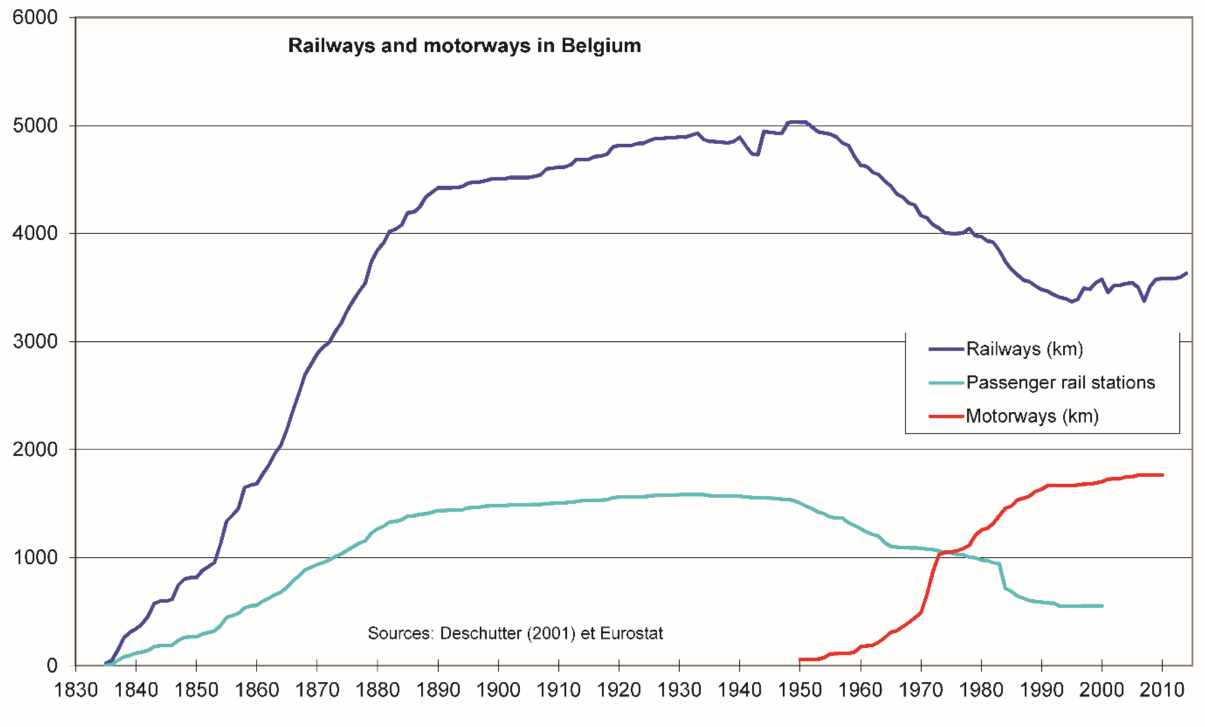

Figure 4. Belgium's railway over time

During the 20th century, especially in the second half, the evolution of railways was oriented mainly toward high-speed rail systems. The first high-speed line was the Tokaido Shinkansen line, built in 1964 between Tokyo and Osaka in Japan. Since then, high-speed lines have been developed in many other countries, mainly in Western European and Asian countries. High-speed lines (HSL) were designed initially as a transport alternative to inter-metropolitan connections, which were working close to maximum capacity and facing growing traffic demand (Vickerman, 2009). Therefore, in the beginning they were oriented to discharge conventional lines servicing the main corridors in different countries. However, it quickly appeared that HSR could compete with airlines mainly for business purposes, securing higher market shares and contributing to a decrease in their absolute level of use (see Givoni and Dobruszkes, 2013, for a review). In recent decades, the development of high-speed rail systems, transitioning from single lines to a complex mode of transportation, and their coexistence with conventional railways, require a global analysis to understand the different factors affecting the evolution of this transport system.

Physical geography

Anyone who would like to develop a railway would first face the constraint of physical geography. Major adverse constraints are water and relief. Rivers, lakes, and seas impose bridges or tunnels, which can only increase the cost of new infrastructure, as well as maintenance costs. Of course, bridges spanning seas and undersea tunnels are limited in length. In 2019, the tunnel with the longest under-seabed section was the Channel Tunnel between France and England (37.9 km, out of 50.5 km). In northern Japan, the Seikan Tunnel is 53.9 km, of which 23.3 km are under the seabed. Beyond these extreme figures, it is much more common for over- or undersea rail tunnels to range from a few hundred meters to a few kilometers. There are actually more long bridges over the water than long tunnels. The longest bridge is currently the Danyang–Kunshan Grand Bridge (164.8 km long in total, with a 9 km section across the open waters of the Yangcheng Lake in Suzhou). The bridge opened in 2010 as part of the Beijing-Shanghai high-speed line. While long undersea tunnels are recent, long bridges over the water date back to the 19th century. For instance, the 9.3-km Norfolk Southern Lake Pontchartrain Bridge in the US was opened in 1884.

Relief is not friendlier to railways. “Heavy” rolling stocks can only face gentle slopes, about 1% (or 2.5%, which is the recommended maximal high-speed rail slope). Lighter rail systems accept higher slopes (with a slope of 7.9%, Zurich’s S-Bahn 10 to Uetliberg is reported to be a record in Europe), but this may restrict operations, especially speed. Rack systems may help to overcome relief, but in most cases relief is overcome by bridges over valleys and tunnels inside mountains. Rail tunnels through mountains were first established during the late 19th century, and at rather high altitudes to make them shorter. For instance, the first Alpine rail tunnel, the Gotthard Tunnel, which opened in 1882, was already 15 km long. Its highest point is 1,151 meters. In addition to high construction costs, its altitude involves rather inefficient access and egress ways, with curves (if not serpentines) and bridges to maintain acceptable slopes. Length has been limited by technology and the use of steam engines, which were difficult to manage in urban underground systems (Dennis, 2013). More recently, some countries have engaged in building so-called base tunnels. In short, these flat tunnels are built at much lower altitudes, but are thus much longer and more expensive. The new Gotthard base tunnel is 57 km and is currently the longest and deepest tunnel in the world. Its highest point is some 602 meters below the older tunnel’s one. Its cost was estimated at CHF 9.56 billion in late 2015 (€8.75 billion euros at that time).

Soils may also make the building of railways more complex. In Scotland (UK), for instance, the construction of the West Highland Line had to confront the problem of peat bogs, which eventually involved the application of specific techniques (Le Vay, 2009).

All this significantly increases the cost of developing railways. In the first instance, the rationale for building railways, despite adverse physical geography, would be balanced by the wealth of countries (public authorities and/or private investors), potential market size, and modal alternatives, which can all change over time. An alternative is to avoid or skirt around obstacles at the cost of detours of all scales. Some stakeholders have proposed restricting HSLs to single-track lines in case of very high infrastructure costs and moderate traffic (Castillo et al., 2014).

Urban systems

The previous modeling exercise, although apparently successful, does not reveal the subtle impact of urbanization patterns on the geography of rail systems. For instance, China is a large country by surface and population, and its GDP per capita is close to the world’s average. But its rail network is apparently less developed than expected because the Chinese population is highly concentrated. In other words, a large part of China is not heavily populated, so railways are scarce in these areas. Actually, the geography of railways could be better understood under the framework of urban systems. An urban system is a combination of city size and the intensity of interaction between them. All other things being equal, this significantly shapes the need for travel, and thus the geography of flows and possibly the rationale for railways. For instance, the national urban system’s shape has affected the design of high-speed lines in recent decades. Figure 5 clearly shows that in a country where one city dominates the urban system (typically Paris in France and, to a lesser extent, Madrid in Spain), the HSR would be star-shaped. At best, radial lines would be interconnected though the city center (Madrid) or its suburb (Paris), but they are built primarily to link the dominant city to other cities. In contrast, a polycentric urban system would spread the demand across more links, which calls for more rail lines, although it may also make them less economically or even socially profitable, given the cost of the infrastructure. Germany is a typical case here. A much easier case is when the urban system is mostly linear, as in Japan or Italy. In such cases, one single, high-speed line makes it possible to serve a significant share of the national population. In extreme cases, however, the demand along this axis may become so large that a second line is needed. This is the case in Japan, where traffic forecasts had the effect of justifying the construction of the Chūō Shinkansen maglev line between Tokyo and Osaka (which is expected to be partially opened in 2027).

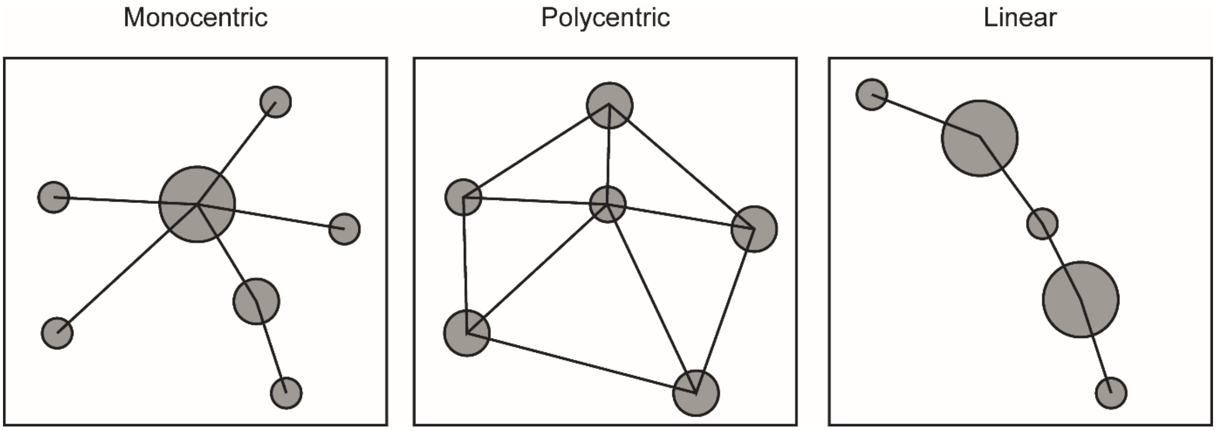

Figure 5. The impact of an urban system on a high-speed rail network

Obviously, the shape of urban systems not only influences the spatial patterns of infrastructures, but also services and passenger flows. The territorial situations of HSR cities (Ureña et al., 2012) in relation to other cities in the network suggested the implementation of different kinds of services adapted to each connection's needs. For instance, in Spain, the existence of regional HSR services between large metropolitan areas and close smaller cities is the cause/consequence of interactions between cities, mainly related to labor markets (in many cases fostered by the new infrastructure itself); or even new low-cost HSR services are oriented to cover the increasing demand for leisure mobility.

Distances, travel times, and intermodal competition

In addition to urban systems (and linked to them), the geography of railway lines and their use is also affected by distances—and thus travel time—between places and related intermodal competition. Once travel time/distance becomes too long, airlines start to gain market share. Considering 161 city-pairs across Europe, Dobruszkes et al. (2014) found the ability of HSR to compete with airlines decreases significantly between 2.0 and 2.5-h of HSR travel time. Conversely, the Brussels case shows that rail use to commute to Brussels increases with distance. Commuters who live in close suburbs underuse trains, usually because the service is poor, but likely also because of lifestyles connected to social attributes (Strale, 2019). Of course, the terms of competition between railways, road transport, and air travel also depend on factors other than travel time (Zhang et al., 2019). At a time when medium- and long-distance accessibility is considered a key element of the attractiveness of cities and regions, intermodal competition goes beyond infrastructure and travel times to also consider services (routes, frequencies, and timetables) (Moyano and Dobruszkes, 2017; Moyano et al., 2018). In addition, potential travelers' income vs. fares is key. There are countries in which trains have remained a transportation mode for the masses. In other cases, especially in the case of HSR, premium fares apply. All other things being equal, this favors competition from other transportation modes.

Railway development and operations have become increasingly challenged by the rapid expansion of air services and decreasing airfares. In many areas, airlines have opened multiple new routes, which increases pressure on railways. Competition is direct (for those passengers whose destination is fixed). But it is also indirect as cheap flying options can divert passengers from trains because they offer new destination options. For instance, a cheap flight from London to Lisbon may divert passengers from British resorts. Especially in Europe, lots of long-distance rail services, both domestic and international, and both daytime and overnight, have disappeared. International rail services from Brussels (Figure 6) are a typical example. At best, some of them have become HSR services. Note that the advent of HSR may also have created links that did not exist before, typically to London via Lille. Precisely, in contrast with air transportation, where the flexibility to fit supply and demand is higher because connections are city-to-city, HSR runs through the territory and potentially generates impacts on the in-between regions. This implies that, in time, HSR acquired a social and political compromise for servicing smaller intermediate cities (Moyano and Coronado, 2018), guaranteeing that smaller communities would remain accessible and (or) that their long-distance accessibility would improve.

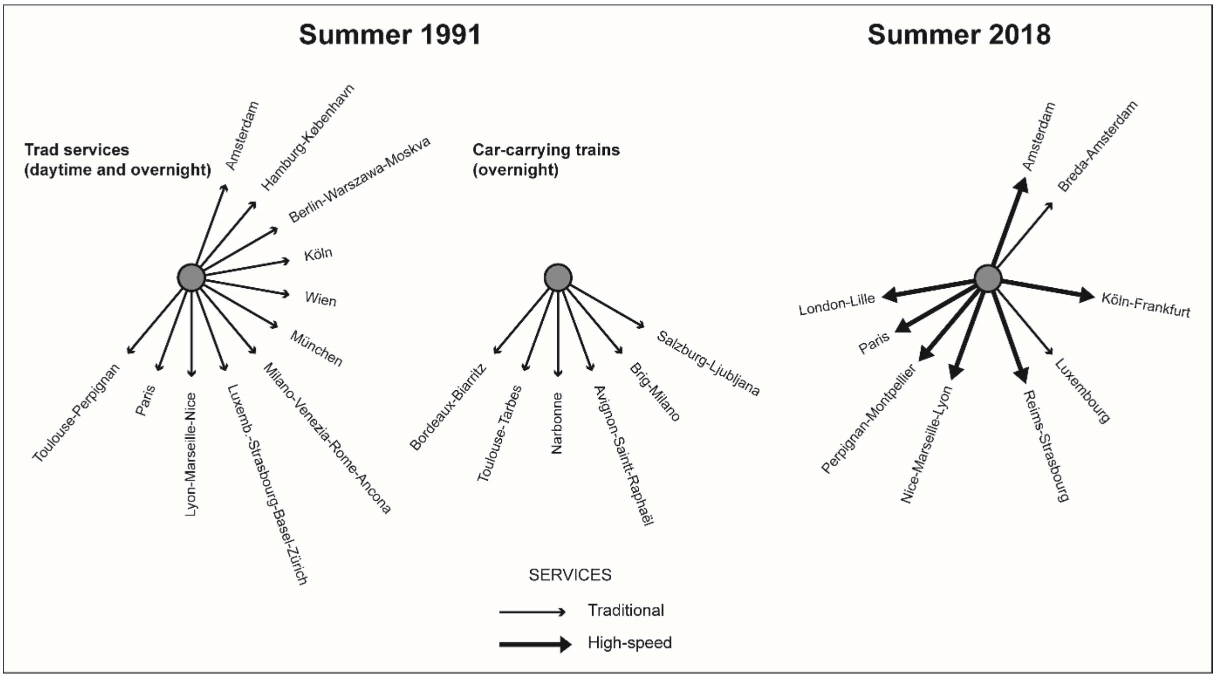

Figure 6. Changes in international services from Brussels.

It is worth noting, however, that the terms of competition can change over time. Today's domination of many markets by air travel could later be challenged in the event of a sharp increase in energy costs or if the implementation of strong regulation forced passengers to reconsider trains in the name of environmental issues (Dobruszkes et al., 2017).

Railway logics

The current shape of railways is also influenced by the essentials of this transport infrastructure itself. Many of the existing lines are the consequence of different steps of the development process: the railway system was not built in one go but is the result of consecutive expansions. Therefore, pre-existing lines condition future corridors and branches. In the case of HSR, the logics of infrastructure growth are strongly related to pre-existing conditions, mainly because the costs of construction are expensive. For instance, in Spain, the new connection to Granada takes advantage of the existing line between Madrid and Málaga (which is still below its capacity of exploitation), and only an HSR branch from Antequera is newly built. For sure, if the Andalusian corridor did not exist, the connection between Madrid and Granada would be different.

Political factors

All the previous factors can be considered natural constraints and market forces, which likely prevailed in earlier times, when private investors took the risk of developing railways and rail travel was nearly the only efficient option. But times have changed. In many countries, the development and maintenance of railways are largely (if not exclusively) funded by public authorities, which also compensate companies for the lack of financial profitability of many services. Public authorities have many rationales for funding railways; these range from social goals (favoring the masses' right to mobility) to environmental concerns (rail operations are "greener" than other transportation modes if traffic is dense enough) to economical concerns (e.g., supporting one's national seaport against competitors) to land planning considerations (e.g., serving remote areas and increasing national or international integration). But of course, the one who pays also decides. As a result, the rationality of natural constraints and market forces is then partially replaced by political considerations. Obviously, in a democracy, governments have the power to fund facilities or services to achieve various goals, whatever the views of many transportation experts, especially liberal economists. In one sense, economical rationality is partially replaced by political rationalities. Of course, the border between dreams and the actual impact of such investments is somewhat unclear. It is thus not surprising that economists have largely opposed investments they deem socially unprofitable (see Albalate and Bel, 2012).

In the meantime, there are many examples of public authorities diverging from market forces, for the best and worst. For instance, Spain first built an HSL between Madrid and Seville in anticipation of the 1992 Universal Exposition of Seville. The authorities argued that the less-developed south needed to be boosted. As a result, the Madrid-Barcelona HSL, which links Spain's two largest cities by any metric, was opened more than a decade later. There's no need to be an expert in spatial economics to understand that the largest market (and higher potential for the modal shift from planes) was between Madrid and Barcelona. Germany is also an interesting case. As long as the country was divided, HSLs were developed only within Western Germany, following a north-south logic. Then, in 1989, the Berlin Wall fell and Eastern Germany's communist regime collapsed in the aftermath. Germany was reunified in 1990, with Berlin (located in the middle of former Eastern Germany) as the capital. As a result, it became necessary to link Berlin with the western cities by HSR, so the priority became the construction of an east-west HSL, which opened in 1998.

The weight of political factors can play out at various levels. For instance, once it has been decided to link two main cities by HSR, the public authorities have to agree on an itinerary. The choice is often a mix of all the factors highlighted in this section. But because HSR has become an appealing facility that is supposed to boost the economy (Delaplace, 2017; Vickerman, 2018; Zhang et al., 2019), influential elected persons located en route would want to secure some services too and thus influence the HSL's shape (Moyano and Dobruszkes, 2017). Figure 7 clarifies this in the case of the so-called Northern European HSR, designed primarily to connect Paris to the Channel Tunnel but also to Lille, Brussels, and beyond (Amsterdam and Cologne). Without any cost constraints, a triangle going straight from Paris to the Channel Tunnel and to Brussels may have been considered. But this would have maximized the length of the HSL, and thus the cost. Furthermore, Lille, which is one of the largest of France's cities, would have been bypassed. Various HSL designs via Lille were analyzed (Figure 7). The final compromise mixes attractive travel times between the main cities and reasonable costs, on the one hand (market force), and Lille's location in a central position, if not an HSR hub, on the other hand (notwithstanding the real services that would later serve the city, see Moyano and Dobruszkes, 2017).

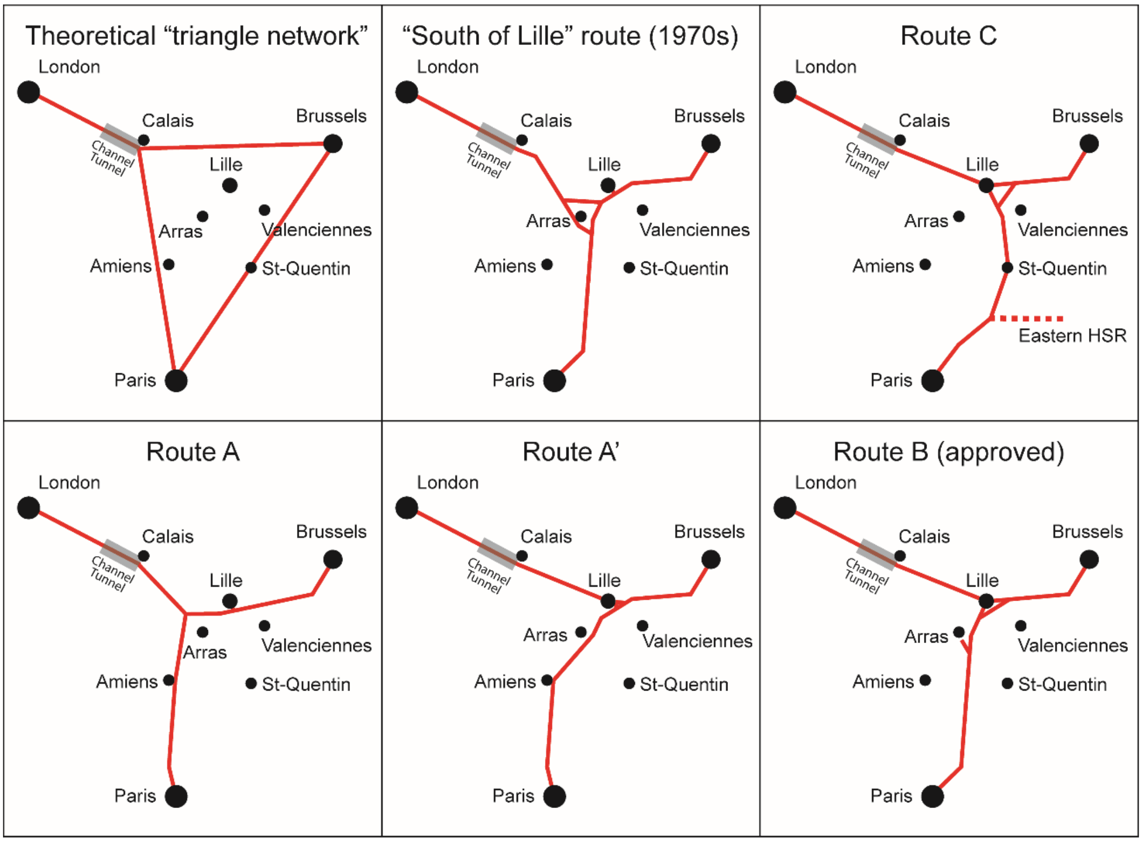

Figure 7. Potential itineraries for the Northern European HSR (adapted from Moyano and Dobruszkes, 2017, after SNCF, 1998)

The Northern European HSR was partly justified by its contribution to European integration. But railways are like the Janus face, and they can also serve much darker designs. Existing railways were intensively used by the Nazis to send people to concentration and extermination camps. And under the Apartheid regime in South Africa, railways were a concrete tool the government used to manage spatial-racial segregation (Pirie, 1987; Baffi, 2014). Non-white persons were forced to live in townships. Such suburban townships were either built along railways, or suburban railways were built to serve townships. The result of this design was a deliberate separation of non-white and white residents that still allowed for the exploitation of the segregated workforce via suburban line transport. In contrast to Jefferson's idea of "civilizing rails," Pirie (1982) was right to conclude that "decivilizing rails" existed in Southern Africa.

4. Conclusions

This chapter presents an overall geography of railways worldwide, identifying a typology of countries, which depends on the characteristics of their national rail systems, and evaluating the main factors affecting the spatial patterns of both rail infrastructures and traffic. These main factors are related to natural/physical constraints, market forces, and political interests and, although they are discussed separately in this chapter, all of them are interconnected: some factors influence others in one way or another. In addition, not only railways are influenced by the presented factors; transport systems can also reinforce or even create certain logics: for instance, while urban systems condition railway infrastructure and services, a good railway connection can influence inter-urban relationships (a new HSR connection with regional services can foster new mobility patterns). In this sense, this chapter exposes the relevance of these factors in the development of railways, and how their importance and relationship have been changing depending on the context (geographical, economic, political, etc.) during decades of evolution.

Acknowledgment

We would like to thank the Paris-based UIC team for letting us access the data utilized in Section 2.

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6. Cross references

10021: Demand for Passenger Transport

10070: How to finance transport infrastructure?

10076: Competition of air and high-speed rail

10024: The economic rationale for high speed rail

10281: Rail Freight

10461: The history of rail transport

10464: Rail transport and territorial scale

10474: Rail vehicles classification

10604: Transport modes and inequalities

10693: High Speed Rail

Biography and Photo

Frédéric Dobruszkes holds a PhD in Geography (2007) from the Free University of Brussels (ULB). He is currently an FNRS Research Associate and lecturer at the same institution. His main research interests are transport geography (especially long-distance mobilities, urban transport, and social conflicts around aircraft noise) and transport policy, including the design of public transport networks and accessibility issues faced by persons with reduced mobility.

Amparo Moyano holds a PhD in Civil Engineering (2018) from the University of Castilla La Mancha (UCLM), Spain. She is currently an assistant professor and researcher in the School of Civil Engineering of the same. Her main lines of research relate to transport and urban planning, especially focused on 1) territorial effects of high-speed rail systems and their influence on mobility patterns and 2) urban mobility and accessibility analysis using new data sources (Big Data), mainly oriented to the integration of rail stations into urban structure and local transport systems.