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New design concepts for High-speed lines and the limits of the ballasted track

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Abstract

The correct decision regarding to what type of track should be used in High-speed lines is one of the topics that has generated more discussion and controversy over the last few years. In addition, this decision is very influenced by the tradition, philosophy and design principles of the different countries. This fact is fundamentally due to the multitude of constraints and influencing factors that define as most appropriate, the use of a ballasted track against a ballastless track, or vice versa. However, the present research intends to look beyond and review the main High-speed projects of greater relevance and transcendence that are being or will be realized in the next years, around the world, to observe if some of the two typologies is presenting a greater implementation, and the main factors that are motivating this decision. In addition, the new conditions that are appearing in some countries will be analysed, related to the demand for greater performance of design speed and design life, as well as the influence that these new demands will have on the decisions related to the type of superstructure to be installed. Finally, a comparison of all these different design philosophies will be carried out, in relation to the Spanish High-speed model, in order to generate a brief discussion of the main differences and similarities found. The final objective of the present study is to analyse current trends in superstructure design and to help the debate on the type of track to be used in the High-speed lines that will be developed in the near future.

Keywords: superstructure comparison, High-speed trends, High-speed rail, ballasted track, ballastless track .

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1. Introduction

High-speed railway systems have been widely accepted in modern society, positioning themselves as one of the most important means of transport to guarantee the territorial structure. These systems present different conceptions or design philosophies regarding the superstructure subsystem, which has led to the generation of different infrastructure models characterized by a predominance of ballasted track or by a predominance of ballastless track.

Although historically the first lines had only the typology of ballasted track, nowadays, it is possible to find regions in which the implementation of the slab track is majority. The choice of typology will depend on technical factors such as relief, environmental conditions, design speed, availability of materials, etc.; and economic factors mainly characterized by the financing capacity and operating and maintenance costs.

However, in the last years, different High-speed projects have been launched in different parts of the world, where new technological challenges are being pursued, among them, the achievement of a maximum speed of around 400 km/h or, the fact of leading a High-speed line through an environment with extreme meteorological conditions. The main objective of this article is to make a deep reflection on the typology of railway superstructure that will be used to face these new technological challenges and to discuss the main limitations that can present the typology of ballasted track regarding to its use in the future High-speed lines.

With this aim, a brief historical review of the main track typologies used in the High-speed lines will be carried out, then the main limitations of the ballasted track will be described, in the third place, the main High-speed projects that are currently being developed around the world will be shown and, finally, it will be analyzed if there is any trend for the implementation of a typology of superstructure in particular.

2. State of the art

2.1 Historical review

With a length of 515 kilometers, the first High-speed line came into operation in Japan in 1964 from Tokyo Central to Shin Osaka, as shown in Li et al. (2016). This line has currently a maximum operating speed that reaches 285 km/h and has a track superstructure belonging to the ballasted track typology, as per UIC (2015). However, it was not until 1975, with the completion of the Sanyo line, when the first High-speed line with a ballastless superstructure was implemented in Japan, as explained by Yokoyama (2010), which currently has a maximum operating speed that reaches the 300 km/h, as per UIC (2016). This line was the first Highspeed line in the world that introduced the use of the slab track in a percentage around 50% of the total length of the infrastructure. The Japanese High-speed network had a total length of 1,244 km of slab track in the year 2001, as shown in Ando et al. (2001).

However, before 1964 there were already several attempts by countries such as Germany, France or the United States to launch High-speed Rail projects, which eventually became separated historical records, as described by Hughes (2015).

In the case of Germany, in 1903, 200 km/h was exceeded with an electrically powered train between Marienfeld and Zossen, over a ballasted track, as shown in Ebeling (2005). Nevertheless, it will not be until 1991 when the regular High-speed service will finally be implemented with the ICE train, using a superstructure of ballasted track, on the lines from Mannheim to Stuttgart and from Hannover to Würzburg, with a maximum speed of 280 km/h, as explained by Beck (2006). Although, the first ballastless track system is developed in 1972 at the Rheda Station, it will not be until 1998 with the construction of the line between Hannover and Berlin, when it starts to use the slab track on the German High-speed network, as shown in Sugrue (2013).

France set its first world record in 1955 reaching a speed of 331 km/h, as described by Givoni (2007). However, it will be necessary to wait until 1981 to witness the inauguration of the TGV's first High-speed line between Paris and Lyon, reaching a speed of 270 km/h on a ballasted track, as shown in Kim (2000).

On the other hand, in 1992, the first High-speed line between Madrid and Seville was inaugurated in Spain, with a maximum speed of 300 km/h over a ballasted track, as described by Gutierrez Puebla (2004). This line reduced the travel time by train between Madrid and Ciudad Real from 160 minutes to 50, generating an increase in the mobility between the two cities from 310,161 passengers in 1990 to 740,972 in 2000, as shown in Ureña et al. (2005).

Both the Spanish High-speed model and the French model have developed their entire network under the typology of ballasted track for a maximum operating speed of 300 km/h and 320 km/h, respectively, as shown in UIC (2017).

2.2 Multicriteria assessment to choose the superstructure typology

As can be seen in the previous paragraphs, there are very different philosophies depending on each country, with respect to the type of superstructure to be used in High-speed lines. Therefore, this topic has been widely discussed by authors such as Esveld (1999) and Esveld et al. (2003), who explained the advantages of the use of the slab track against the ballasted track. Koriath et al. (2003) established the main criteria for the objective selection of the typology of the railway superstructure on the German rail network. Then, in 2008 the studies carried out by CEDEX (2008) showed the medium and long-term behavior of both superstructure typologies.

Ren et al. (2009) performed an economic analysis of the life cycle of a ballasted track and compared it with a slab track. Kollo et al. (2015) developed also a detailed technical-economic comparison between both types of superstructure. Finally, Giunta et al. (2017) made a comparison between the use of slab track or ballasted track in High-speed lines from the point of view of the overall study of the life cycle costs of both solutions.

2.3 Limits of implementation of a ballasted track in a High-speed line

On the other hand, some authors have highlighted the main problems that arise with the use of ballasted track with High-speed traffic. López Pita (2001) analyzed the acceleration experienced by the ballast deterioration when subjected to High-speed traffic. Riessberger (2006) developed a study to defend the use in High-speed lines of the ballasted track but applying certain improvements or modifications to the traditional design.

Al-Shaer et al. (2008) developed a study on the dynamic behavior of the ballasted track and its settlements, in High-speed lines, by using a physical scale model. Nguyen et al. (2011) made a model to study the mechanisms of deterioration of High-speed lines with ballasted track.

Finally, Giannakos et al. (2012) outlines the main requirements to be met by ballast for its use in High-speed lines.

However, slab track systems also have important disadvantages such as the impossibility of great geometrical corrections after track construction, the very tight limitation regarding to earthwork settlements and the higher installation costs, as shown in Blanco-Lorenzo et al. (2011).

3. Experimental analysis

3.1 Main ballasted track issues

Although ballast has been widely used for railway infrastructures throughout the world, its use in High-speed lines will present important limitations that cannot be ignored in the case of lines with speeds above the 300 km/h, as shown in González-Cancelas et al. (2012). Some of the main effects that ballast can suffer if placed in lines that have maximum speeds above this limit are: a higher speed of deterioration that will significantly reduce the useful life of the ballast and that will modify its elastic and resistant properties; a proliferation of differential settlements above the normally accepted limits; and, in the third place, second-order effects such as ballast flight, which may cause significant damage to the rolling stock and imply a risk to the safety of the circulation.

With respect to the two main effects, the accelerated ageing of the ballast layer and the appearance of higher differential settlements in the track, it is worth mentioning that both phenomena are connected and both follow a direct relation with the train operating speed. Both deterioration mechanisms will follow a law of exponential acceleration with the time due to the feedback of the mechanisms that generate them.

Firstly, because high speeds produce higher dynamic loads, an important impact will be generated in the ballast increasing its stiffness and causing the appearance of the first settlements in the track. Due to these two factors, during the next load cycles that are generated when passing the trains, the dynamic loads generated by them will be increased, due to the increases of stiffness and the increase of the imperfections existing in the track due to the settlements, and there will again be a greater stiffening of the ballast layer and larger settlements in the track. This mechanism will continue to occur at a higher speed until the track failure occurs.

In conclusion, in two tracks that present the same characteristics and the same number of load cycles, it is observed that the one in which the trains circulate at a higher speed, bigger settlements and a greater deterioration of the ballast will be produced, as shown in Nguyen et al. (2011).

3.2 Analysis of rail superstructure in High-speed lines around the world

For this reason, in spite of the multitude of economic and technical factors that can define the use of a track typology or another in High-speed lines, it would be necessary to establish an approximate limit from which a ballasted track can constitute a technical restriction for a certain line can reach the maximum speeds for which it was designed, without prejudice to reduce the useful life of the infrastructure.

This fact implies that due to the high proliferation of High-speed lines being built all over the world, which are continuously seeking speed limits higher than those established as conventional, such as 300 to 320 km/h, the implementation of slab track systems will be increased, because they allow to guarantee a high performance and continuous behavior of the superstructure when the train reach the maximum speeds.

An extract of the main High-speed lines that are in operation and the type of track that they present will be made, in order to observe the possible trends that are occurring, according to the data provided by Yokoyama (2010), SSF (2010), Sugrue (2013) and UIC (2017).

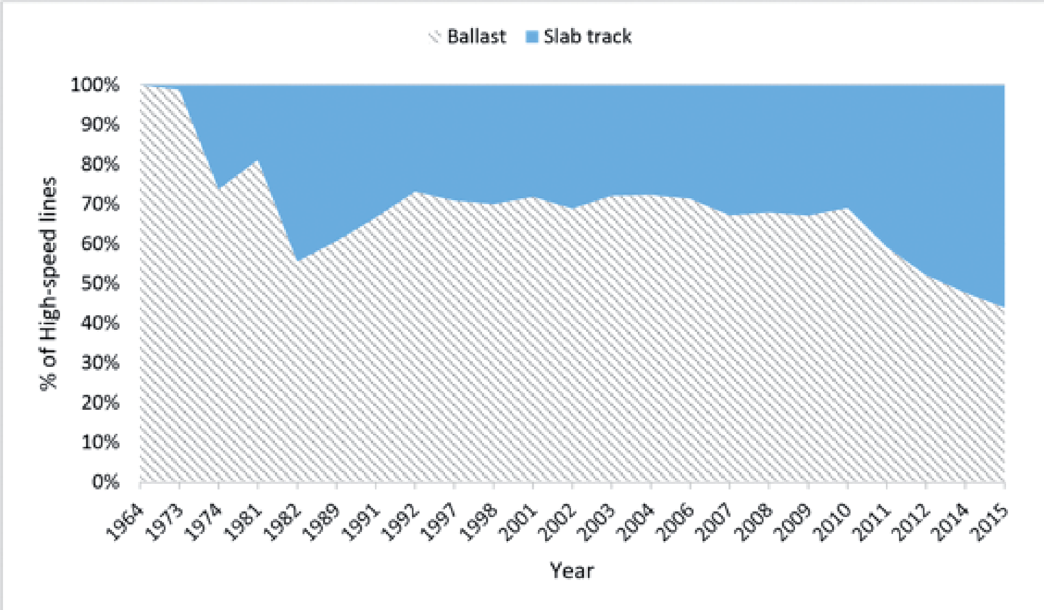

Figure 1. Historical evolution of ballasted track vs. slab track

From the results shown in figure 1 it is observed a significant increase in the use of the slab track in High-speed lines during the last 5 years. This increase is mainly due to the fast expansion of High Speed lines in China, which is using slab track in the main lines of its Highspeed network and has developed more than 4,000 km during the last years. The use of the slab track is, among other reasons, due to the high design speed that has been set in values between 350 to 380 km/h for some of the main lines. This is the case of the Beijing - Wuhan line with more than 1,200 km of slab track designed for a maximum speed of 380 km/h, the case of the Beijing - Schanghai line with 1,318 km of slab track, also, for a maximum speed of 380 km/h or, the case of the lines between Changsa - Hangzhou with 840 km and Heifei - Fuzhou with 810 km of slab track respectively, both designed for maximum speeds in the range of 350 km/h.

Secondly, this growth in the installation of ballastless track includes countries that have traditionally used it, such as Germany or Japan, which continue to expand their already consolidated High-speed networks. In the case of Germany, the construction of the Leipzig / Halle - Erfurt line, in which more than 123 km of slab track was installed for a speed of 300 km/h and, in the case of Japan, construction of the Nagano - Kanazawa line, with the installation of 228 km of ballastless track for a maximum speed of 260 km/h.

3.3 Spanish High-speed model

By contrast, Spain and France continue to have the ballasted track as the base of their Highspeed network, using the slab track in specific cases, such as long tunnels. In Spain, this philosophy is motivated by the abrupt orography that presents the Spanish territory that forces the construction of embankments with a height higher than the 10 meters.

The settlement caused by rail traffic is completed over the course of a few months, accounting for approximately 0.1% of the embankment height, as estimated by Pérez-Romero et al. (2016). Hence, the requirements to build slab track generally set the maximum embankment height around 10 meters, as shown in DB Netze AG (2014), in order to control the postconstructive settlement because the ballastless track allows only a maximum settlement in the range of 30 to 50 mm.

Due to this fact, the implementation of the slab track in Spain would require a significant reduction of the height of the longitudinal profile of the infrastructure, in order to avoid having such high embankments, generating a massive increase of the length of tunnels to be constructed in all the High-speed network, with its consequent increase in the total construction costs of these lines.

In addition, the reduction of height in the longitudinal profile would imply in the second instance a greater concern with other factors, such as the drainage systems to be built, this being another of the most important technical issues to be solved, since Spain has a large amount of areas where total precipitation is concentrated in a few days throughout the year.

On the other hand, because the Spanish High-speed model does not reach operating speeds above 300 km/h currently, it has not become indispensable to think about the possibility of installing a slab track on the main sections of the network.

In conclusion, these important constraints together with the budgetary constraints justify the use of the ballasted track instead of the slab track in the Spanish High-speed model, with 2,938 km of length.

3.4 Relationship between the rail superstructure and the speed

It can be observed in figure 2 a relation of the type of track used regarding to the maximum design speed. For the realization of this figure, only the projects developed in the last 10 years have been used.

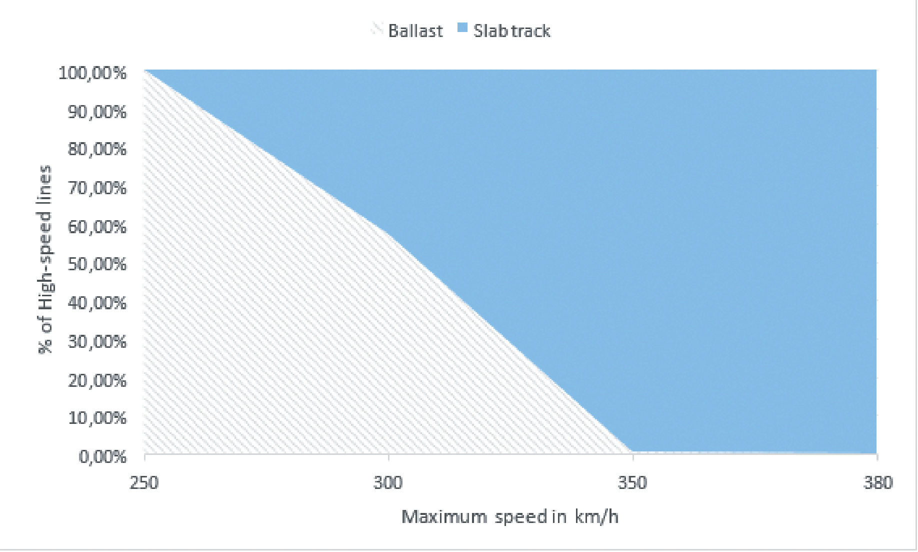

Figure 2. Track typology depending on the maximum design speed

As shown in figure 2, there is a relationship between maximum speed and type of track to be installed. Therefore, in the first instance it could be assumed that as long as the trend in the construction of High-speed railway is to increase the maximum speed of the line, the type of track that will predominantly be used will be that of slab track.

3.5 High-speed trends around the world

Therefore, it is observed that there is a clear tendency to justify the use of one type of track against the other, for High-speed projects. In addition, in recent years the implementation of High-speed networks has been accelerated around a multitude of countries throughout the world, generating a greater technical demand in the design of the new lines and searching for new challenges that allow improving the existing service, as shown in Campos et al. (2009).

In the case of the United Kingdom, this fact has clearly been reflected in the design requirements established for the development of the HS2 project, which will provide a Highspeed line connection among the cities of London, the West Midlands, Leeds and Manchester, as explained by Greening (2012). These requirements set the future maximum design speed at 400 km/h, as shown in Cornet et al. (2017), and 120 years of infrastructure design service life. Therefore, the planned railway superstructure will be of slab track type due to the important condition of the maximum design speed of the project.

On the other hand, in the case of Saudi Arabia, with the project of the Haramain High-speed Line, there have been important problems such as the fight against the desert sand, as shown in Sesma et al. (2012), and resistance to the extreme temperatures, as explained by Durand et al. (2012). The line has been designed for a top speed of 320 km/h, with 758.6 km of ballasted track and 128.88 km of slab track. This decision regarding the track typology is completely reasonable because of speed and country factor. According to the data shown above the design speed of this project is in the range in which there is a mixed use of track typologies and, on the other hand, Spain, which is one of the countries above defined as main user of ballasted track in its High-speed lines, is the designer of the railway superstructure.

In the case of Sweden, the East Link project, called Ostlanken in Swedish, is being developed for a speed of 320 km/h, and it is expected that a slab track type will be implemented, as per Trafikverket (2016, January). This decision is taking into account the two main factors again. In first place, the design speed is in the range of using slab track as shown figure 2 and the companies which are designing most of the track sections are from Germany, which is one of the countries above defined as user of slab track systems in its High-speed lines.

Finally, in the case of the United States, the High-speed line of California is still under development and has been designed to reach top speeds of 350 km/h in the section between San Jose and Los Angeles. The technical specifications leave open the door to the application of slab track or ballasted track, although the latest reports of cost estimation suggest that it will be used almost exclusively the ballasted track, reserving the slab track only for sections of viaduct or tunnel.

4. Conclusions

Throughout the article a historical journey has been made on the different types of railway superstructure installed since the appearance of the first High-speed line and have been described two of the main factors that influence it: the maximum speed and the tradition of design of the installer.

As it has been observed in the previous sections, in general, the typology of slab track is experiencing a greater implementation in the High-speed lines that are being constructed at the moment. This fact is mainly based on that the designs are being made for speeds higher than the current ones and trying to reach the limit of 400 km/h. However, this trend has important exceptions, such as the Haramain line or the California High-speed line that has installed ballasted tracks, reserving the slab track only for those sections where it is specifically needed. In the case of California, only in the areas of greater seismicity and in the sections of tunnel or viaduct, and in the case of the project of Haramain for those section that need a greater protection against the attack of the desert sand.

Finally, it has been shown that the requirements regarding the design of High-speed rail are changing to be more restrictive, taking into account not only the achievement of higher speeds, but the achievement of longer infrastructure service life.

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