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Methodology to determine the optimal design speed in a High-Speed Line

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Abstract

Over the past 30 years, high-speed railway in Europe has experienced a great development due to, among other things, the reduction of travel times, the increase of frequency and the continuous improvement of service quality.

However, the construction of a new high-speed railway infrastructure requires an enormous mobilization of resources, has a long lifetime and the alternative uses of this huge investment are very few. Consequently, this kind of investment is always preceded by a rigorous analysis in order to ensure the best possible results.

In an analysis of these characteristics, there are different variables that have an influence on costs and benefits that a high-speed line could generate and, therefore, it can be asserted that there are certain parameters with direct impact on the profitability of a high-speed line; among them, maximum design speed of a high-speed line can be highlighted. If real experiences are analysed, real high-speed lines currently in service or under construction, maximum design speed is, essentially, the same all over the European high-speed networks (300km/h or 350km/h), a solid reason behind this pre-determined speed has not been found.

The design speed plays a crucial role in a framework in which the efficiency and the social benefit are essential. A higher design speed implies higher investment costs and, sometimes, implies slight increases in exploitation costs, but also brings journey time reductions and, consequently, an increase in the number of passengers that implies an increase in revenues and time savings.

At this point, this paper develops a methodology capable of obtaining the maximum design speed that allows obtaining the maximum revenues with the minimal cost, which implies achieving the maximum profitability of a high-speed railway line.

Keywords: design speed, financial profitability, socio-economic profitability, revenues and benefits.

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1. Introduction and methodology

1.1 Planning a high speed line

The construction of a new transport infrastructure, such as a railway high-speed line, requires an enormous mobilization of resources, has a long lifetime but the alternative uses of this investment are very few. Consequently, this kind of investment is always preceded by a rigorous analysis and occasionally also by a public debate in order to ensure the best possible results.

Normally, the final decision made about the construction of a railway infrastructure is based on a Cost Benefit Analysis (CBA) methodology, supported by different indicators (i.e. NPV, IRR…) which, depending on the value obtained, will support or reject the final decision of building the infrastructure.

The methodology (CBA) is based on intermediate results obtained from different models (exploitation cost models, revenue models…). These intermediate models also process different input parameters, which usually are: (i) characteristics of the infrastructure (maximum speed, slopes, etc.), (ii) socio-economic variables (such as population, GDP per capita…), (iii) train parameters (e.g. maximum speed, architecture…), (iv) service variables, as load factor, frequency, and (v) unit costs. Thereby, it can be said that the final decision made, in an indirect manner, is influenced by the value of a set of parameters (input parameters), and depending on the value they take will increase or decrease the profitability of the project.

Among the input variables capable of increasing or decreasing the profitability of a HS project, it can be stated that the maximum design speed of a railway line is of a major significance to the final output and to the socio-economic profitability, due to it has an influence on each and every of the parameter that feed a CBA (see Figure 1).

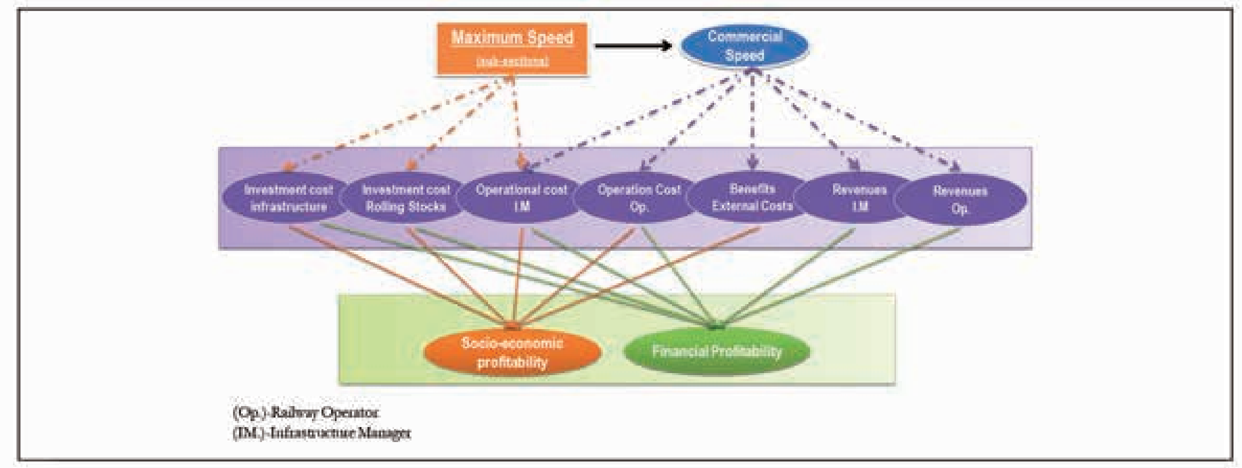


Figure 1. Effect of the speed on the economic and financial profitability.

As well as, many others manageable parameters are, occasionally, field of study within the CBA (i.e. fare, frequency…); maximum design speed usually is a pre-defined value and previously established to an economic appraisal. If real high-speed lines currently in service or under construction are studied, maximum design speed is practically the same (300km/h or 350 km/h) all over the European high-speed networks.

Maximum design speed plays a crucial role in a framework in which the efficiency and the social benefits are essential. A higher design speed implies higher investment costs and, sometimes, implies small increases in exploitation costs, but it also brings journey time reductions and, consequently, an increase in the number of passengers that implies an increase in revenues and time savings.

In addition, an increase of the commercial speed (journey time reduction) also brings new indirect effects on the demand. Traditionally, journey time reduction is accompanied by improvements in the services offered by the operator (frequency increases, trains with greater capacity…). These improvements imply greater number of passengers, either because of the operator reduces its costs (higher train capacity) and reflect these reductions in the ticket price or because passengers have greater “possibilities” for travelling (higher number of frequencies).

1.2 Design speed of a high-speed line

In view of the above, this paper develops a methodology capable of obtaining the combination of maximum design speeds for each sub-section and, consequently, commercial speed that allows obtaining the maximum incomes with the minimal cost, which implies obtaining the maximum profitability of a high-speed line (greater socio-economic NPV).

The methodology proposed in this paper carries out a financial and socio-economic assessment of a new high-speed infrastructure, which links Madrid, Cuenca and Valencia aiming to obtain the combination of the maximum design speed to which the infrastructure should be built. Therefore, all the different combination of the maximum design speed assigned to each sub-section defined are analysed in terms of social and financial profitability. The combination of maximum design speed and therefore the commercial speed, which obtains the maximum social profitability, will be the one selected.

In addition, the economic and financial analysis is also assessed for two different ticket prices, allowing not only to determine the commercial speed that obtains the maximum profitability of the line, but also allows knowing the effect of the ticket price paid by the travellers on the economic and financial profitability.

The methodology developed is defined in five more sections. Section 3 defines the study case and the initial hypothesis used. Section 4 will address the demand calculation and its relationship to the commercial speed and, consequently, the revenues and the benefit of the project. Section 5 will define and explain the cost models used both in the operational costs model and the investment cost model. Section 6 estimates the economic and financial profitability of the study case, taking into account the model defined in previous sections and, finally, section 7 establishes the conclusions of the work.

It is important to mention here that the models developed not only have one application or use (one high-speed line), as it is for this paper, but also allow its use in the different degrees of development of a railway network or corridor.

2. Definition of the study case and initial hypothesis used

2.1 Study case

The scenario chosen corresponds to the study of the financial and economic profitability of a generic high-speed layout. This layout would link the cities of Madrid, Cuenca and Valencia (see Figure 2) and would be composed of two sections and four sub-sections.

For each of the sub-section different types of terrain will be assigned (flat profile, slightly-rough profile, mountainous and very mountainous profile) and the percentage of type of terrain and, therefore, the length of each of the sub-section used in the analysis carried out is described in the following table (Table 1).

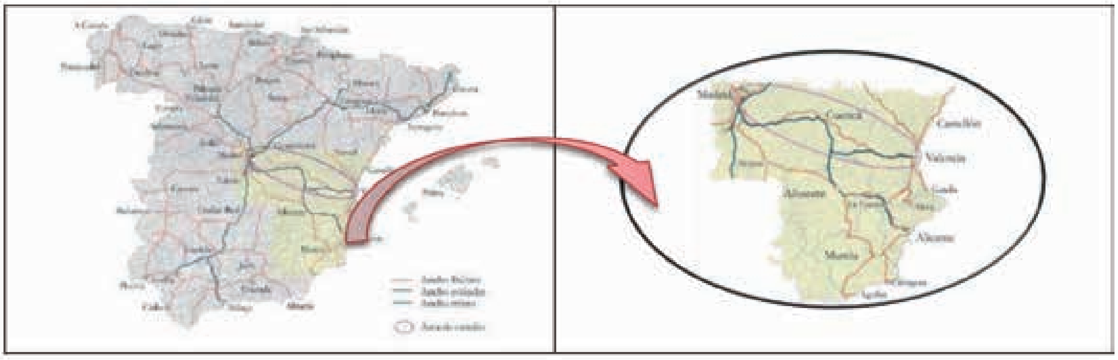
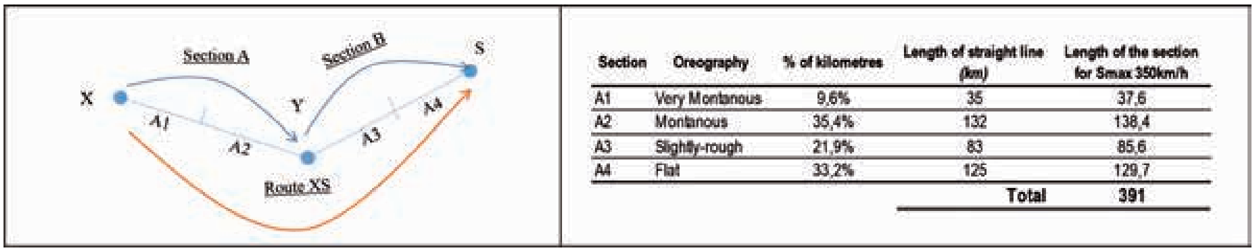


Figure 2. Study case analysed.

For each of the sub-section different types of terrain will be assigned (flat profile, slightly-rough profile, mountainous and very mountainous profile) and the percentage of type of terrain and, therefore, the length of each of the sub-section used in the analysis carried out is described in the following table (Table 1).

Table 1. Types of terrain of the study case.



Section	Oreography	% of kilometres	Length of straight line (km)	Length of the section for Smax 350km/h
A1	Very Montanous	9,6%	35	37,6
A2	Montanous	35,4%	132	138,4
A3	Slightly-rough	21,9%	83	85,6
A4	Flat	33,2%	125	129,7
			Total	391

The percentage of the type of terrain that the line would cross has been determined and predefined from average values of the Spanish high-speed lines. Furthermore, for each of the subsections a maximum design speed is assigned within a range between 200km/h and 500km/h with increments of 10km/h, which implies that it is necessary to solve 923,521 scenarios.

Table 1: Combination of the maximum design speed for each scenario proposed.

	Section A1 Very Montanous	Section A2 Montanous	Section A3 Slightly-rough	Section A4 Flat
	Max. Speed (km/h)	*Max. Speed (km/h)*	*Max. Speed (km/h)*	*Max. Speed (km/h)*
Case 1	200	200	200	200
Case 2	200	200	200	210
...	...	...	...	...
Case 923.521	500	500	500	500

$$V_{31}^{4} = 31^{4} = 923{,}521$$

2.2 Hypothesis of a CBA

The table below (Table 2) gathers the main hypothesis used in order to apply the CBA model.

Table 2. CBA input parameters.

Baseline year	2011 euro
Time Horizon	30 años
Financial Rate of Return (FRR)	5%
Economic Rate of Return (ERR)	5,5%

2.3 Rolling stock characteristics

Some of the characteristics of the rolling stock considered differ depending on the scenario analysed, since the train used in the model developed will be one or another depending on the maximum design speed considered. Essentially, the parameters which vary are the train maximum speed and, as a result, the power output.

The rest of the characteristics have been established and correspond to the train Velaro. Velaro is a family of high-speed EMU trains used in Germany, Belgium, the Netherlands, Spain, China, Russia and Turkey and are based on the ICE 3M/F high-speed trains manufactured by Siemens for Deutsche Bahn. The table included below (Table 3) show the main train parameters considered in the model.

Table 3: Main train characteristics.

Seats	404
Articulated Coach	Articulated_bogies
Traction	Distributed
Body width	Normal-Body (2,550mm-3,400mm)
Single or double-deck	Single-decker
Signalling System	ASFA+ETCS 1+ETCS 2
Seats density	Luxurious (3 classes and dining car)
Installed Power (kW)	3.074kW -27.900kW

3. Effect of the speed on revenues and benefits

Before explaining the existing relationship between commercial speed and revenues and benefit it is necessary to define the relationship between speed and passenger mobility (demand model). Essentially, because revenues and benefits are monetary compensations paid by passengers for the service rendered by the railway operator.

There is a clear link between transport mobility and commercial speed; the effect produced by the commercial speed in the market share (demand) lies in the influence that the commercial speed has in the travel time and in the travel cost (also called travel "resistance" or generalized cost). As the commercial speed increased, the travel time decreased and, therefore, the generalized cost that every passenger has to pay is also reduced. Provided that the rest of variables that affect to the generalized cost remain constant, if the generalized costs is reduced the "attractiveness" of the transport increases.

Based on the classical methodologies that allow determining the market share (i.e. Logit Model) it is possible to demonstrate how the railway market share will increase (if the generalized cost of the rest of transport modes remains constant) with a travel time reduction and, therefore, with a reduction of the generalized cost of the railway line.

$$P_i = \frac{exp(\beta \times C_{gi})}{\sum_{j=1}^{n} exp(\beta \times C_{gj})} \qquad (1)$$

Where: P_i: Market share; Cgj: generalized cost; "i" railway transport mode; "j"; n: transport modes; β: model parameter

(González Franco, 2015b) has applied this empirical demand model in the HS Levante Corridor, obtaining that the demand elasticity for commercial speed (travelling time) varies with the journey time. This study obtained the following elasticities:

- Journey times shorter than 40 minutes obtain demand elasticities between -0.2 and -0.5 with an average value of -0.35.
- Journey times between 40 minutes and 80 minutes obtain demand elasticities between - 0.4 and -1.2 with an average value of -0.6.
- Finally, journey times between 80 minutes and 180 minutes obtain demand elasticities between -0.6 and -1.7 with an average value of -0.95.

It can be asserted that the demand elasticities determined in **(González Franco, 2015b)** are in line with other studies, as **(Yousefi Mojir, 2011)** or (**Cascetta & Coppola, 2011)** and they will be used in the study case analysed in this paper.

3.1 Effect of the speed on revenues

As it has been mentioned, revenues obtained in the transport sector are the monetary compensations by the service provided, that means, the revenues of a railway transport operator mainly come from the traffic and the price paid by the service. Therefore, when thinking about the revenues of a railway operator, two basic concepts are quickly related: (i) number of tickets sold and (ii) the price of them (ticket price).

If the analysis is focused on each of the two issues independently, without analysing the relationship that exist between them, it can be assumed that, the higher the number of passengers transported, the higher the number of tickets sold and, therefore, it is clear that the incomes of the operator will increase. In addition, it is understood that if the ticket price is increased, the price paid by the passenger is higher and, therefore, the operator will "earn" more by passenger.

This study will focus on the analysis considering that the price established by the operator remains fixed, without any interference of the speed on its establishment. The effect of the speed in the ticket price has been studied and analysed in detail by the author in **(González Franco, 2015b).**

In this case, to determine the revenues of the operator is relatively simple, basically, it is a matter of calculating of the number of passengers transported by the operator (based on the demand model) and multiply it by the revenue per traveller obtained by the operator.

3.2 Effect of the speed on social benefits

Therefore, it should not be forgotten that a socio-economic analysis is a counterfactual analysis, which means that in order to determine the benefits (savings on external costs) of a railway project, it is necessary to obtain the number of passengers transferred from each transport mode to high-speed train mode.

Therefore, the estimation of the benefits is based on the calculation of the difference between the passengers who use each mode before the construction of the new infrastructure (*"baseline scenario"*) and those who would use each mode after the construction (*"high-speed scenario"*). In addition, it is also necessary to know the induced demand due to the new service, the length of the line and the travel time of each mode. As it was mentioned before, a proper demand model is vital to estimate the benefits.

However, what are the benefits that a high-speed line may provide? according to the **(INFRAS/IWW., 2004)**, the savings on external costs (social benefits) obtained from the construction of a new railway infrastructure may be sourced from: (i) net excess of new traveler consumer (induced traffic), (ii) net saving on travel time, (iii) net savings on operational costs, (iv) net savings on accidental costs and (v) net shavings on environmental costs.

Quantifying all these effects and integrate all of them in a complete economic analysis is a very complex task that it has been broadly studied the last years. As a relevant work can be cited **(INFRAS/IWW., 2004).** The methodology and monetary values provided in this study have been used in order to determine the benefits in the study case proposed for this paper.

3.2.1 Study case: Effect of the commercial speed on demand revenues and benefit

According to the demand, elasticities for journey time (commercial speed) determined in **(González Franco, 2015b)** and shown in chapter 3, the relationship between demand and commercial speed and, consequently, the relationship between revenues and benefits and commercial speed is estimated for the study case.

Figures below (Figure 3) show, for two different ticket prices (12c€/passenger-km and 20c€/passenger-km) the influence of the commercial speed on the demand, revenues and social benefit in the study case analysed (HS Madrid-Valencia).

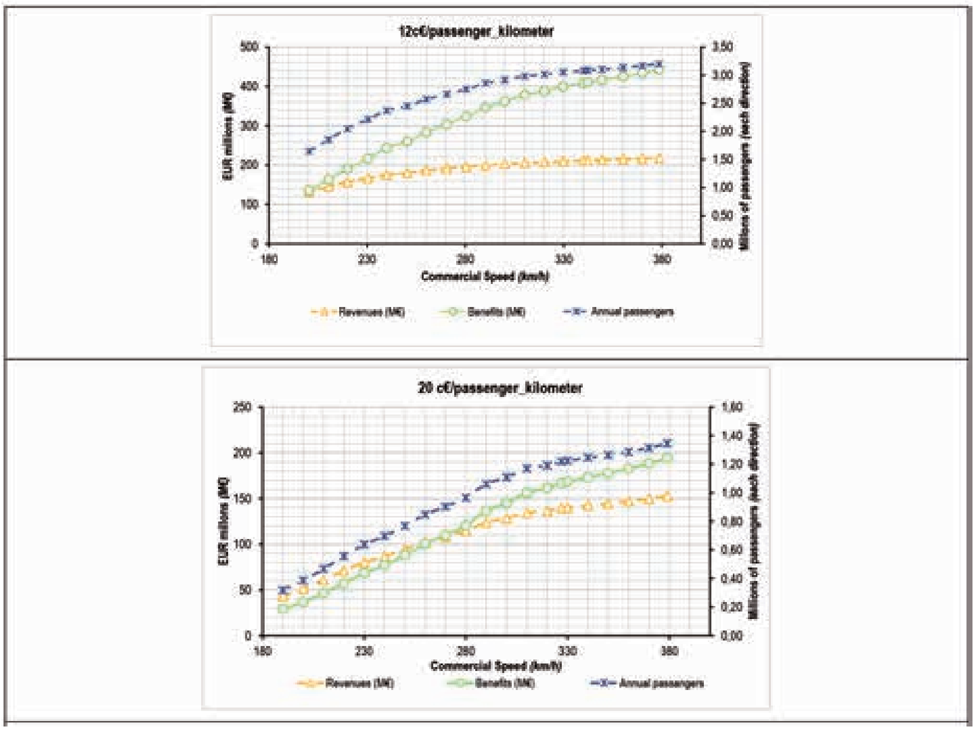


Figure 3. Relationship between demand, revenues and savings on external costs and commercial speed

According to the results obtained, the following can be highlighted:

- Whatever the ticket price is, the higher the commercial speed (or, in other words, reductions in the journey time), the greater the number of passengers transported, the revenues and the savings in the external costs (benefits).
- Finally, it is found that for low-ticket prices, whatever the commercial speed is, savings in external cost are higher than incomes. However, in case of high tariffs and low commercial speeds, revenues are lower than savings in external costs. The reason behind this statement is that the demand gained by the high-speed train, with reference to other transport modes, is not enough and lower than the revenues generated multiplying the number of passengers by the price paid by them.

4. Effect of the speed on costs

The final aim of this section is to establish the relationship between speed and the different costs and then apply it in the study case in order to analyse the results obtained.

This section will focus on: (i) operational and Exploitation costs, (ii) investments costs.

4.1 Operational and exploitation cost

Not necessarily, an increase on the speed (commercial or maximum speed) implies increases in operating costs. An increase in commercial speed implies a reduction in the journey time, which entails, a reduction in the usage time of the available resources (i.e. rolling stock), and therefore, it may cover a higher number of kilometres and increase its production (seats-kilometre).

This effect (an increase in the speed and a reduction in costs) is even bigger in the case of on board personnel. An increase in the commercial speed implies an increase in the kilometres covered during its service hours, thus the annual productivity of the staff increases and, therefore, the cost per kilometre assumed by the operator is reduced.

This can be asserted, although there are not many studies which relate both parameters. As a relevant analysis the one performed by **(Kottenhoff, 2003)** can be highlighted. In the Spanish case, others can be highlighted, on the one hand **(Minayo de la Cruz, F. & García Álvarez, 2009)** and on the other hand, the paper presented for the 7th High Speed Congress held in Beijing (García Álvarez, 2010).

Besides, the doctoral thesis written by **(García Álvarez, 2012)** may be underlined where a detailed analysis of the relationship between the exploitation costs and the speed of the trains is carried out. This study defines, quantifies and provides the methodological foundations for the calculation of the cost function and for the estimation of the influence of the speed in them; methodology used in **(Roanes-Lozano, González Franco, Hernando, García Álvarez, & Mesa, 2013)**, and also used by the author in this paper.

As a summary, the cost assumed by the transport operator can be divided into two different costs; exploitation cost and operational and, in turn, each of them can be also divided into different items, as follows:

- Regarding exploitation costs, costs produced by the movement of the trains, the following have been identified: (i) Costs related to train ownership; (ii) Cleaning and maintenance costs; (iii) Traction energy costs; (iv) Train operation personnel costs.
- The operational costs are those incurred by the movement of vehicles (exploitation cost) and by offering safe, fast and quality service. These costs include: (i) Passenger services; (ii) Distribution, sales and access control costs; and (iii) Overhead cost.

4.1.1 Study case: Effect of the commercial speed on exploitation costs

After using the methodology defined in **(García Álvarez, 2012)** for each of the costs assumed by the operator in the study case here analysed, the following results were obtained Figure 4.

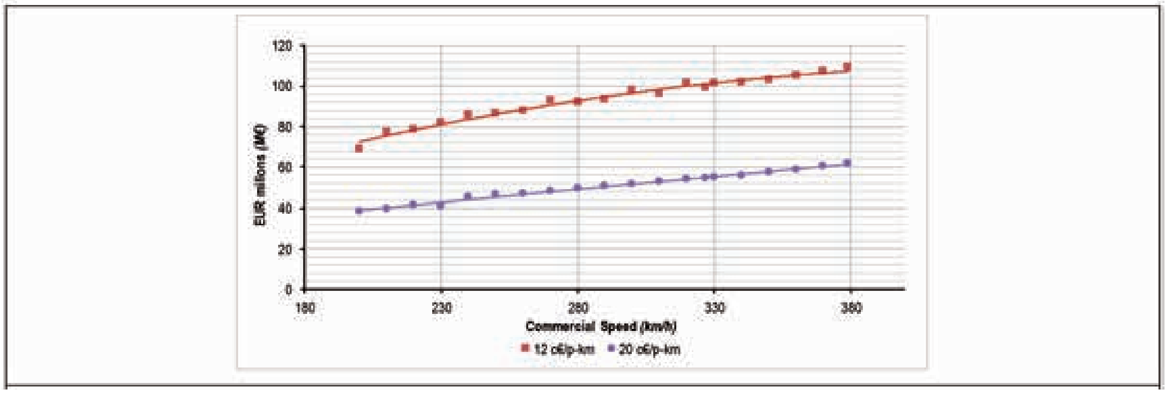


Figure 4. Total operational costs (M€) generated in the study case for two different ticket prices.

Note: the figure depicts the annual operational costs for the first year of service.

The results obtained can be summarized in:

- The lower the ticket price is, the higher the operational cost is. That is because the number of passengers increase and, therefore, the operator needs more trains or trains with higher capacity (higher acquisition cost) in order to provide the service required.
- Commercial speed influences the operational costs in two ways:
    - The higher de speed is, generally, the lower the number of trains needed to provide the service, since the operator can increase the use of the rolling stock.
    - In those scenarios, where the speed (journey time) does not reduce the number of trains required to provide the service, the operational costs can be slightly increased by an increase of the commercial speed, this can be because of, in some cases, an increase in the speed which can imply an increase in the energy consumed.

It is important to mention that the results here shown may suffer significant variations if it were considered a different train (different characteristics), with different capacity (seats). The operational costs it is clearly linked to the train seats and these are linked to the number of trains needed to provide the service required.

4.2 Effect of the maximum speed on investment costs

As the previous cost model, there are not many studies that could be used as a basis. However, it does not mean that there is not any relationship; it is clear that, the higher the maximum speed, the greater the line investment costs. For example, a greater maximum speed leads to wide curve radii and, therefore, it leads to straighter railway lines, which, in mountainous areas, results in a longer length of the line built under tunnel and/or length of bridges.

Before explaining the methodology used and the results obtained for the relationship between speed and investment cost, different studies in this field were analysed. It can be asserted that the existing literature is focused on two main fields:

Analysis of the cost structure of building a railway infrastructure designed to a certain maximum speed. Among the studies more relevant may be highlighted **(Campos, De Rus, & Barrón, 2009)** and the report **(Atkins, 2002)**.

Those studies focusing on solving particular problems, which limit the speed of the train, amongst them **(Subhash & Verma, 2007)** it is underlined.

There is also a large amount of studies linked to other disciplines aiming to determine the optimal layout taking into account the investment cost **(Lee & Cheng, 2001)** and other studies which take into account the optimization of the layout depending on the limitation of the railway system (radii of curve, grades…). Important studies in this field may be cited **(Malo Gaona, 1992)** or **(Linkerhägner, 1985)**.

Besides, there is relevant literature focusing on construction methods, definition of the different construction phases of a railway line and important analysis about the different costs generated in building a new railway high-speed line **(López Pita, 2008)**.

Regarding the relationship between speed and investment costs, the following studies may be highlighted **(Fröidh, 2012)** and **(Fröidh, 2014)**. In these papers a detailed costs analysis and indepth analysis of the influence of the maximum speed on investment costs is carried out. Another outstanding work is the study performed in **(Baumgartner. J.P, 2001)**. This study determines different infrastructure building costs for two different design speeds (100km/h and 300km/h) and provide a number of values for the different parts of the infrastructure.

As it was previously mentioned, the influence of the maximum design speed in parameters such as radii, slopes… is widely studied. However, the relationship with other parameters and elements of the infrastructure is not so obvious (percentage of tunnels, bridges…) and even less its relationship with the investment cost. These relationships have been duly quantified in **(González Franco, 2015a)**. A brief qualitative summary of the findings follows.

1. **Effect of the speed on the line length**. It can be said that, the higher the speed, the lesser winding layout the line will have and, therefore, there will be a shorter distance between origin and destination, this will affect the final cost of an infrastructure, since less line kilometres will be built.
2. **Effect of the speed on the type of construction and investment cost**. Maximum speed plays a very important role in the construction cost, mainly in very mountainous and mountainous areas. It also has a very important relationship with the quantity and length of the tunnels and bridges built; the lower the speed, the higher possibility of "escape" of those areas with orographic difficulties, since the line has smaller curve radii, that situation offers the possibility of building a more winding layout, which in most cases skirted round the hillsides.
3. **Effect of the speed on the maximum slope.** Greater upward slopes, allow a better adaptation of the layout of the line to the terrain (orography) and, therefore, shorter distances (kilometres) of tunnels and bridges are needed, which means a reduction in the investment costs. Besides, greater upward slopes imply trains with a higher power output; the higher the power output, the greater the capacity of the trains to climb upward slopes.
4. **Effect of the speed on the transversal section of a tunnel**. The greater the transversal sections of a tunnel, the lower the drag resistance of a train and, therefore, the lesser the pressure difference experienced by passengers. It is considered very important to increase the transversal section of a tunnel in order to increase the maximum speed that means an increase of the investment costs.
5. **Effect of the speed in the track width**. The greater the speed, the greater the distance between tracks, which increases the width of the track bed, therefore the cost grows.
6. **Effect of the speed on the track**. The greater the speed, the greater the thickness of the ballast layer underneath sleepers. The speed also affects the typology of the siding equipment; the higher the speed the greater the complexity of the technology used, therefore, the cost increases considerably.

7. **Effect of the speed on the electrification costs**. It can be highlighted that, the higher the speed, the greater the power output of trains and, therefore, the power of the substations must be greater (greater power of the traction transformer), and the electrical current through the cable, increases. If the electrical current increases, it is necessary to use cables with greater transversal section. Both effects (increase the power of substation and the greater section of cables) imply an increase in the investment costs.
8. **Effect of the speed on the signalling cost**. The influence of the speed lies, essentially, on the technology installed, both on-board and on ground. If the speed increases, the signalling systems must be more technologically advanced, since the safety requirements are increased, which means an increase in the investment costs.

Each and every effect of the speed on the different parameters or infrastructure elements have been quantified in the doctoral thesis **(González Franco, 2015b)** and in **(González Franco, 2015a)** The following graph shows a summary of the results obtained after the application of the different models developed.

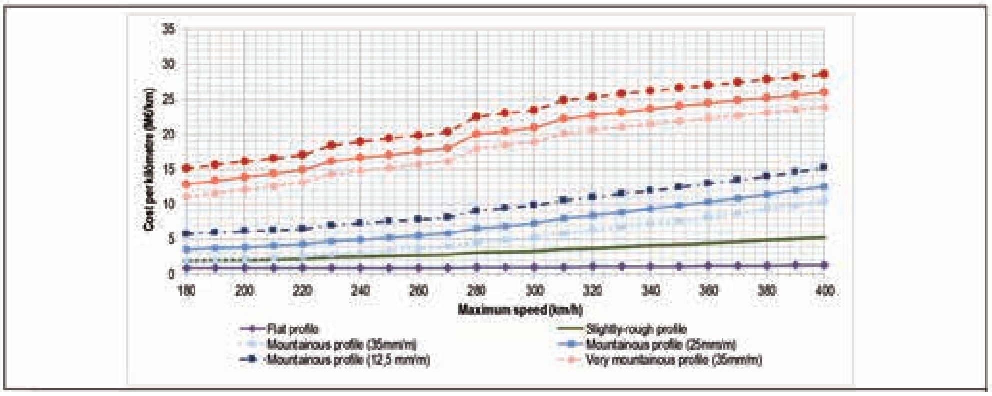


Figure 5. Investment cost per kilometre.

From the results obtained it can be highlighted that:

- The higher the maximum speed, the higher the investment cost, and that happens in all types of terrain. It can be said that, this growth is approximately linear in all analysed cases.

- Under equal conditions, the costs increase with orographic difficulties. The range of costs per kilometre, considering the same speed, is wide (i.e. for 300km/h the cost varies between 4 and 25M€/km).

- The largest increases in cost, due to the increase in the maximum speed are observed in slightly-rough profile and mountainous areas. In this type of terrain, an increase in the maximum speed entails a larger increase in the percentage of tunnel over the total length of the line.

- It is also remarkable that, the cost per kilometre of building a high-speed railway infrastructure in a mountainous area can be ten times higher than build the line in a flat profile. Even, it can be five times higher that build the line slightly-rough profile. Regarding the difference between the cost per kilometre of building a line in mountainous terrain or in a very mountainous terrain is approximately 2.5 time bigger.

In the following table (Table 4), the range of total investment cost obtained for each type of terrain considering different speed intervals is shown.

Table 4: Range of cost per kilometre depending on the type of terrain and maximum speed.

	Investment costs per kilometre *(M€/km)*		
	Smax<200km/h	**200km/h<Smax<350km/h**	**Smax>350**
Flat profile	4	4,2 - 5	5 - 6
Slightly-rough profile	5,3	5,3 - 8,5	8,5 -16
Mountainous profile	5,5 - 9,5	6 -17	12 - 42
Very mountainous profile	15,5 - 20,5	16 - 32	27- 60

4.2.1 Study case: Effect of the maximum speed on the investment cost

The idea of this section is to allocate, for each of the sub-sections defined in the scenario (chapter 2.1), a maximum design speed and estimate the investment cost of this sub-section according to the values obtained in Figure 5. The total investment cost of the line will be the sum of the investment cost for the four different sub-sections in which the line has been split.

For each combination of maximum design speed (one maximum design speed for each subsection) an investment cost is obtained, but also (knowing the length of each sub-sections) a commercial speed. Thus, it can be asserted that for each commercial speed there are different investment costs, since there are numerous combinations of maximum speed that obtain the same commercial speed.

Below it is included graphically (Figure 6) the relationship between commercial speed and investment cost (total cost and cost per kilometre) for the study case here analysed.

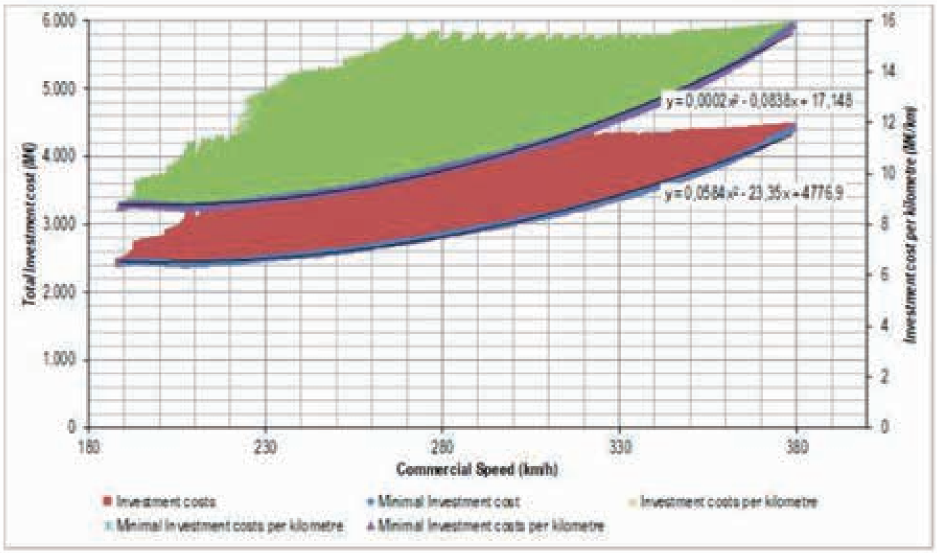


Figure 6. Study case: relationship between commercial speed and investment cost.

As it can be observed in Figure 6, cost per kilometre lies within a range between 8.6M€/km and 15.8M€/km, depending on the maximum speed considered. In view of the results, in can be asserted that the values obtained for the study case are in line with the real cost of the MadridValencia high-speed line.

If the influence of the speed in the investment costs is analysed, the results clearly show that the higher the speed the higher the costs. This make sense because, in order to increase the commercial speed, it is necessary to increase the maximum design speed of some or all of the sub-sections. As it was shown in the previous section, an increase in maximum speed, whatever the type of terrain is, implies an increase in the investment cost.

Other important issue to point out from the results is that each commercial speed has a minimal investment cost, which results from a certain combination of maximum design speed per subsection. If it is determined for each combination of maximum design speed the minimal investment cost, as it been performed in Figure 6, it is obtained the curve of minimal investment, which establish the boundary of the minimal investment.

5. Study case: Effect of the speed on the financial and socio-economic profitability

$$VAN_{fT0} = -\left[I_{T0} \times (1+r)^{(T_0 - T_{0+s})}\right]_{t=T_{0-s}} - \cdots - \left[(I_{T0} + CF)_{T_0} \times (1+r)^0\right]_{t=T_0} + \left[CF_{T_0+1} \times (1+r)^{-1}\right]_{t=T_{0+1}} + \cdots + \left[(CF + RV)_{T_{0+n}} \times (1+r)^{(T_0 - T_{0-n})}\right]_{t=T_{0+n}} \tag{2}$$

The tools or parameters used that allows supporting the decision of tackling a project from costs and revenues previously studied are the "Financial value of infrastructure" and the "Economic value of infrastructure" calculated from a profitability indicator called Net Present Value (NPV).

The Net Present Value (financial and economic) allows calculating the flow of profit and cost from total life of an infrastructure, therefore it allows knowing the economic value of the infrastructure with the ability to update this value to the start-up period of infrastructure exploitation **(Jaro Arias, 2011)**. The equation used to calculate the NPV is:

where I_{To} is the initial investment *(€)*, *CF* estimates the cash flows *(€)*, *RV* is the residual value of the project *(€)*, *t* is period/year, *s* are the periods from the action starts to exploitation starts, *n* are the periods from the beginning of the exploitation to the end of the assessment, *r* is the economic or financial discount rate and $(1+r)^{(T_0-t)}$: is the discount factor for the value of r in the t period.

Knowing the relationship between speed and investment costs, revenues and social benefits and also knowing the relationship between exploitation and operational costs (see previous sections), the financial and economical profitability of all scenarios proposed (923,521) by means of NPV decision tool is determined.

Below the results obtained for the different scenarios and fares considered are shown graphically (Figure 7 and Figure 8).

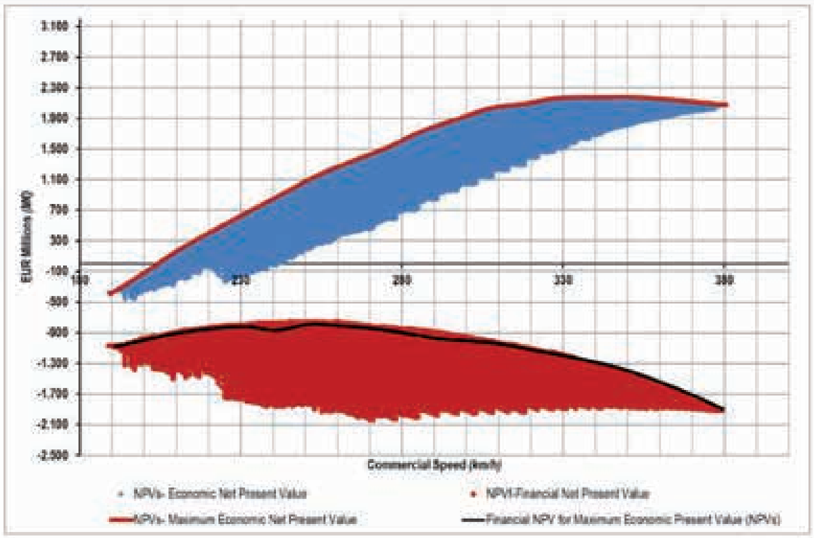


Figure 7. Financial and Economic NPV for 12c€/pkm.

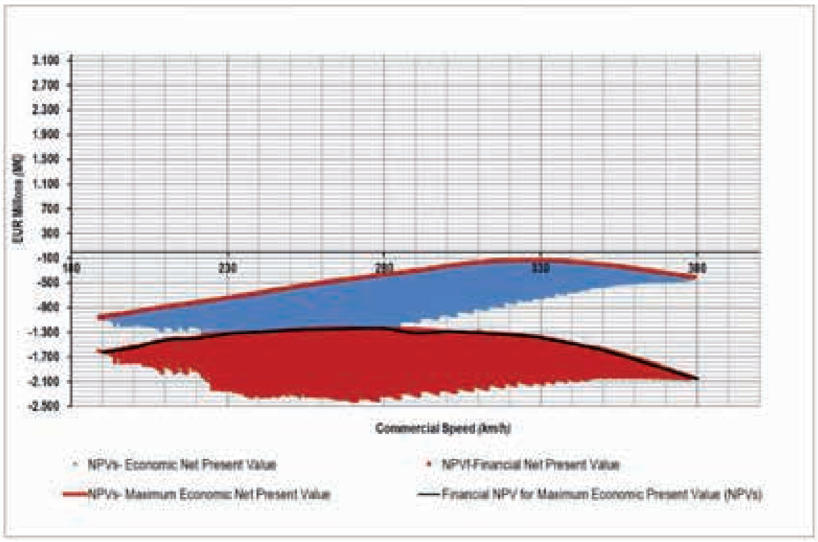


Figure 8. Financial and socio-economic NPV for 20c€/pkm.

If the decision-making criterion is to obtain maximum economic profitability (maximum Economic NPVs) without any additional restriction, as it is for this study case, it is necessary to analyse in which point (commercial speed) the economic NPVs reaches its maximum. The maximum economic NPVs corresponds to a certain commercial speed and to a certain combination of maximum design speed for each sub-section, therefore, this commercial speed will be the one that maximizes the profitability of the project. For the study case analysed in this paper the maximum economic profitability is reached at different speeds depending on the ticket price considered. Below (Table 5), the commercial speed and the combination of the maximum speed for each sub-section, which maximized the study case analysed, are shown.

Table 5: Commercial speed and combination of maximum design speed which maximize the Economic NPVs.

		12c€/p-km	20c€/p-km
Sub-section 1	*Very Mountanuos*	380	360
Sub-section 2	*Mountanous*	390	360
Sub-section 3	*slightly-rough*	410	360
Sub-section 4	*Flat*	500	500
Commercial speed	*(km/h)*	342	327
Journey Time	*(h)*	1,11	1,17
Anual passenger	Millons	3,08	1,219
Revenues	*(M€)*	212	139
Social Benefits	*(M€)*	410	167
Investment Cost	*(M€)*	3.593	3.364
Operatinal Costs Operator and IM*	*(M€)*	101,85	54,37
Socio-económic NPVs	***(M€)***	**2.172**	**-136**
Socio-económic IIR	*(%)*	12,1%	5,0%
Financial NPVf	*(M€)*	-1.322	-1.359
Financial IIRf	*(%)*	1,7%	1,1%

*IM - Infrastructure Manager

The following can be highlighted:

a. The higher the commercial speed, the higher the socio-economic profitability of the project. This increase is produced until certain commercial speed, above which the economic profitability starts to decrease.

   It can be said that, for each fare an optimal point in terms of economic profitability, which correspond to a certain commercial speed is obtained. The results obtained, show: for a tariff of 12c€/pkm the optimal (maximum economic profitability) is reached at 342km/h and for a tariff of 20c€/pkm the optimal is obtained at 327km/h.

b. The economic profitability is reduced with the increase of the ticket price; this argument is in line with **(García Álvarez, González Franco, & Rubio García, 2015)**. The higher the ticket price the lower the savings on external costs but the investment cost remains constant.

c. There are some differences between financial profitability and economic profitability. The higher the commercial speed, the higher the financial profitability of the project, in all cases analysed (tariffs). As in the economic profitability, this increase is produced until certain commercial speed, above which the financial profitability starts to decrease. It is seen that this "optimum financial" is reached at commercial speed lower than the commercial speeds that obtain the "optimum economic".

d. Furthermore, the results obtained also show the combination of maximum speed which should be built each sub-section. It can be observed, in order to obtain the optimal commercial speed, the maximum design speed is always assigned to the flat terrain and the minimal maximum design speed is allocated to the very mountainous terrain.

6. Conclusions

The conclusions of this study are grouped into three big sections:

6.1 Effect of the speed on revenues and benefits

a. **Effect of the speed on the demand:** As the commercial speed is increased, the travel time decreased and, therefore, the generalized cost that every passenger has to pay is reduced. Decreasing the generalized cost implies increases in the market share and therefore increases in the demand. An increase in the commercial speed (journey time reduction) can also bring more passengers. Traditionally, journey time reduction is accompanied by improvements in the services offered by the operator (frequency increases, trains with greater capacity…). These improvements imply a greater number of passengers.

b. **Effect of the speed on revenues:** Considering a fixed fare, the lower the travel time, due to an increase in the commercial speed, the higher the demand and, therefore, the higher the revenues obtained by the operator.

c. **Effect of the speed on external costs.** Speed is an important parameter in terms of savings in external costs, due to the high volume of passengers transferred from other transport modes to the high-speed trains and increases with it.

6.2 Effect of the speed on exploitation costs and investment costs

a. **Effect of the speed on exploitation costs.** After the analyses carried out, it can be said that (in the generic examples where the methodology was implemented) an increase in the commercial speed could imply a slightly increase in the exploitation costs.

b. **Effect of the speed on investment costs**. The higher the maximum speed, the higher the investment cost, and that happens in all types of terrain. It can be said that, this increase is approximately linear in all analysed cases. The largest increases in cost, due to the increase in the maximum speed are observed in slightly-rough and mountainous areas. In this type of terrain, an increase in the maximum speed entails a larger increase in the percentage of tunnel over the total length of the line.

   It is also remarkable that, the cost per kilometre of building a high-speed railway infrastructure in a mountainous area can be ten times higher than building the line in a flat area. It can even be five times higher that building the line in slightly-rough profile. Regarding the difference between the cost per kilometre of building a line in mountainous terrain or in a very mountainous terrain is approximately 2.5 time bigger.

6.3 Effect of the speed on the economic and financial profitability

a. **Effect of the speed on the economic profitability** The higher the commercial speed, the higher the socio-economic profitability of the project. This increase is produced until certain commercial speed, above which the economic profitability starts to decrease.

b. **Effect of the speed on the financial profitability.** The higher the commercial speed, the higher the financial profitability of the project, in all cases analysed (fares). As in the economic profitability, this increase is produced until certain commercial speed, above which the financial profitability starts to decrease. The results obtained for the study case are: (i) for a tariff of 12c€/pkm the maximum profitability is reached at 342km/h and (ii) for a tariff of 20c€/pkm the maximum is obtained at 327km/h.

   In addition, it is remarkable that the optimum financial profitability is reached at commercial speed lower than the commercial speeds that obtain the optimum economic profitability.

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