RAILWAYS PROJECT AND DESIGN. HIGH SPEED RAIL IN SPAIN

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1. RAILWAYS PROJECT AND DESIGN

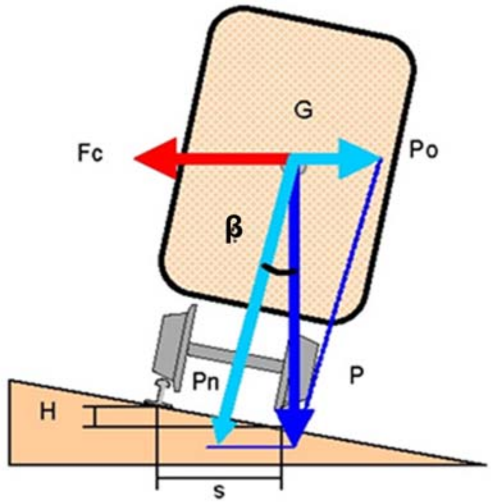
1.1. Line Layout

1.1.1. Line layout in plant

Starting with the layout (in plant) of a rail line, the main condition is the comfort of the passengers.When a train is running along a curve, as happens in cars, the passenger suffers a force towards the outside of the curve that causes discomfort. This force is known as centrifugal force (Fc), and it is equal to the mass of the train (m) multiplied by the centrifugal acceleration (α).

$$F_c = m\,x\,\alpha = m \times \left[\frac{S^2}{R}\right]$$

So, to limit the discomfort, centrifugal acceleration must be limited. The centrifugal acceleration is equal to the square of the speed (S) divided by the radius of the curve (R).



The centrifugal force is applied on the gravity center (G), and acts in the horizontal plane. To partially compensate the centrifugal force, a superelevation (H) is implemented on the track.Through the superelevation of the track, a horizontal component of the weight (Po) appears. This horizontal force decreases Fc.

$$\propto_{vehicle} = \left[\frac{S^2}{R} - \frac{g \times H}{s}\right]$$

Thus, the centrifugal acceleration acting on the train ($\alpha_{vehicle}$) will be the centrifugal acceleration (α) minus the centrifugal acceleration compensated by the superelevation, that is equal to the acceleration of gravity (g) multiplied by the superelevation (H), and divided by the distance between the rails (s). Thus, the higher the superelevation, the more centrifugal acceleration compensated. But in practice, the superelevation varies between 140 and 160 mm.

Finally, to understand the circulation of trains in curves, the effect of suspensions must be taken into account. Keep in mind that, in the vast majority of trains, the center of gravity is above the suspension. Therefore, when a train circulates in a curve, the centrifugal force deforms the suspensions (the external shock absorber compresses and the interior lengthens). This causes that the vehicle inclines towards the outside of the curve. This rotation causes an effect contrary to the superelevation. That is to say, the inclination of the railway vehicles when passing through the curves counteracts the effect of the superelevation, thus increasing the discomfort of the passengers. The magnitude of this inclination depends on the quality of the suspensions (through the parameter f). Thus, the older or worse a train is, the greater the tilt and the higher the value of f. In practice, f varies between 0.2 for new trains and 0.6 for old trains. For comfort of passengers, the maximum centrifugal acceleration is limited in practice to 1.2 meters per squared second.

$$\propto_{passenger} = (1+f) \times \underbrace{\left[\frac{S^2}{R} - \frac{g \times H}{s}\right]}_{a_{\text{vehicle}}} \leq 1.2\ \frac{m}{s^2} \Rightarrow$$

Therefore, given a train and a certain curve, it can be deduced from the expression that the greater the radius (R), the lower the centrifugal acceleration, and the greater the speed (S) that the train can reach without exceeding the maximum centrifugal acceleration (that is, without compromising the comfort of passengers).

That is, given the other parameters, the maximum speed of a train running along a curve depends on the radius, and that the higher the radius, the greater the maximum circulating speed.

Keeping in mind the previous considerations, it follows that, for the layout design of a railway line, a minimum radius will be required for each maximum speed. According to this, the Table shows that the minimum radius must increase with the speed of circulation.

Maximum speed (kph)	Minimum radius (m)
140	1,000
150	1,125
160	1,275
170	1,450
180	1,600
190	1,800
200	2,200
210	2,400
220	2,600
230	2,850
240	3,100
250	3,550
260	3,850
270	4,150
280	4,450
290	4,750
300	5,350
310	5,700
320	6,100
330	6,500
340	6,850
350	7.250

Source: ADIF (2011)

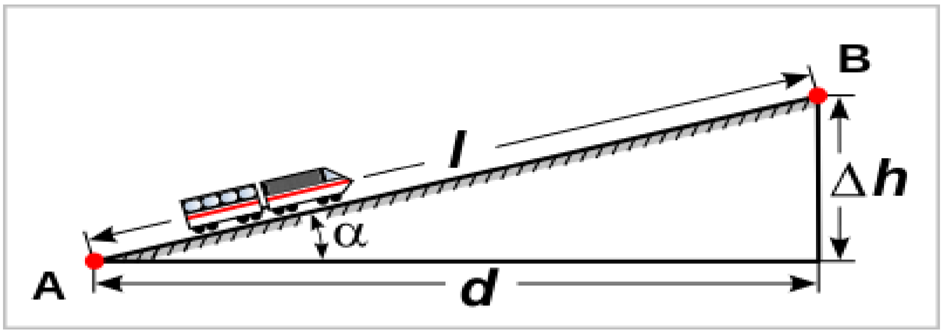
Minimun radii for maximum speeds

This Table is based on the Spanish Regulation for the project of railway lines. Thus, it is observed that, for conventional rail lines (maximum speed of up to 160 kilometers per hour), radii around 1,300 m are enough. However, for high-speed lines, much larger radiii are needed. Thus, above 300 kph, radii greater than 5,300 m are necessary.

At this point, it must be noticed that the adoption of higher speeds (and therefore the implementation of larger radii) will lead to a much more rigid design. This means that the alignment of the line will adapt much worse to the orography of the land. Therefore, the construction of larger and a greater number of civil works (embankments, cuttings, bridges and tunnels) will be needed, which will increase the construction cost.

1.1.2. Line layout in elevation

The layout in elevation (vertical projection) of a railway line is designed mainly based on the maximum allowed gradient (that is to say, the degree of the slope, also known as grade, or tg α). The choice of this parameter depends mainly on the type of trains that are expected to circulate (mainly, its speed and weight).



Source: Z22 (Wikipedia)

The inclined plane in railways

So that, the high-speed trains are very light and powerful, which allows them to face great gradients. The use of large gradients allows reducing the number and length of tunnels and bridges, since the layout adapts more to the topography of the terrain. This means great savings in the construction costs.

On the other hand, in the case of a conventional line (used for mixed traffic), the lower maximum gradients required for freight trains (slower and heavier trains) increase the construction costs. This is so because, with lower gradients, the layout adapts worse to the terrain, which implies the need to build more tunnels and viaducts.

Thus, the maximum gradient in high-speed lines is fixed at around 30 per thousand (that is, 30 meters of slope (Δh) for each 1000 meters in horizontal distance (d)). The use of these maximum gradients is conditioned to not produce an excessive decrease in speed (maximum: 10% reduction), or not to be applied during a section too long (maximum 6 km).

On the other hand, in the construction of new conventional rail lines it is usual to adopt maximum gradients of 15 per thousand. This is due to the fact that these lines are for mixed traffic (passenger and freight trains) and, especially to freight trains (which are usually very heavy and slower than passenger trains), since they have trouble climbing steep slopes.

Finally, the design of the layout of a railway line results in plans like the one shownin the Figure. The plan shows a section of railway line. The upper drawing refers to the layout in plan view (horizontal projection), and the lower drawing, to the layout in elevation (vertical projection). In the plan view it can be seen where a transition curve begins (parameter A), where it ends, and where the curve of radius R begins. Moreover, in the elevation plan the profile of the terrain, the gradient of the line, an embankment, and a cutting section can be seen.

1.2. Track Structure

1.2.1. Rail calculation

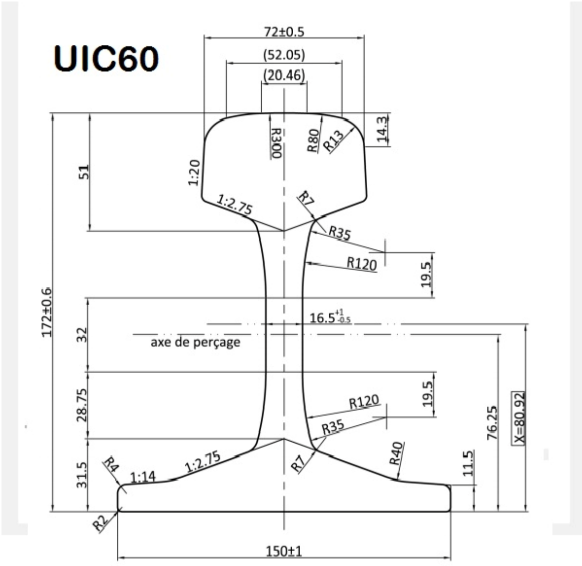
The rails wear out due to trains traffic. Therefore, the useful life of the rails depends mainly on the traffic they support. Thus, to achieve a longer useful life and lower maintenance costs, rails with a minimum cross section must be chosen. The greater the cross section of a rail, the greater its linear weight (weight per meter). This is so important that, in fact, he rails are named according to their linear weight in kg per m. Therefore, with higher traffic, a heavier rail must be installed.

DAILY TRAFFIC VOLUME (GTH)	RECOMMENDED RAIL (kg/m)
< 30.000	46 – 50
30.000 – 60.000	50 – 60 (UIC-54)
> 60.000	≥ 60 (UIC-60 ó 71)

Source: Office for Research and Experiments (ORE)

Recommended rail by the ORE

There are several methods (all of them empirical) to calculate the rail. One of them was developed by the Office for Research and Experiments (ORE). As the Table shows, the ORE method classifies the lines according to their daily traffic in GTH (Gross Tonne Hauled). For example, a line with a daily traffic of about 65,000 GTH,would need a rail of 60 kg per meter. According to this result, the UIC-60 standard rail should be chosen (in the Figure).



Source: Suyu (2015)

UIC-60 standard rail

1.2.2. Sleepers

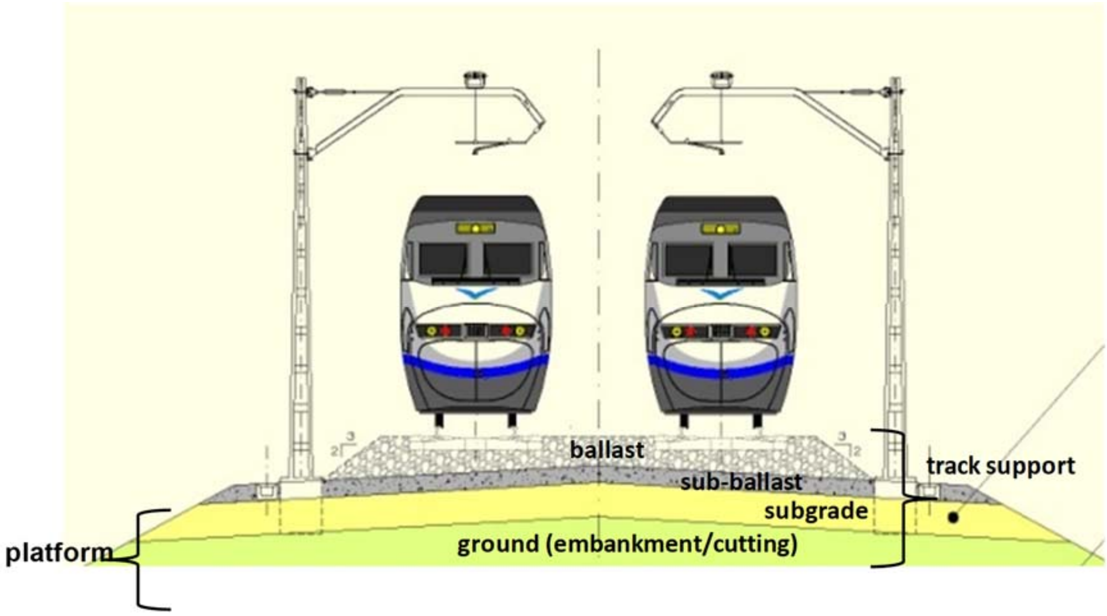
Nowadays, monoblock concrete sleepers with flexible fastenings are commonly used. This is because their long useful life, and because they contribute to maintain the geometry of the track very well. The figure shows monoblock sleepers of international or standard UIC gauge.

Source: Prefabricados Delta

AI (international gauge) monoblock sleeers

1.2.3. Track support calculation

The Figure shows the cross section of a railway track, in which the following parts can be seen:



Railway line cross section

- Rails: the rail is the element that guides the train and transmits the loads to the lower layers; the sleepers maintain the track gauge and distribute the loads in the track bed (integrated by the ballast and de sub-ballast); the fastenings keep the rail and sleepers together.

- The ballast is an aggregate that constitutes formed by crushed rock, with sizes comprised, between 25 and 60 cm. It provides the track with the necessary vertical elasticity to absorb the dynamic loads coming from the trains, facilitates drainage and transmits the train loads to the sub-ballast.

- The sub-ballast: is an aggregate consisting on a well graded sandy gravel, with some fine elements so that it is easily compactable. It protects the platform from the punching by the ballast, and the ballast from the intrusions of polluting materials coming from the platform (clay, organic materials, etc.).

- The platform (embankment of bottom part or a cutting) supports the track bed and the track. It must support the static and dynamic loads of the trains, avoiding vertical displacements that may affect the functionality of the track, as well as guarantee the evacuation of rainwater through the provision of transversal slopes. The upper layer of the platform is called the subgrade (also known as the “form layer“), and it is must have the highest bearing capacity to support the loads coming from the upper layers. Therefore, it is generally made up of better soils than the embankments, in order to improve the bearing capacity of the platform. Moreover, a greater compaction degree is required for this layer.

The design of the track support layers consists on the calculation of the thickness of the different layers (ballast, sub-ballast and subgrade) and on the quality selection of the materials to be used as construction material for the body of the embankment and for the subgrade. This methodology is based in the Spanish regulation “Instruction for the Project and Construction of Railway Lines IF-3” by the Ministry of Public Works (2015), which, in turn, is based on two regulations coming from the International Union of Railways (UIC, 2008, and UIC, 2009).

The design of the track support depends on the quality of the ground support and on the expected traffic (number of trains, weight of the trains, speed and axle-load). The axle load of a rail vehicle is the weigh that rests on an axle. The higher the traffic, the higher the quality of the track support must be. For this, the quality of the platform is classified into three levels from highest to lowest quality (in terms of bearing capacity according to the California bearing ratio, CBR): P3 (CBR> 20), P2 (5 <CBR <20) and P1 (CBR <5). P1 quality platforms are not recommended, due to their fast degradation, and higher maintenance costs.

The California bearing ratio (CBR) is a penetration test for evaluation of the mechanical strength of the ground (the load-bearing capacity), subgrades and base layers in roads and railways. The basic site test is performed by measuring the pressure required to penetrate soil or aggregate with a plunger of standard area. The measured pressure is then divided by the pressure required to achieve an equal penetration on a standard crushed rock material. The CBR test is described in ASTM Standards D1883-05 (for laboratory-prepared samples) and D4429 (for soils in place in field), and AASHTO T193.

Therefore, in order to calculate the platform, first of all it is necessary to classify the soil or rock that is going to be the support of the track according to its geotechnical characteristics. According to this classification, the materials are classified as poor (QS1), average (QS2) or good (QS3). Some examples of these materials can be seen in the Table.

Ground			Platform quality	Subgrade	
Quality	Clasification	Examples		Clasification	Minimum thickness (cm)
Poor	QS1	clay, paster, soft rocks	P1	QS1	-
			P2	QS2	50
			P2	QS3	35
			P3	QS3	50
Average	QS2	sand, intermediate strength rocks (limestone, sandstone, slate, conglomerate)	P2	QS2	-
			P3	QS3	35
Good	QS3	High strength rock (hard limestone, siliceous, igneous rocks such as granite, metamorphic, quartzite, etc.)	P3	QS3	-

Source: Own source, based on Ministry of Public Works (2015), UIC (2008) and UIC (2016)

Railway platform support calculation

To obtain platforms of different qualities, it will be necessary to build different types of subgrade (in terms of thickness and quality of the material), depending on the quality of the support ground. So, for example, to build a platform of intermediate bearing capacity (P2) on a poor quality soil (QS1: clay, for example), a subgrade of intermediate quality material (QS2.: conglomerate, for example) with a thickness of 50 cm will be needed.

The trains traffic volume is taken into account according to the concept of “Theoretical traffic” (Tf), defined by the International Union of Railways (UIC, 1989). Tf depends on the speed, the weight of the trains, and their maximum axle-load, and has the following expression:

$$Tf = S \times K \times T$$

Next, the influence of traffic on the calculation of the track will be explained.The parameter S represents the influence of the speed on the deterioration of the track, and therefore, S increases with the speed (from 1.0 to 1.5). The limitation of this document of the UIC is that it has not been updated since its first edition in 1989. Thus, the parameter S is considered constant from 250 kph. Today there are many high-speed lines operating at 300 kph, and it is known that the dynamic loads of trains on the track increase very much with speed, so S should reflect this effect.

S (kph)	S
V≤ 60	1,0
60 < V ≤ 80	1,05
80< V ≤ 100	1,15
100< V ≤ 130	1,25
130< V ≤ 160	1,35
160< V ≤ 200	1,40
200< V ≤ 250	1,45
V > 250	1,50

Source:UIC (1989) and (2009)

Effect of the speed

The more weight a railway axle supports, the greater loads it transmits to the track and, consequently, the greater the track deterioration that it produces. The parameter K allows taking into account this effect. Thus, K increases with the axle-load. The maximum axle-load is usually higher in the traction-motor axles of locomotives and passenger multiple units (because these axles are supporting the motor), as well as in the axles of the freight wagons (when they are loaded to the maximum). Regarding passenger multiple units, the maximum axle-load corresponds to concentrated traction multiple units (i.e., multiple units with tractive units, like the series 101 HS trains, on the left in the Figure), while it is lower in distributed traction multiple units (since there are equipped with small engines located in several axles along the train, like the series 103 trains on the right in the Figure) .

Source: F. Calvo (2004 y 2013)

HS passenger multiple units with concentrated and distributed traction

Therefore, K is generally assigned the value of 1.0 for distributed traction and 1.4 for concentrated traction.

Vehicle	Maximum axle-load (t)	K
Passenger car	(low)	1.00
Locomotive	(high)	1.40
Passenger multiple units	> 17 (concentrated traction)	1.40
	≤ 17 (distributed traction)	1.00
Freight wagon	<20	1.15
	20	1.35
	22,5	1.45

Source:UIC (1989) and (2009)

Effect of axle-load

As mentioned before, traffic is one of the main factors determining the choice of platform quality. The UIC classifies traffic into 6 groups, according to its theoretical traffic. In general, the greater the expected traffic, the greater the quality of the platform must be, in order to increase its useful life and decrease maintenance costs. Therefore, P3 platforms would be recommended for Groups 1 and 2, and P2 for Groups 3 and 4. As previously mentioned, the worst quality platforms (P1) are not recommended. In any case, if there is the possibility of building a P3 platform (the necessary materials are available, or they can be brought from a quarry), it is always better to choose a P3, because its higher strength, longer useful life , and lower maintenance costs.

According to the Table, for each platform quality, a minimum track bed (layer including the ballast and the sub-ballast) thickness will be required. As it can be seen, the higher the quality of the platform, the lower the thickness of the track bed (since the track has better support). This is very convenient, since the ballast and the sub-ballast are the most expensive aggregates used in the construction of the track.

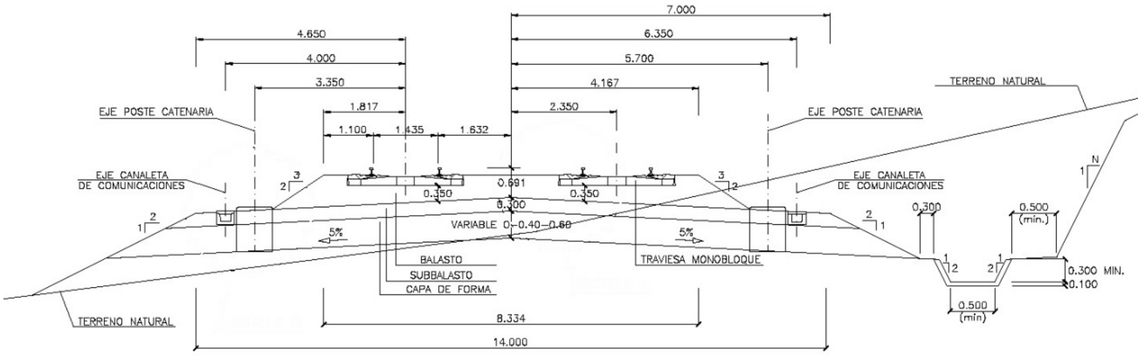
Next, the thickness of the track bed is decreased (10 cm) in the lower traffic groups (Groups 5 and 6), increased for high the axle-load (between 5 and 12 cm), and decreased with the length of the sleepers.

Finally, and according to the practice, the following minimum values are adopted:

- 25 of ballast.
- 25 cm of sub-ballast if the speed is higher than 160 kph.
- 30 cm ballast if the speed is higher than 120 kph.
- 60 cm of track bed if the speed is higher than 200 kph.

For example, if a P2 platform is projected, because the traffic is intermediate (for example, Tf = 30,000 tons/day, which would correspond to a Group 4), the thickness of the track bed would be around 55 cm. In addition, if the design speed is 180 kph, and considering the minimum values, 25 cm of sub-ballast and 30 cm of ballast could be a solution.

At this point, it must be noticed that the values obtained through this methodology are minimum values. Therefore, they are recommended to be increased if very high speed or high traffic volume are expected. Thus, in high-speed lines (and because the method is based on the UIC 1989 instruction, as stated before), 5 cm of extra thickness is usually adopted, resulting in 30 cm of sub-ballast, 35 cm of ballast, and 60 cm of platform. According to the previous considerations, the cross section of a railway line could be designed, which in the case of double track high-speed line, would be as shown in the Figure.



Source:ADIF (2011)

Cross section of a high-speed rail double track line

2. HIGH-SPEED RAIL (HSR) IN SPAIN

2.1. Definition of HSR

The European Directive 2008/57/EC on the Interoperability of the rail system within the European Union includes de definition of HSR. Interoperability between railway lines is the possibility of connection between them. Therefore, interoperability allows trains passing from one national railway network to another without any problem at the border. For this, the European railway lines must include common (that is to say: interoperable) systems: track parameters, gauge, length of the platforms, signaling and communications, train drivers training, electrification, etc. According to the mentioned regulation, the Trans-European high-speed rail system can be integrated by:

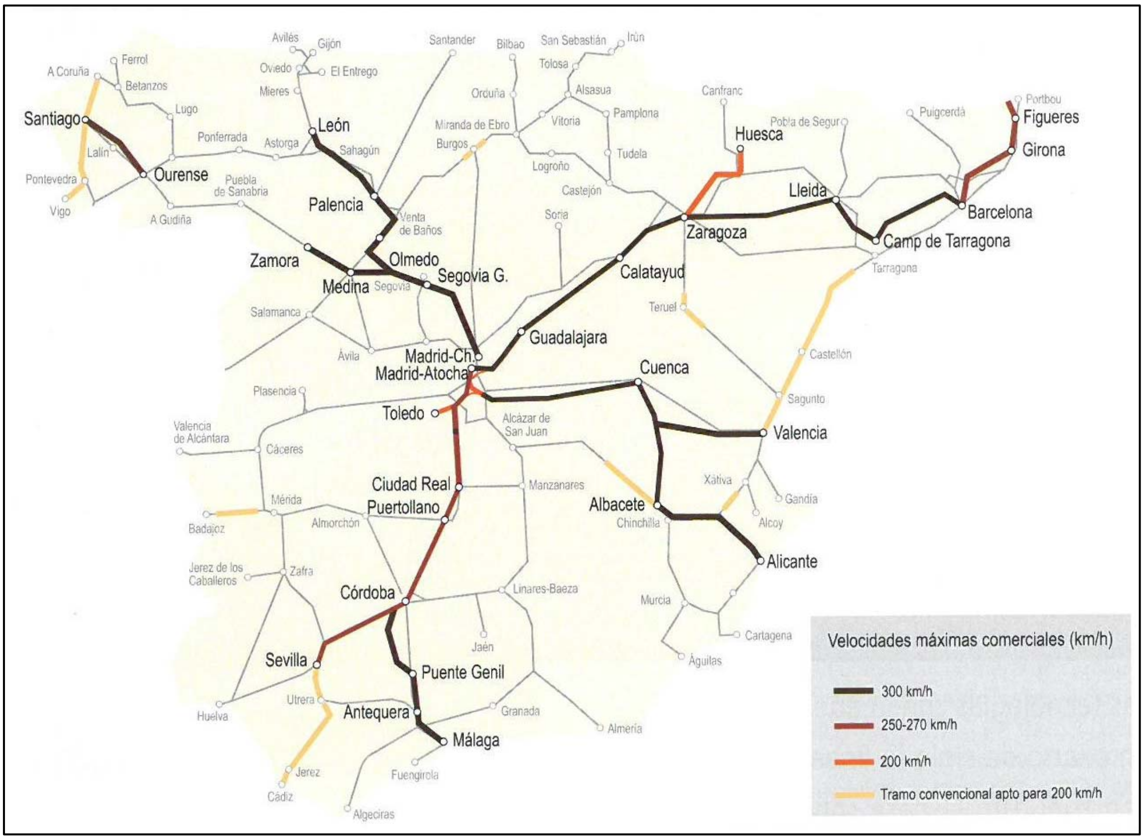
1. New high-speed lines equipped for speeds generally equal to or greater than 250 kph,
2. Upgraded rail lines equipped for speeds of around 200 kph,
3. Upgraded rail lines projected for lower speeds as a result of topographical, environmental or urban constraints.

So, as it can be deduced from the previous definition, speed is not an exclusive factor for a line to be part of the European high-speed network.

Otherwise, one factor that is decisive for a line to be part of the European high-speed network is that it can connect with the rest of the European network. That is to say that the line complies with the interoperability requirements.

2.2. Maximum speeds

The Figure shows the Spanish railway network in 2017. In gray appear the conventional lines, and in color the high-speed lines. According to the previous definition, there are specially built high-speed lines with different maximum speeds (from 200 to 300 kph). Moreover, yellow lines are conventional lines that have been adapted to high speed standards (as upgraded rail lines, according to the definition).



Source:VíaLibre (2018)

Maximum speeds in the Spanish HSR network

Some examples of these types of HSR lines (according to the numbers of the definition in the precious section) are:

1. Madrid-Barcelona: specially built high-speed line (dedicated passengers' traffic).

1. Barcelona-french border: specially built high-speed line (mixed traffic).

2. Mediterranean Corridor (Alicante- Valencia-Tarragona): upgraded rail line (mixed traffic).

3. Madrid-Seville: specially built high-speed line (dedicated passengers' traffic) with lower speed sections as a result of topographical and environmental constraints (like the Sierra Morena mountain range crossing).

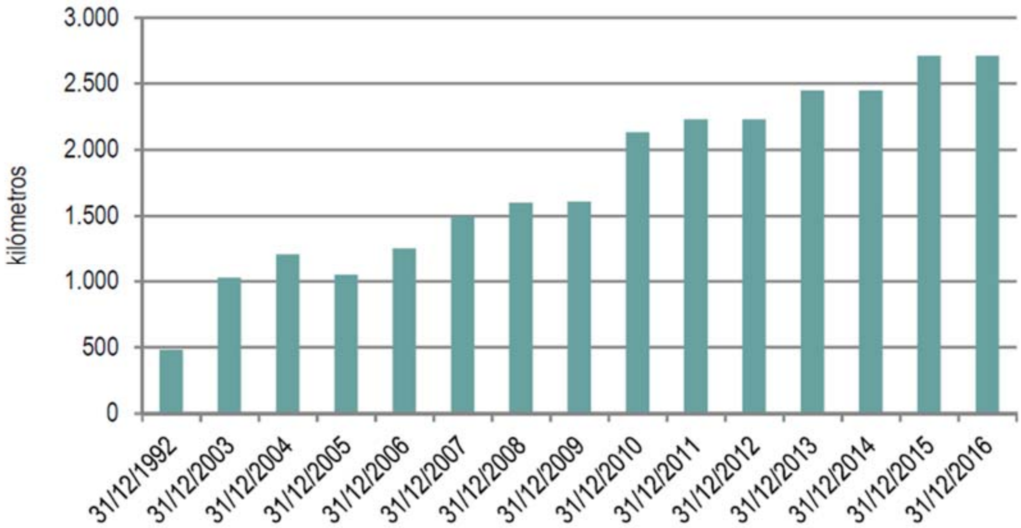
2.3. Network evolution

The construction of the Spanish HSR network began in 1992, with the Madrid-Seville line. More than 56,000 million € have been invested for the development of the Spanish high-speed network until 2021.

In 2022, the Spanish railway network is 15,652 km long, comprising 11,121 km of conventional lines (Iberian gauge, 1,668 mm), and 3,359 km of High-speed lines (Standard gauge, 1,435 mm). The high-speed network is composed of:

- High-speed Standard gauge lines: 3,030 km.
- High-speed Iberian gauge lines: 84 km.
- High-speed Standard and Iberian gauges (3 rails): 245 km .

Spain has the longest High-speed network in Europe, and second in the world, after China (38,000 km).

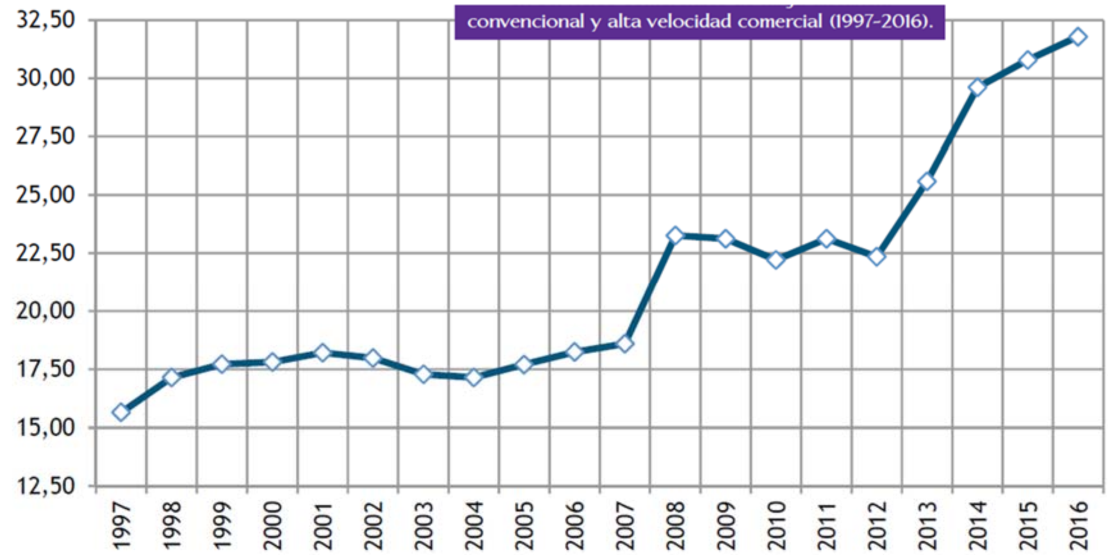


Source: Vía Libre (2018)

Maximum speeds in the Spanish HSR network

2.4. Demand evolution

Since the opening of the first high-speed line, long-distance trains (and some regional ones) that used conventional rail lines were transferred to the high-speed network. For this reason, a large part of former conventional rail passengers were transferred to the high-speed train services. The Figure shows the evolution of demand of high-speed train services. As it can be seen, the number of passengers multiplied by two in the last 20 years. In 2017 circulated 677 trains daily in the Spanish HSR network, and the annual demand reached 32.5 million passengers.

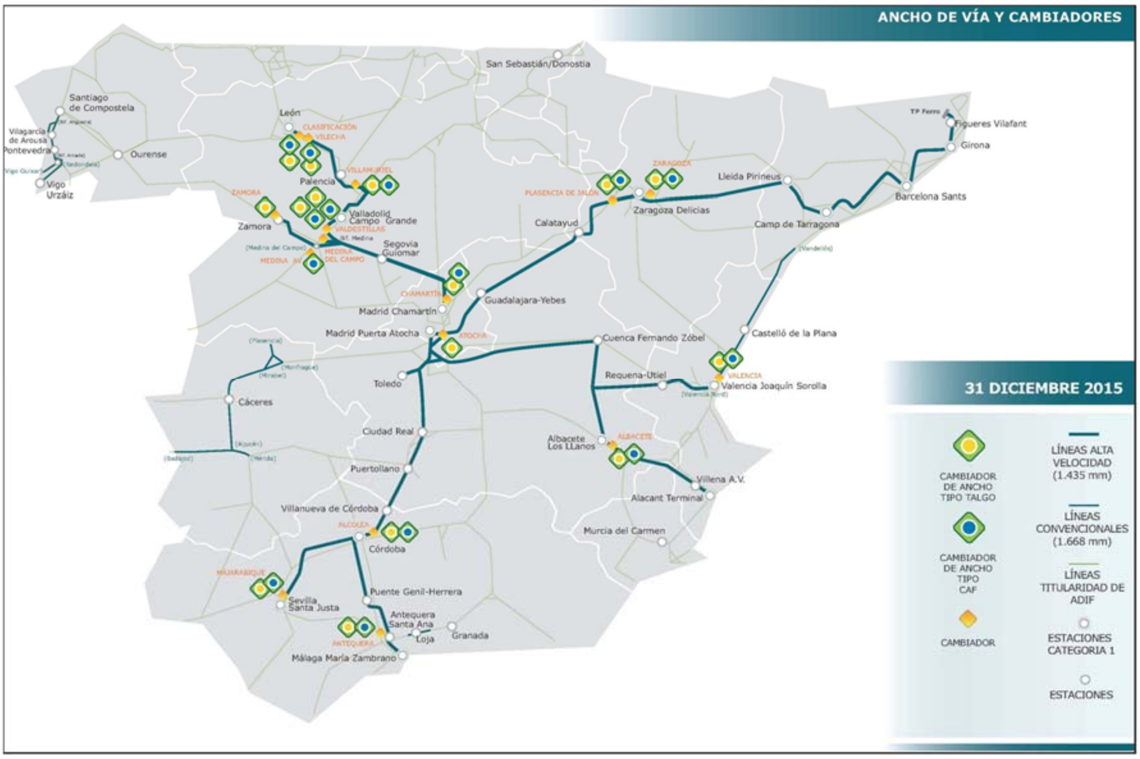


Source: Vía Libre (2018)

Demand evolutionof the high-speed train services

2.5. Current situation

At this point, it is necessary to mention that the Spanish conventional rail network (11,600 km long, in grey in the Figure) is composed of Iberian gauge (1,668 mm)lines, while high speed lines (in green in the Figure) are built in standard gauge (1,435 mm). This results in an interoperability problem between them, which is partially solved via the gauge changers (represented by diamonds in the Figure).



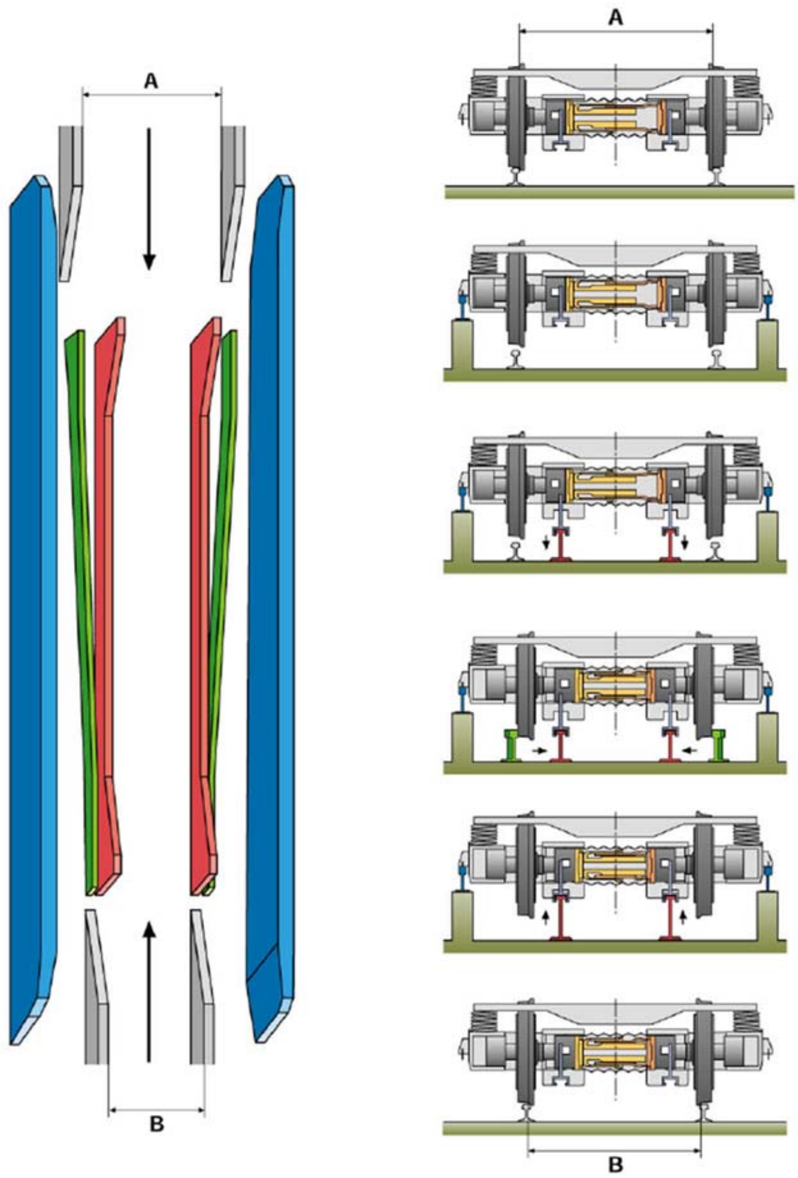
Source: ADIF (2016)

Track gauge and gauge changers

The gauge changers are facilities where the trains (only special trains with variable gauge axles) can change gauge. By this, both rail networks can be operated jointly, and benefits can be increased.

Source:J. Alguacil

Gauge changer



Source:Talgo

Gauge changing process

2.6. Final horizon

As shown in the Figure, the Transport Infrastructures Plan of Spain proposes to build a high-speed network of about 10,000 km. This means the construction of a new a rail network parallel to the existing conventional one (although, as stated before, in some cases, some sections of the old line are upgraded and incorporated to the high speed network).

Source: Ministry of Public Works (2015)

Proposed Spanish HSR network

2.7. Trains and services

Respecting to the rolling stock used in the Spanish high-speed network, it is mainly composed of electric train units (mostly manufactured in Spain). The long distance trains that run exclusively along the high-speed lines are called AVE (Spanish High Speed). These trains offer the maximum capacity (300-400 seats) and speed (300-325 kph). All of them are day trains.As it can be seen in the Figure, in Spain circulate high-speed trains with concentrated traction (AVE series 100, on the right), and trains with distributed traction (AVE series 103, on the left). As previously mentioned, the former are more aggressive to the track than the latter.

Source: F. Calvo (2018)

High-speed long distance trains in Seville

The medium distance transport services (regional trains) are called Avant. They are smaller capacity trains (240 seats) and lower maximum speed (250 kph). In addition, for social reasons, the tickets are subsidized (30-45% cheaper).

Source: F. Calvo (2013)

Avant Seville-Málaga

Finally, there are trains that run both along high-speed and conventional lines, which, as mentioned before, have different gauge. Thus, the trains must be of variable gauge and, moreover, multi-voltage (since the electrification system is different in the high-speed network than in the conventional one) and trains must incorporate several traffic control systems (which are different as well). Within these train services there are:

- Alvia: they are electric train units with concentrated traction (like the series 130 in the Figure) or distributed traction (series 120), and even, dual traction (electric and diesel, to allow them to circulate through non-electrified lines, like the series 730). They have a capacity of about 290 seats and reach 250 kph in the high speed lines and the maximum allowed speed in the conventional ones.

Source: F. Calvo (2013)**Alvia (s/130) Barcelona-Vigo**

Source: C. Peña (2013) **Alvia (s/730) in Granada**

- Altaria: Talgo train towed by locomotive (200 kmph).
- Hotel Trainl: Talgo train towed by locomotive (night train).

Source: F. Calvo (2013)

Alvia (s/120) Madrid-Hendaya (Francia) circulating on a conventional line in Tudela (Navarra)

2.8. Cost

To give an idea of the cost of the Spanish high-speed network, it can be mentioned that, in 2022, the State General Budgets allocates 6,743 million € to the railway. Of this investment, around 80% use to be for the high-speed network, and the rest for the conventional network. At this point, it must be remembered that the conventional rail network is four times longer than the high-speed one, what may give an idea of its high construction cost. In fact, more than 56,000 million € have been invested for the development of the Spanish high-speed network until 2021.

Regarding to the rolling stock, the cost of each electric train unit amounts around 25 million €. Next, the Table shows some examples of the construction cost of some lines.

Rolling stock (unit)	Around 25 million €		
Infrastructure. Line:	**Length (km)**	**€ (million)**	**€ (million)/km**
Barcelona – Figueres (french border): topographical and urban constraints	129 km	4,200	**32.6**
Orense –Santiago: topographical constraints	87.1 km	2,547	**29.2**
Santiago - La Coruña: upgraded line. Topographical constraints	61.8 km	753	**12.2**
Valladolid- León	162.7 km	1,600	**9.8**
Olmedo - Zamora	99 km	748.2	**7.6**

Source:Vía Libre

Data costs of HSR in Spain

- The Barcelona-French border and Orense-Santiago lines had a construction cost per kilometer of 32.6 million €, due to important urban (in the first) and topographic (in both) constraints.
- The Santiago-La Coruña line is an improved conventional line to adapt it to high-speed parameters, and its cost amounted to 12 million € per kilometer.
- Lastly, the cost of the Valladolid-León and Olmedo Zamora lines was between per kilometer, since they had no significant constraints of any kind.
- The Barcelona-French border and Orense-Santiago lines had a construction cost

So it can be said that, in general, when there are significant constraints (topographic, urban or environmental) for the construction of high-speed lines (and therefore, the construction of numerous tunnels and viaducts is required), their cost is around 30 million € per km. On the other hand, when these constraints are not so important, the high speed lines cost can be reduced to 8 million € per kilometer.

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