# The cost of building and operating a new high speed rail line

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**ECONOMIC ANALYSIS OF HIGH SPEED RAIL IN EUROPE**

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# Chapter 2

# The cost of building and operating a new high speed rail line


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## 2.1. Introduction

What is the (approximate) total cost of building, maintaining and operating a new high speed rail (HSR) line? Trying to answer this question is the main objective of this paper. To address it we will make an extensive use of the companion Chapter 4, where a database containing information about 166 actual HSR projects in 20 countries is analysed in detail. This database provides a rough guide about the typical cost structure of any HSR project and suggests tentative estimates for some representative unit values of those costs. This information, together with some additional values gathered from other sources (Levinson et al. 1997; ATKINS 2003; SDG 2004, De Rus and Nombela 2007), allow us to perform a simple simulation exercise capable not only of providing an answer to the initial question, but also of offering insights on the relevance of some elements in determining the total costs of a HSR line.

The cost structure of a HSR project can be mainly divided into costs associated to the infrastructure and costs associated to the rolling stock. Infrastructure costs include investments in construction and maintenance of the guideways (tracks) including the sidings along the line, terminals and stations at the ends of the line and along the line, respectively, energy supplying and line signalling systems, train controlling and traffic management systems and equipment, etc. Construction costs are incurred prior to starting commercial operations (except in the case of line extensions or upgrades of the existing network). Maintenance costs include those related to the overhauling of infrastructure, including labour costs, materials, spare parts, etc. It occurs periodically, according to planned schedules calculated according to the assets depreciation. In general, infrastructure costs can be considered as fixed, since they mostly depend on the size of the infrastructure (line length, number of stations, etc.) instead of on traffic figures.

Rolling stock costs include three main subcategories: acquisition, operation and maintenance. With regard to the first one, the price of a HSR trainset is determined by its technical specifications, one of whose main factors is the capacity (number of seats). However, there are other factors that can affect the final price, such as the contractual relationship between the manufacturer and the rail operator,[1] the delivery and payment conditions, the specific

[1] Some rail operators have internal departments for designing their rolling stock; others prefer contracting out.

internal configuration demanded by the operator, etc. With respect to the operating costs, these mainly include the costs of the labour (personnel) and energy consumed for the running of the trains; the costs of the insurance, train formation (if it is necessary), in-train passenger services (food, drinks, etc). These costs usually depend on the number of trains (fleet) operated on a particular line, which in turn, is indirectly determined by the demand. Since the technical requirements (for example, crew members) of the trains may differ with their size, sometimes it is preferable to estimate these costs as dependent of the number of seats or seats-km. In the case of the cost of maintaining rolling stock (including again labour, materials and spare parts), they are also indirectly affected by the demand (through the fleet size), but mainly by the train usage, which can be approximated by the total distance covered every year by each train.

There are other costs involved in the building and operation of a HSR project. For example, planning costs are associated to the technical and economic feasibility studies carried out before construction. These (fixed) costs, as well as those associated to the legal preparation of the land (expropriation or acquisition to current landowners), can be somehow included in the construction cost category. On the hand, there are some operating costs (general administration, marketing, internal training, etc.) that are fixed and cannot be easily assigned either to infrastructure or operations. In most projects these costs represent only a minimal fraction of the operating costs and, therefore, can be globally treated. Finally, it is important to mention here that we will not address the issue of external costs to answer the initial question posed in this paper. The reason is that, even in the case that could reach accurate estimates of these costs, the distribution of their burden over the agents involved in a HSR project is not always clear. This is not the case of the infrastructure and rolling stock costs, which can be both safely attributed to the HSR project.

Although the cost structure of most HSR projects corresponds to the one we have just described, it is also true that the exact values of each cost vary largely across projects in accordance to their specific characteristics. For that reason, this paper proposes a general approach, based on a simulation exercise in which, departing from several justifiable parameter values (*reference case*), we calculate the (net present value) of the total costs of a HSR line (disaggregated into the described infrastructure and rolling stock costs categories). Then, by changing the values of the initial parameters, *ceteris paribus*, we can perform comparative statics, which provide us with useful insights on the overall validity of our exercise. The information found in the database in Chapter 4 related to the unit costs of HSR projects is the cornerstone of the model.

The use of simulation techniques in applied economics has been often criticized as excessively naïve. Although we acknowledge this criticism, the simulation exercise performed in this paper will always try to remain as close as possible to reality, minimizing the number of simplifying assumptions while simultaneously keeping the numbers manageable. At the same time, the information provided in Chapter 4 will be treated with caution, taking into account the observed differences across projects and countries. Whenever possible, we will distinguish between *best*, *medium* and *worst* alternative scenarios and, when in doubt, we will opt for the most cost-favourable option, so that our final estimates can be seen in each case as a lower bound to the actual cost of HSR.

Other papers on HSR make use of simulation techniques, either to make estimates about their social profitability (see chapter 3, for example) or to study counterfactuals that are not currently happening but could happen in a near future (as in chapter 4, or Ivaldi and Vibes 2005, to study intermodal competition). They all share a basic economic model with simplifying assumptions where data from different sources is plugged into in order to get the simulation results.

After this introduction, the structure of the paper is as follows. Section 2.2 describes the most relevant features of the project (building and operating for 40 years a single HSR line connecting two cities without intermediate stops) and its most significant operating characteristics. Section 2.3 describes demand projections and how supply is calculated accordingly. In Section 2.4 the infrastructure and rolling stock costs are simulated under several assumptions on demand, train capacity, speed and line length, simultaneously considering three alternative scenarios (best, medium, and worst) for the estimates of the unit costs. Finally, Section 2.5 is devoted to a complete discussion of the results and their implications.

## 2.2. Project characteristics

### 2.2.1. Overview and timeline

Consider that a new high speed line is going to be built to connect two similar-sized cities, *City O* (origin) and *City D* (destination), separated by a distance of 500 kilometres. Most of the infrastructure and rolling stock used in this project will be completely new (it is not an upgrade of an existing conventional line), although the existing train terminals in both cities will require only minor refurbishment.

The time needed for planning and technical design of a HSR line varies largely across projects, depending on their specific legal and administrative arrangements. In some projects, with favourable legislation, efficient contracting procedures and adequate political pressure, can take less than one year, whereas in other cases —particularly, when legal conflicts arise on land occupation or there are other issues of public concern —the planning period may be delayed up to 20 years (Flyvbjerg et al. 2004).

Once the required technical and economic studies have been carried out, the actual deployment of the infrastructure and other sideworks is mainly conditioned by the characteristics of the terrain. In our simulation exercise, we will make the simplifying assumption that most of the area covered by the line is countryside flat, with only a few difficult segments (either mountain or density and continuously urbanised areas) which may require viaducts and/or tunnels.[2] For that reason, and assuming that the planning and design stage is done with the maximum celerity, we will consider that total construction period (denoted as $T_c$) will be 5 years.[3] Once built, the line starts commercial operations immediately and operates during 35 consecutive years, so that the project total duration is $T = 40$ years (from $t = 0$ to $T$), as depicted in Figure 2.1.

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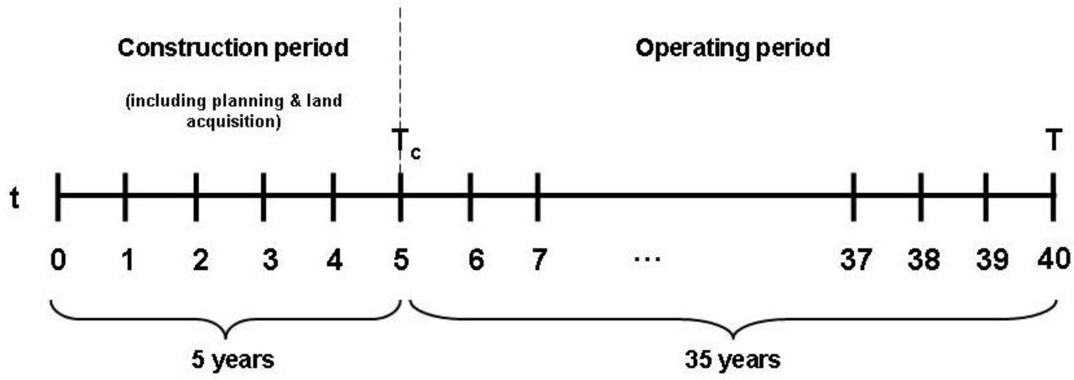
[2] Note, as mentioned at Section 2.1, that this is a cost-reducing assumption that favours the project. A more difficult orography would imply a longer construction and planning period and, subsequently, higher costs.

[3] We will also consider that, on average, the same number of kilometres is built every year. In practice, however, projects evolve at different speeds, depending on the technical limitations, the delivery of materials and the official termination dates of each stage.

**Figure 2.1. Project timeline: construction and operation period**




Setting $T = 40$ is a decision that responds to the estimated evolution of the HSR technology. While a shorter period would seem rather uneconomical (most of the infrastructure costs would be hardly recovered), a much longer period would be unrealistic, since the HSR technology is advancing so fast that in a few decades it is quite likely that the current equipment will be obsolete. In the real world, only a few Japanese *Shinkansen* lines (started in 1964) have enjoyed such a large lifespan so far, but during this period they have been largely improved at least twice (Hood 2006).

Finally, note that the construction (and planning) period involves much more than track building. It requires the design and building of depots, maintenance and other sites, as well as hiring and training of personnel, testing of the material and many other preparation issues. In our project, we will assume that all these tasks are adequately performed in time, that no major delays occur and that the line is ready for commercial use at $T_c$.

## 2.2.2. Operational characteristics

There are two closely related operational characteristics of the line – the average speed of the trains running over it and the total distance covered by them – that are very relevant from the point of view of construction and operation, and thus deserve a closer look. In addition, the ratio between line length and speed determines the travel time, which is a key factor in attracting demand.

▪ SPEED

Obviously, speed is a crucial piece in the characterization of a high *speed* line. However, the technical definition of speed is not unique,[4] since there are several related terms whose economic implications have to be separately considered. First of all is the *maximum track speed*, a technical parameter mainly related to infrastructure that, in the design stage, determines the radius of the curves and the gradient of the slopes. The ability of a train to trace closed curves without derailments or climb steep mountains or hills is inversely related to its speed. For that reason, a HSR line faces tougher construction restrictions and may require a longer length the higher the maximum track speed of the project.

A second concept is the *maximum operating speed*, which is related to the technical characteristics of the trains and the way in which these are operated. This operating speed evolves with the technology and generally increases over time, only constrained by the maximum track speed. For example, in its early stages, the *Shinkansen* system's main line was hardly capable of speeds of up to 220 km per hour. But in its latest specifications, these *bullet trains* have earned their name by reaching speeds close to 600 km per hour (Hood 2006). Today, most European HSR services operate with trains capable of maximum speeds in the range of 280-300 km per hour.[5]

Under normal operating conditions, and depending on the incidence of delays and the characteristics of the terrain, HSR services are usually provided at *average operating speeds* of 20-25 km per hour below their maximum operating speed, which is the optimal technical speed in relation to which the useful life of the rolling stock is calculated and the recommended maintenance plans are designed by the manufacturers.

The final (and most widely used) speed concept is the (average) *commercial speed*, which is simply calculated by dividing the total travel time over the line length. It can be noted that this is not only a technical concept (determined by the operating and track speeds), but an economic one as well: travel time is affected by technical considerations, but also by other (non-technical) elements, such as the commercial schedule, the number of intermediate stops,

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[4] In Chapter 2 we argue that speed is not just a technical concept, but also an economic one, since it is related to the infrastructure exploitation model chosen by the rail operator.

[5] In Europe new maximum speed tests have been recently (2007) announced by the TGV in France (www.sncf.com/news) and for the Paris-London route. Furthermore, we do not include here the (much faster) magnetic levitation technology (MAGLEV), since its commercial use is still very limited.

the quality assured to customers,[6] etc. In our simulation exercise we will use a commercial speed (***s***) of 250 km per hour and consider that it will not change during the operating lifespan of the project.[7]

- LENGTH

HSR projects are very diverse across the world and their lengths vary accordingly. Most countries start with single point-to-point lines that are later expanded by adding new corridors or by connecting the existing ones to larger networks. A typical example is the Madrid-Seville AVE (471 km), which – apart from smaller legs (such as La Sagra-Toledo, 22 km) – has been recently expanded with the Madrid-Lleida (481 km) line and other upcoming ones also departing from Madrid (De Rus and Román 2005). The same centralized structure corresponds to the French TGV, which started with the Paris-Lyon line (417 km) that was later continued (Paris-Marseille, 750 km) and connected to the high speed network (TGV North, TGV Atlantic, etc.).

From the point of view of our simulation exercise we have chosen a standard distance of 500 km between cities O and D by taking into account that with a commercial speed of 250 km per hour travel time would be approximately of 2 hours. This is compatible with the results in chapter 4 regarding the intermodal competitiveness of HSR services. They find that rail market share quickly decreases when travel time is below 1 hour (when road transport is much more attractive for passengers) and over 3 hours (since this would imply a distance that could be covered faster travelling by plane). In any case, since the length of the HSR line is a key variable that determines to a great extent the infrastructure costs, we will test alternative length assumptions in our simulation exercise.

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[6] For example, when there are punctuality commitments. In the Madrid-Seville line, in Spain, commercial speed is around 210 km per hour, but it can be increased on certain services to reduce delays.

[7] This final assumption is discussable (since technology improvements are likely), but it is related to the simplifying assumption (see below) that the fleet is homogeneous and technology does not change until $T$=40.

## 2.3. Demand and supply

### 2.3.1. Demand estimation and distribution

From a microeconomic point of view, individual travel demand within the O-D corridor is an endogenous variable that depends on the relative generalised cost faced by the passengers on each alternative transport mode. From a broader perspective, aggregate demand depends on macroeconomic (such as the population density, the distribution of personal income), or cultural factors (traditions and history associated to rail travel) related to that corridor. For those reasons, and assuming that the relevance of intermodal competition in our corridor is minimal, annual traffic estimates can be simply calculated by projecting a reasonable initial figure along the operating period of the project.

Chapter 4 show that the initial demand figures are quite different across countries. They are usually large in Japan and Korea (where the high speed lines inaugurated in 2004 gained more than 40 million passengers in two years) and exhibit a more timid start in Europe (between 1.5 and 5 million passengers in the first year, depending on the line). In general, chapter 3 prove that the lowest initial demand value for 500-km HSR to be socially profitable is around 6-7 passenger-trips. For simulation purposes we have chosen the slightly more conservative figure of 5 million passengers per year ($Q_5$, that is, starting at $t$=5), and consider that only in very densely populated corridors larger figures (10, 20 million) would make sense.

A final but relevant simplifying assumption related to the demand is the fact that we consider that it is completely symmetrically distributed in three dimensions: between cities $O$ and $D$, along the day (no peak-off peak periods within the day), and along the year (no peak seasons within the year).[8]

With respect to the annual growth rates, reflecting the 'maturity effect' also detected at Chapter4, we can consider that there is a expansion period (say, the first 5 years of operation) where the initial demand grows at a larger rate ($g_1$ = 5% from $t$ = 6 to 11), while growing at a lower rate ($g_2$=3%) afterwards.

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[8] Again, these are cost-reducing assumptions, since the existence of demand asymmetries would increase the capacity needed on peaks periods, which would not be used in off-peak ones.

**Table 2.1. Traffic projections with alternative initial demand assumptions**

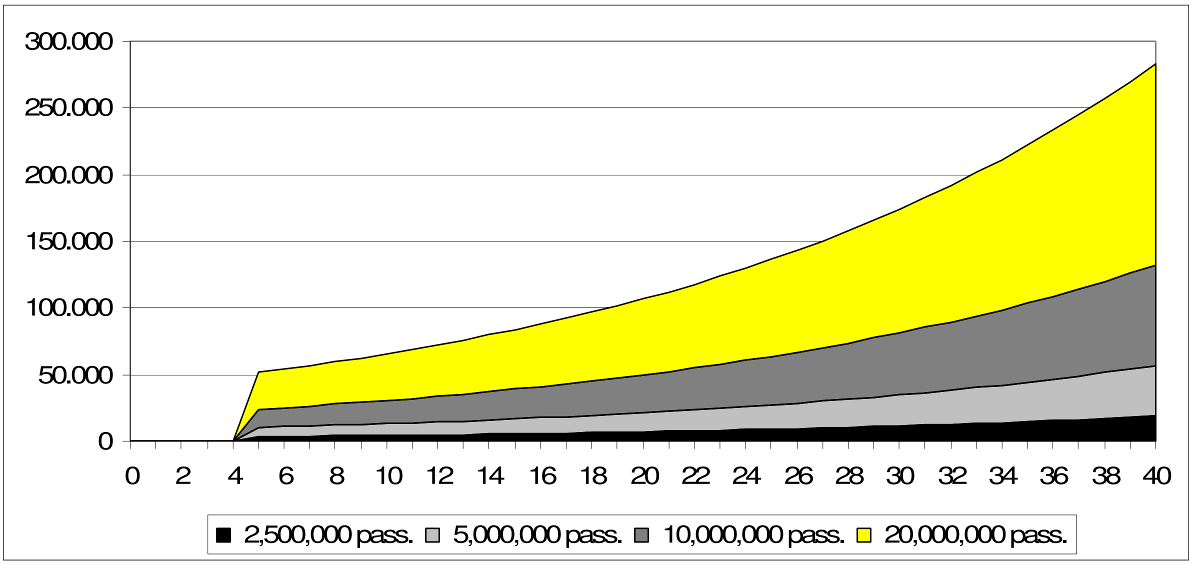
| *Annual demand initial assumption* | One-way traffic estimate (passengers per day) | | |
|---|---|---|---|
| | Initial year ($t$ = 5) | After 20 years ($t$ = 25) | After 35 years ($t$ = 40) |
| **$Q_5$ = 2,500,000 pass.** | 3,425 | 6,942 | 10,815 |
| **$Q_5$ = 5,000,000 pass.** | 6,849 | 13,884 | 21,630 |
| **$Q_5$ = 10,000,000 pass.** | 13,699 | 27,767 | 43,261 |
| **$Q_5$ = 20,000,000 pass.** | 27,397 | 55,535 | 86,521 |

With all these values, and departing from four alternative initial annual demand estimates (2.5, 5, 10 and 20 million, respectively), Table 2.1 shows the resulting one-way traffic projections (in terms of passengers per day) at three different points: the start of the operating period, 20 years later and, at the end of the project lifetime.[9] The variability is large; for example, if the initial demand is 2.5 million passengers per year, at $t$ = 40 it would imply a daily (one-way) traffic of 10,815 passengers; for 20 million, the corresponding value would be eight times larger (86,521).

These differences would be even worse if, alternatively, the projections were made ignoring the "maturity effect", that is, under the assumption that the demand grows at the same rate from $t$ =5 to $t$ =40 (that is, $g_1 = g_2 = 5\%$). Figure 2.2 shows the corresponding (faster-growing) projections, where the final daily demands at $t$=40 would range from 18,890 (starting with 2.5 million passengers per year) to 151,124 (starting with 20 million). Since these figures seem less realistic, our simulation exercise will be based on the projections depicted in Table 2.1.

[9] Daily traffic estimates are simply calculated by dividing annual demand between 365 days and between 2, since the *O-D* traffic is symmetric.

**Figure 2.2. One-way traffic projections (under faster growth assumption)**




*Note*: Vertical axis measures the number of passengers per day. Demand grows at 5% ($t$ = 6-40).

## 2.3.2. Defining supply: train capacity and frequency

If demand is measured as the daily number of (one-way) passengers, the corresponding definition of supply is the number of seats offered everyday from O to D (or vice versa). Then, train capacity and frequency become the key factors that determine the supply of HSR services in our O-D corridor.

- TRAIN CAPACITY

The capacity (number of seats) of a train designed for HSR services depends on the technical specifications envisaged by the manufacturer and the specific internal configuration agreed with the prospective buyer. Nowadays, most train models can be easily adapted to project-specific needs (legal requirements, cultural differences, passenger density, intensity of use, etc.) and their costs vary accordingly. In general three *size groups* can be identified in the existing manufacturers catalogues: low-capacity trains (between 200-250 seats), medium-capacity trains (between 300-400 seats) and high capacity trains (more than 500 seats). The first group includes, for example, the ALARIS and TALGO units in Spain; the second group includes, most models of the French TGV (including the THALYS), the Spanish AVE and some German ICE trains, whereas in the final group would be the TGV duplex and most of the Japanese units. For our simulation exercise we have assumed an average value of $\overline{q}$ = 330 seats.

As mentioned above, a relevant simplifying assumption made here is that we shall consider that all the trains in the fleet are exactly equal and that they all operate in single composition. We acknowledge that is one of our less realistic assumptions, since in the real world, when demand grows over time the operator may respond by incorporating higher-capacity trains or by operating the existing ones in double composition, thus duplicating its supply. Despite it weakness, the assumption is necessary to keep simple the supply calculations.[10]

- FREQUENCY

There are several alternative methods to calculate the number of seats (and, given their capacity, the number of trains) that the operator should provide to service the daily demand. Our calculations about the number of daily services and their frequency (defined as the number of services per hour) will be based on an average load factor of 75% ($l$), which gives us the basic relationship between supply and demand that will be maintained through the exercise.

In the real world, most existing HSR services are characterized by relatively high load factors (well above 70%), or at least larger than other equivalent rail services. This is explained by the fact that HSR lines are specifically designed for passenger traffic in dense traffic corridors, with minimal intermediate stops and a marketing focus, centred on the travel time and price. In our particular example – a direct service between *O-D* with a very regular and symmetric demand – the load factor must be large by definition. However, note that a load factor close to 100%, for example, is impractical because it would imply that all trains would be always fully booked and some travellers could not use them.

Apart from our assumption of l =75%, a few other values are needed. In particular, we will use the average commercial speed of $s$ = 250 km per hour (which yields a travel time of 2 hours per direction), and the train average capacity of $\overline{q}$ = 330 seats (which implies that the effective occupation is $\overline{q}_e = 0.75 \cdot 330 = 248$ seats). In addition we consider that there is a

[10] It is unclear the net effect on costs associated to dropping this assumption. On one hand, with higher-capacity trains, the total number of trains needed is reduced; but, on the other hand, their operating and maintenance costs could be larger, particularly if they are more intensively used.

boarding and train preparation time before each service of 15 minutes (0.25 hours) and that trains operate 18 hours a day (from 06:00 to 24:00).[11]

Using these values and departing from our projections of the (one-way) daily demand (denoted by $q_t$), the total number of daily services per direction is obtained from the ratio $q_t / \overline{q}_e$. The frequency ($F$) is then given by:

$$F_t = \frac{(q_t / \overline{q}_e)}{18},$$

in terms of number of services per hour. For example, for the reference case, if $q_5$= 6,849 passengers, $F_5$= 1.54 services per hour, which in turn implies a service every 39 minutes.[12]

Since the demand is symmetric and total travel time of a return trip (including boarding times) is 4h 30' (τ =4.5 hours), the (minimum) number of trains (of capacity $\overline{q}$, at speed $s$, and with a load factor of 75%) needed daily in the *O-D* corridor would be given by the ratio $\frac{\tau}{1/F_t}$, that is

$$\tau \frac{q_t}{18\overline{q}_e}.$$

In order to face unforeseeable contingencies (delays, external damages, breakdowns, etc.) this minimum number is multiplied by a (exogenous) 'contingency factor', which we will set in 1.5.[13] Thus, the supply (in terms of the number of trains) would be finally given by:

$$RS_t = (1.5) \cdot \tau \frac{q_t}{18\overline{q}_e},$$

where $RS_t$ stands for 'rolling stock needed at $t$'.

Figure 2.3 illustrates the supply calculations results and their evolution under alternative train capacity assumptions. Note, for example for the reference case (with $\overline{q}$ = 330 seats) that our

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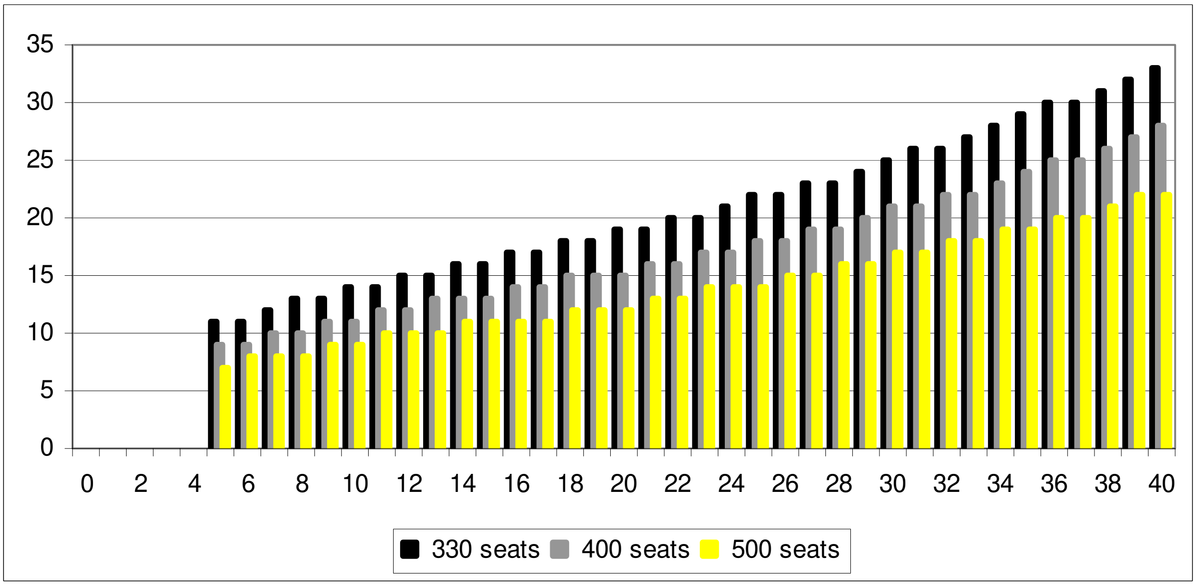
[11] A summary of all the parameter values for the reference case are provided, as a quick reference, in Table 2.2, below.

[12] This is a low value when compared to the real world. It corresponds to an initial demand of 5,000,000 passengers per year. In subsequent years, when the demand grows, the frequency ($F_t$) would also increase, reaching more reasonable values of one service every 15 or less minutes.

[13] This factor is quite firm-specific and it is associated to the risk of failing to provide services vs. the cost of acquiring, operating and maintaining an over-sized fleet. The range of values found in the real world varies from 1.25 to 1.6, depending on the corridor.

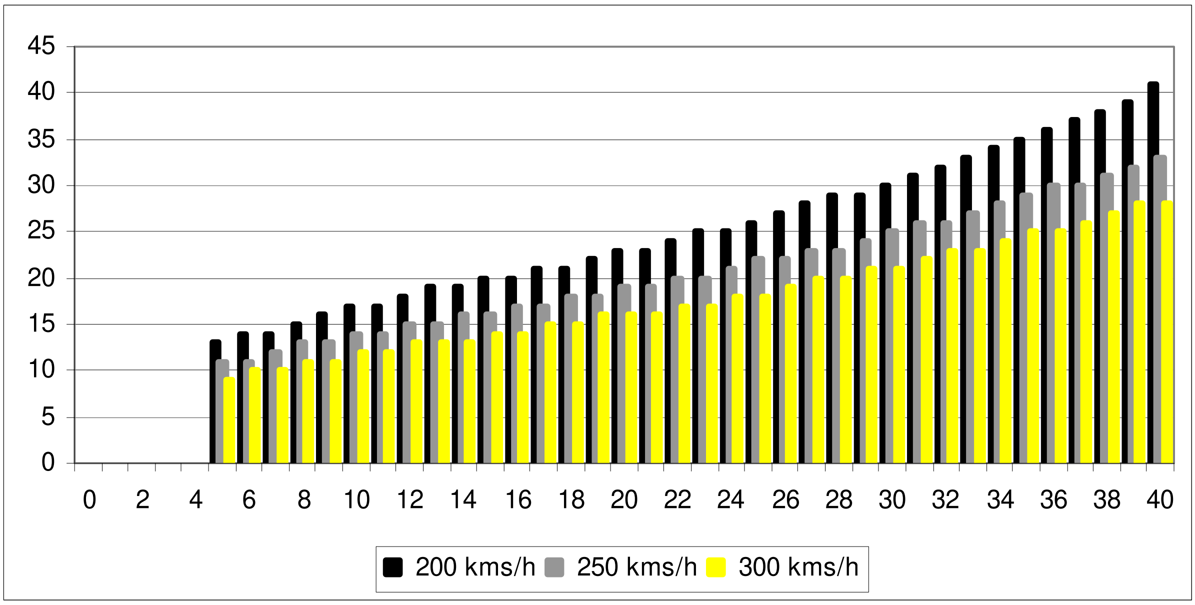
HSR service would start its operations with 11 trains, but in $t$=40 the figure would be 33, due to the increase in the projected demand. With $\overline{q}$ = 400 and $\overline{q}$ = 500 the corresponding initial values would be 9 and 7, whereas the final ones would be 28 and 22, respectively. These figures fit reasonably well with international standards, which sets the number of trains used for lines in the range of 300-500 km (although with intermediate stops and shorter legs) between 30 and 80 (around 10-15 trains per 100 km of HSR line).

**Figure 2.3. Number of trains needed under alternative capacity assumptions**



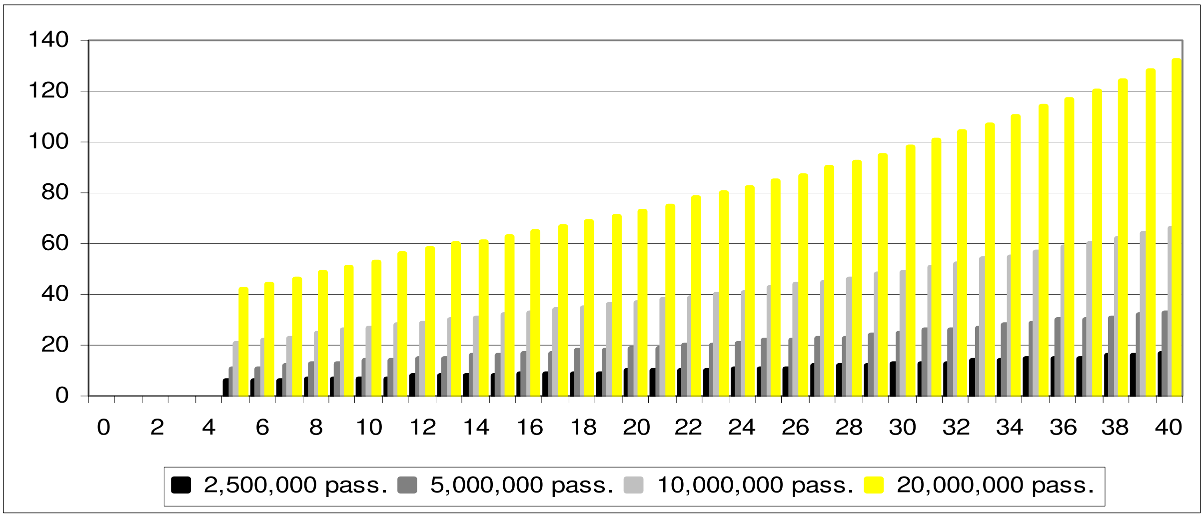

In practice, actual rolling stock provision in HSR lines around the world is directly affected by several project-specific parameters such as the average commercial speed or the specific technology used in each case. Other elements, such as the seasonality of demand or the existence of peak periods have been ruled out from this exercise.

**Figure 2.4. Number of trains needed under alternative speed assumptions**




With respect to the first one, total travel time is reduced when average commercial speed is increased and vice versa, thus affecting the supply calculations. Figure 2.4 illustrates these effects by recalculating the number of trains needed under different speed assumptions. Obviously, the figures in the reference case (250 km/h) are the same than those in Figure 2.3 with $\overline{q} = 330$. However, note that if speed is reduced to an average of 200 kms/h (not an unrealistic assumption, nowadays) the number of trains need at $t$=40 would jump to 41; on the other hand, increasing the speed to 300 kms/h would imply that 28 trains (only five less than in the reference case) would be needed.

**Figure 2.5. Number of trains needed under alternative initial annual demand assumptions**



Finally, Figure 2.5 proves the strong dependence of the supply calculations with respect to the demand projections. It shows the number of trains needed every year under alternative values for initial annual demand (as in Table 2.1, above). Note, for example, that departing from 2.5 million passengers per year, we will only need 6 trains in the first year (and 17 at $t$=40). But if the initial demand were 20 million, then the figures would be 42 and 142. Therefore, a wrong demand projection could be more relevant for supply calculations than changes in train capacity or in average speed.

## 2.4. Methodology of cost calculations

### 2.4.1. Objectives

The main objective of this paper is to provide an estimate of the total cost of building, operating and maintaining a HSR with technical characteristics and the supply and demand conditions described in the previous section. In order to provide a quick reference of our reference case, Table 2.2 summarizes the main parameter values considered in our analysis.

**Table 2.2. The reference case: main parameter values**

| | |
|---|---|
| **Line length** (L) = 500 kms | **Train capacity** ( $\overline{q}$ ) =330 seats |
| **Project timeline**: t= 0 to t= 40 (T) | **Load factor** (l) = 75% |
| **Construction period** ($T_c$) = 5 years | **Operating hours (daily)** = 18 hours |
| **Operation period** ($T-T_c$) = 35 years | **Average commercial speed** (s) = 250 kms/h |
| **Initial annual demand** ($Q_5$) = 5 mill. passengers | **Boarding time** (between services) =15 minutes |
| **Growth rate 1** ($g_1$) = 5% (from t=6 to 11) | **Train contingency factor** = 50% |
| **Growth rate 2** ($g_2$) = 3% (from t=12 to 40) | |

Although all these values can be individually modified upwards or downwards – *ceteris paribus* – to illustrate their particular effect on our costs results, we will restrict our comparative statics exercises only to changes in the initial demand, the train capacity, the commercial speed and the line length, since these four factors summarize the most salient economic characteristics of any HSR line.

As described at Section 2.1, cost calculations will be categorized into two main groups: infrastructure costs and rolling stock costs, respectively denoted as *IC* and *RSC*. Thus, formally, the total cost (*TC*) of our HSR project (evaluated at $t$=0) is just given by the net present value:

$$TC = \sum_{t=1}^{T} \frac{IC_t + RSC_t}{(1+i)^t} . \tag{2.1}$$

We now describe the components of each of these costs and how each of them has been calculated in our particular example.

### 2.4.2. Infrastructure costs

Infrastructure costs (IC) can be divided into construction costs ($IC^C$) and maintenance costs ($IC^M$). Both of them are relatively independent on the volume of the traffic and instead can be calculated as dependent of the line length (L), just multiplying the number of kilometres by an average unit cost (denoted as c and *m*, respectively). Construction costs spread out over the construction period, whereas the maintenance takes place during the operating period (see Figure 2.1). Formally, the infrastructure costs can be denoted as

$$IC_t = IC_t^C + IC_t^M = \sum_{t=1}^{T_o} \frac{(c \cdot L)(1+\rho)}{(1+i)^t} + \sum_{t=T_o+1}^{T} \frac{m \cdot L}{(1+i)^t} , \tag{2.2}$$

where we have additionally assumed that construction costs also include a surcharge (ρ = 10%) to take into account planning costs.

The actual values of the average costs per km (c, m) have been estimated from the values found in Chapter 4 database of actual HSR projects. In particular, to err on the side of precaution, we did not considered just one value, but three: the lowest unit cost in the database (named, the *best scenario*), the highest unit cost in the database (the *worst scenario*) and the average value in the database (*medium scenario*).[14]

[14] Note that is equivalent to implicitly assume a probability distribution where the three cases are equally likely.

**Table 2.3. Infrastructure costs per year (reference case)**

| | Construction | Maintenance |
|---|---|---|
| **Period** | *t*= 1 to *t*= 5 | *t*= 6 to *t*= 40 |
| **Line length (kms)** | 500 | 500 |
| **Unit value (€ per km)** | | |
| **Best scenario** | 9,000,000 | 12,919 |
| **Medium scenario** | 18,000,000 | 35,624 |
| **Worst scenario** | 39,000,000 | 71,650 |
| **Planning cost (%)** | 10% | -- |
| **Total value (€ per year)** | | |
| **Best scenario** | 990,000,000 | 6,459,500 |
| **Medium scenario** | 1,980,000,000 | 17,812,000 |
| **Worst scenario** | 4,290,000,000 | 35,825,000 |

Table 2.3 summarizes the results from these calculations for the reference case (where the line length is 500 kms). The lowest construction (maintenance) cost per km is 9 million euros (12,919 euros, respectively), whereas the highest is 39 million and 71,650, respectively. Note in Table 2.4 that total infrastructure costs are fixed costs that evolve linearly with the length of the corridor: for the largest case (650 kms) construction costs might reach a peak of €5,517 million per year in the worst scenario.

**Table 2.4. Annual infrastructure costs under different line lengths (in €)**

| | L= 250 kms | | L= 500 kms | | L= 650 kms | |
|---|---|---|---|---|---|---|
| | Building | Maintenance | Building | Maintenance | Building | Maintenance |
| **Best scenario** | 495,000,000 | 3,229,750 | 990,000,000 | 6,459,500 | 1,287,000,000 | 8,397,350 |
| **Medium scenario** | 990,000,000 | 8,906,000 | 1,980,000,000 | 17,812,000 | 2,574,000,000 | 23,155,660 |
| **Worst scenario** | 2,145,000,000 | 17,912,500 | 4,290,000,000 | 35,825,000 | 5,577,000,000 | 46,572,500 |

A final element to take into account in the previous calculations is the residual value of the infrastructure at t = 40. This amount – once discounted to t = 0 – reduces the total cost of the infrastructure. In general, since there are different assets (tracks, buildings, etc.), with different useful lives and depreciation rates, it is quite difficult to provide an accurate value of this residual value. To simplify calculations we will just assume that it will be equal to 30% of the total construction cost for each particular scenario. Thus, for the reference case in the best scenario, with a total building costs of €990 x 5 years = €4,950 million, the residual value at $t$ = 40 is €1,485 million. The corresponding residual values for the medium and worst scenarios would be €2,700 and €5,850 million, respectively.

### 2.4.3. Rolling stock costs

Rolling stock costs (RSC) are divided into three categories: acquisition ($RSC^A$), operation ($RSC^O$) and maintenance ($RSC^M$) of the trains needed to run the services. With respect to the acquisition costs they are simply calculated by multiplying the number of trains bought every year ($RS_t - RS_{t-1}$) by the unit cost per seat (a) and their average capacity ($\overline{q}$), so that their NPV would be

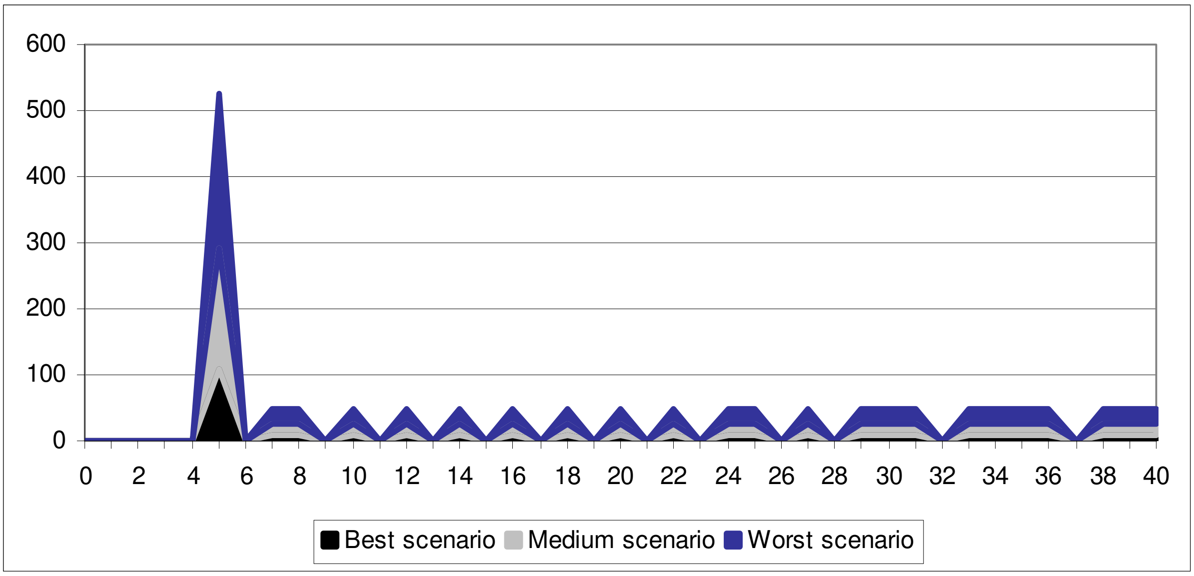
$$RSC^A = \sum_{t=1}^{T} \frac{(RS_t - RS_{t-1}) \cdot a \cdot \overline{q}}{(1+i)^t} \tag{2.3}$$

In practice, the process of contracting, designing, building, delivering and testing new rolling stock usually lasts several years; in our example, we will make the assumption that —since demand projections are known well in advance— rolling stock is delivered just-in-time. This implies, for example, according to our supply calculations, that in 11 trains start operations at t = 5 in the reference case. At t = 6, since $RS_6 = 11$, no new train is bought; however, at t = 7 and additional unit is acquired (since $RS_7 = 12$), and so on.

Another simplifying assumption is related to the useful life of the rolling stock. We will consider that, under adequate maintenance, each trainset is economically usable for at least 40 years (which corresponds with the average useful life in the industry nowadays). For this reason, no technical renewals or replacements are needed and all the new acquisitions are related to the growth in demand.

With respect to the effective cost calculations, the database in the companion Chapter4 provides three alternative acquisition unit costs in terms of euros per seat, which again we label as best scenario (lowest value = 30,000€ per seat), medium scenario (average value = 50,000€ per seat), and worst scenario (highest value = 65,000€ per seat). Figure 2.6 summarizes the evolution of total acquisition costs from $t$=0 to $t$=40 for the reference case (330 seats per train) under the three alternative scenarios.

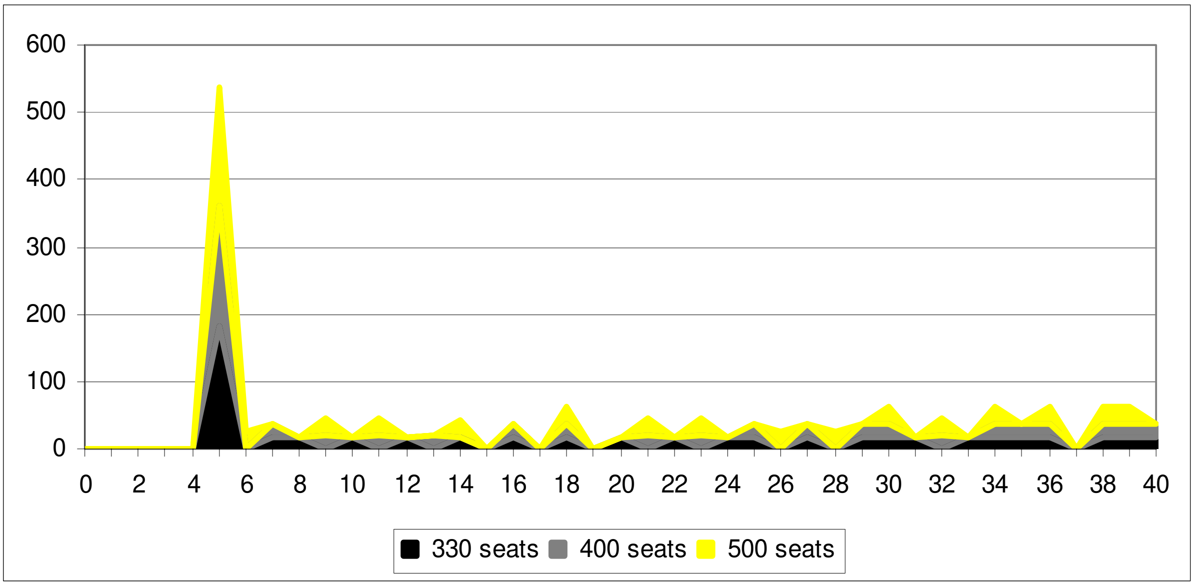
**Figure 2.6. Acquisition costs per year under alternative scenarios (in € million)**




Obviously, the peak at $t$=5 corresponds to the initial acquisition of rolling stock to start operations; afterwards, there are minor periodical acquisitions. This pattern is mimicked in Figure 2.7, where we intended to test the potential existence of cost economies associated to train size. When the capacity of the trains increase so does their acquisition cost, but fewer trains are needed. Although the periodicity of the renewals can be changed (for example, a new train is added every three years instead of every two years), these two opposing effect tend to cancel each other, thus reducing the possibility of economies of vehicle size.[15]

[15] Wei and Hansen (2005) discuss this idea for the case of aircrafts. Their results also suggest that there are no large cost reductions associated to larger vehicle sizes.

**Figure 2.7. Acquisition costs per year under alternative train capacities (in € million)**




Note that in the previous figures we have just considered the gross acquisition cost. If we assume that the average useful life of each rolling stock unit is 40 years and that its value is reduced 1/40 every year (linear depreciation), at t = 40 there will be some residual values that —once discounted to t = 0— should be reduced from the acquisition costs. These residual values depend on the year each particular unit is bought. For example, in the reference case, the residual value at t = 40 of the 11 trainset units acquired at t =5 will be 5/40 of their acquisition cost; the additional unit bought at t =7 will be worth 7/40 of its initial cost, and so on.[16] By adding the residual values of all the units bought from t =5 to t =40 we finally get the total residual values (at t = 40) of the rolling stock under each possible scenario: in the best one, it would be €149,242,500; in the medium scenario, €248,737,500, and in the worst scenario €323,358,750.

On the other hand, the operation and maintenance costs of the rolling stock are heavily dependent on the volume of traffic along the line which, indirectly, can be measured through the number of trains. In the case of the operation costs ($RS^O$), its main determinants are labour and energy. The number of technical crew members per train depends on its technical specifications and is usually set in transport regulations. On the contrary, there are no

[16] Note for example, that a rolling stock unit bought at $t$ = 40 has a residual value of 40/40 (that is, 100%).

minimum standards on cabin attendants and auxiliary personnel, and their number depends on the level of service offered to passengers. Energy consumption is calculated in accordance to the technical specification of the rolling stock.

For these reasons, in our simulation exercise we have used the expression:

$$RSC^O = \sum_{t=5}^{T} \frac{r_o \cdot RS_t \cdot \overline{q}}{(1+i)^t}, \tag{2.4}$$

where $r_o$ is the annual unit operation cost per seat (and $\overline{q}$ the average train capacity). Once more, the actual value of $r_o$ is obtained from the database in Chapter 4, which provides us with three alternative estimates: best scenario ($r_o$ = €40,000 per seat), medium scenario ($r_o$ = €53,000 per seat), and worst scenario ($r_o$ = €65,000 per seat). The evolution of total operation costs from t=0 to t=40 for the reference case is given in Figure 2.8.

**Figure 2.8. Operation costs per year under alternative scenarios (in € million)**

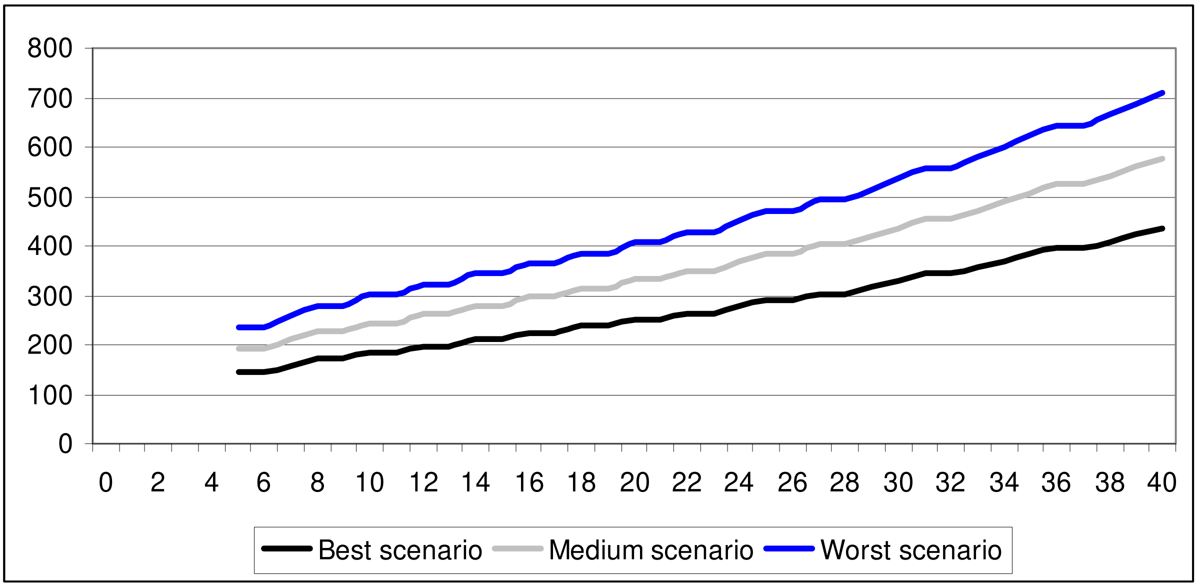
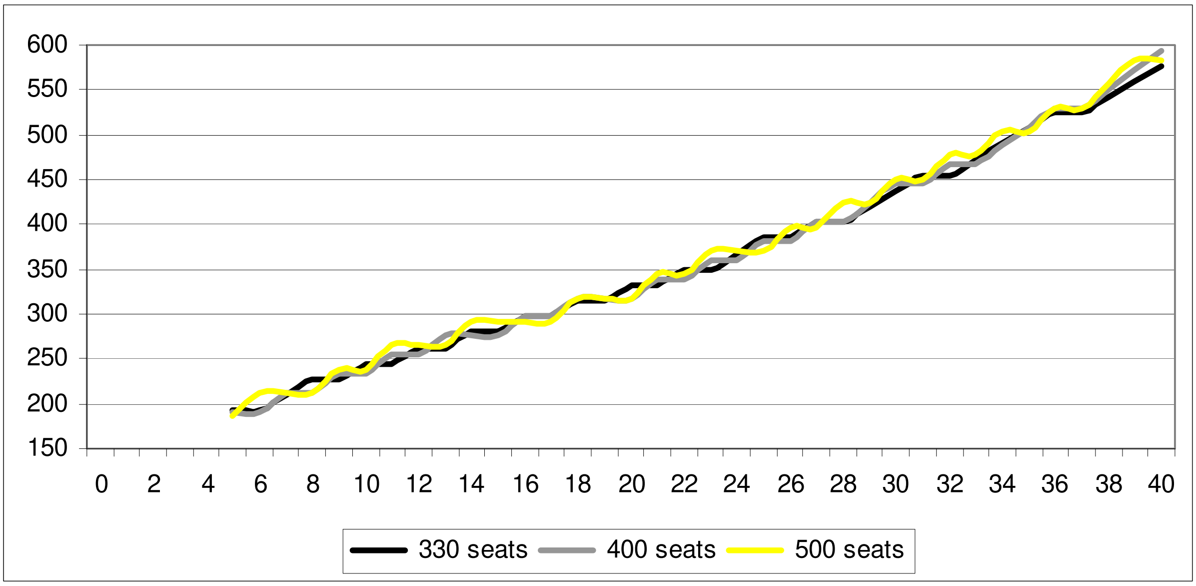


**Figure 2.9. Operation costs per year under alternative train capacities (in € million)**




Interestingly, when the train size is increased (up to 400 and 500 seats), there are no clear cost advantages, as illustrated in Figure 2.9 (drawn for the medium scenario, only). In some years it is cheaper to operate larger sized trains, whereas in other years they are too expensive. It is important to recall here our simplifying assumption that all trains are equal in size, which is somehow unrealistic.

Finally, the maintenance costs of the rolling stock are not only related to traffic (measured through the number of trains) but also to train intensity usage. Thus, a better estimate of the NPV of this cost would be given by

$$RSC^M = \sum_{t=5}^{T} \frac{r_m \cdot D_t \cdot RS_t}{(1+i)^t}, \tag{2.5}$$

where $r_m$ is the unit maintenance cost per train and kilometre, and $D_t$ is the average distance travelled by each train.[17] According to Campos *et al.* (2007), $r_m$ can be estimated around 2€/km for trains running around 0.5 million kilometres per year. For Chapter 4, our reference case, this value yields a total maintenance cost of 20,202,020 euros at $t$ = 5 and 63,798,448 euros at $t$ = 40. Note that, as depicted in Figure 2.10, larger-size trains are cheaper to maintain, since the average distance they travel is lower.

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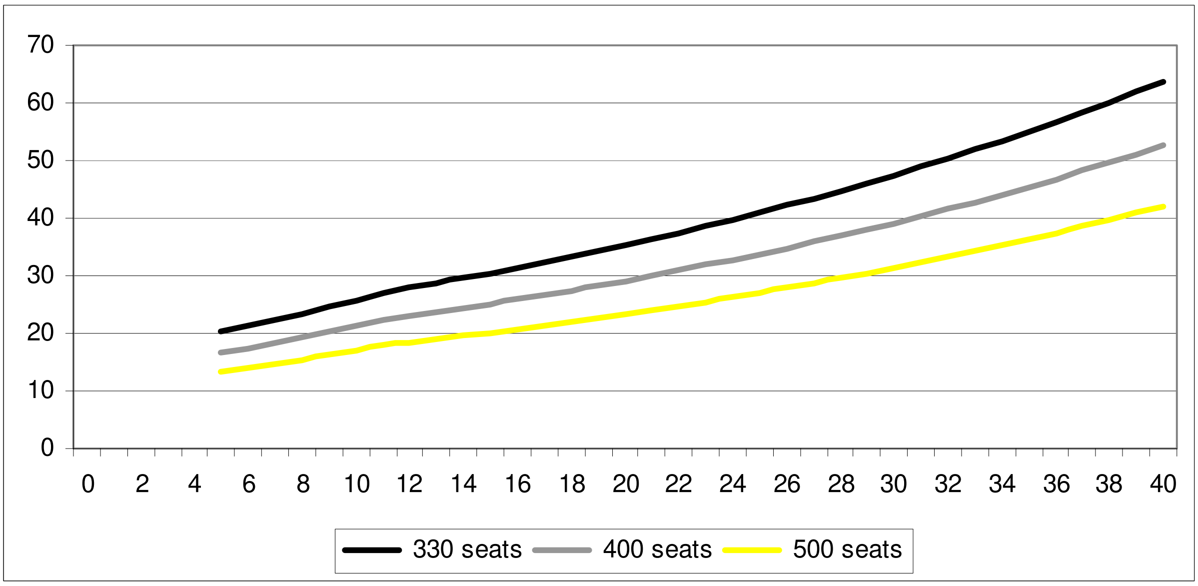
[17] This average distance has been calculated dividing the total distance covered by all trains every year (number of total annual services multiplied by line length) between the number of trains.

**Figure 2.10. Maintenance costs per year under alternative train capacities (in € million)**




## 2.5. Conclusions

By collecting together all the formulae and calculations in the previous sections, our estimate of the total cost (at $t$=0) of building, operating and maintaining a HSR line would be obtained from expression (2.1):

$$TC = \sum_{t=1}^{T} \frac{IC_t^C + IC_t^M + RSC_t^A + RSC_t^O + RSC_t^M}{(1+i)^t}, \quad (2.6)$$

that is,

$$TC = \sum_{t=1}^{T_o} \frac{(c \cdot L)(1+\rho)}{(1+i)^t} + \sum_{t=T_c+1}^{T} \frac{m \cdot L}{(1+i)^t} + \sum_{t=1}^{T} \frac{(RS_t - RS_{t-1}) \cdot a \cdot \overline{q}}{(1+i)^t} + \sum_{t=5}^{T} \frac{r_o \cdot RS_t \cdot \overline{q}}{(1+i)^t} + \sum_{t=5}^{T} \frac{r_m \cdot D_t \cdot RS_t}{(1+i)^t} \quad (2.7)$$

Although it jus provides a lower bound to the actual cost, this expression summarizes the critical factors that must be taken into account when analyzing the costs of HSR lines. These include the line length (L), the number of trains needed to respond to the demand (RS), train capacity ( $\overline{q}$ ), average distance (D) and the corresponding unit costs (c, m, a, $r_o$, $r_m$).

Table 2.5 summarizes the numerical estimates of this total cost considering a discount rate ($i$) of 5% under alternative assumptions on initial demand, train capacity, commercial speed and line length. We also considered three scenarios regarding the unit costs obtained from the database in Chapter 4: the 'All the best' scenario always uses the lowest value of the unit costs in each case; the 'All the medium' scenario always uses the average value of the unit costs in each case; the 'All the worst' scenario always uses the highest value of the unit costs in each case. The implicit assumption behind these compound-scenarios is that there exist a perfect positive correlation between all the unit costs: if a country has a large construction cost, then its operating cost will be also large, and vice versa. In practice, this is not always the case, since in several projects it is observed that the correlation could be even negative.

**Table 2.5. Total costs (at *t*=0) of a HSR line under alternative assumptions (in euros)**

| | All the best scenario | All the medium Scenario | All the worst scenario |
|---|---|---|---|
| **Initial demand assumptions** | | | |
| **2,500,000 pass.** | 6,000,067,777 | 10,785,250,118 | 21,065,618,421 |
| **5,000,000 pass.** | **7,730,285,037** | **13,029,676,448** | **23,777,416,675** |
| **10,000,000 pass.** | 11,187,484,570 | 17,513,729,139 | 29,194,942,065 |
| **20,000,000 pass.** | 18,108,860,949 | 26,491,173,260 | 40,041,479,687 |
| **Train capacity assumptions** | | | |
| **330 seats** | **7,730,285,037** | **13,029,676,448** | **23,777,416675** |
| **400 seats** | 7,648,681,646 | 12,945,753,435 | 23,691,415,005 |
| **500 seats** | 7,626,652,900 | 12,940,793,841 | 23,701,794,353 |
| **Commercial speed assumptions** | | | |
| **200 kms/h** | 8,390,219,242 | 13,913,020,245 | 24,863,968,621 |
| **250 kms/h** | **7,730,285,037** | **13,029,676,448** | **23,777,416,675** |
| **300 kms/h** | 7,277,305,302 | 12,423,499,186 | 23,031,845,523 |
| **Line length assumptions** | | | |
| **250 kms** | 4,080,508,403 | 6,803,021,727 | 12,243,154,507 |
| **500 kms** | **7,730,285,037** | **13,029,676,448** | **23,777,416,675** |
| **650 kms** | 9,909,604,536 | 16,751,534,490 | 30,680,581,170 |

*Note:* Results in bold correspond to the reference case.

According to Table 2.5, the total cost of a 40-year HSR project lies between €7.7 and €23.7 billion in the reference case, depending on the scenario (best and worse, respectively). On average the NPV is 13.0 billion, which implies an average estimate of €25-30 million per kilometre.

Table 2.5 also shows that when the initial demand is halved with respect to the reference case (that is, only 2.5 million passengers per year), the total cost is reduced (on average) just a 20%, but if demand is duplicated (10 million passengers) total cost can increase up to 31%. Similarly, it is interesting to note that neither the increase in train capacity nor the commercial speed have a large impact reducing the total costs of the project. Their effects on the supply tend to cancel out. On the contrary, changes in the length of the line are critical: shorter (larger) lines are dramatically cheaper (more expensive) to build and operate when compared to the reference case.

This final result is explained by the fact that most of the costs of the projects are fixed. This is confirmed in Figures 2.11 to 2.14, where the NPV cost distribution between fixed and variable cost (under different assumptions) is displayed.

**Figure 2.11. NPV cost distribution depending on initial demand**

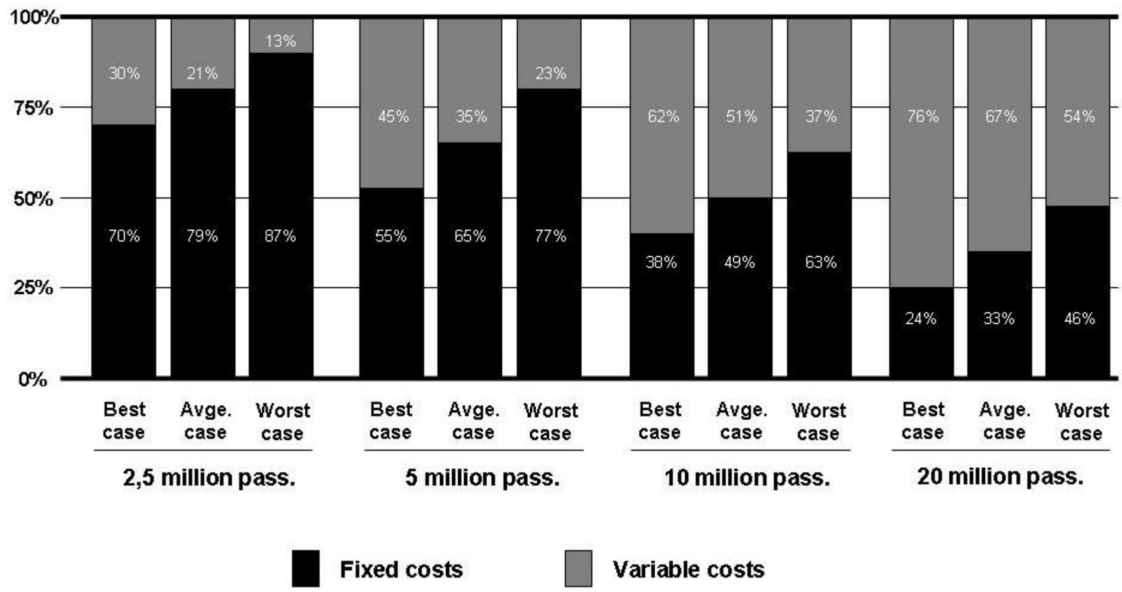


**Figure 2.12. NPV cost distribution depending on commercial speed**

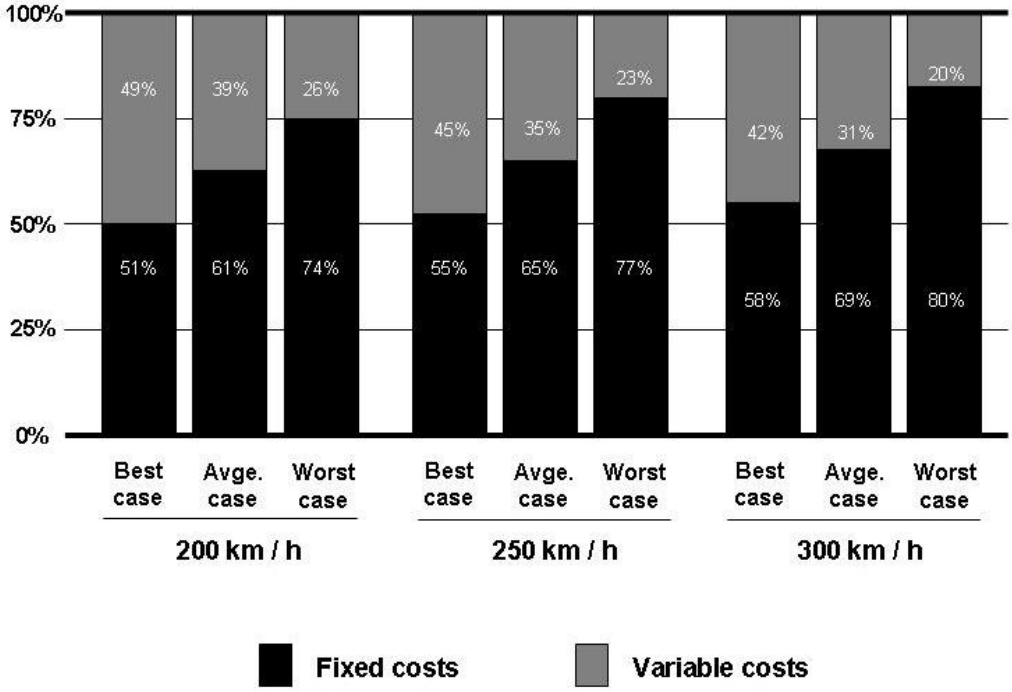



**Figure 2.13. NPV cost distribution depending on train capacity**

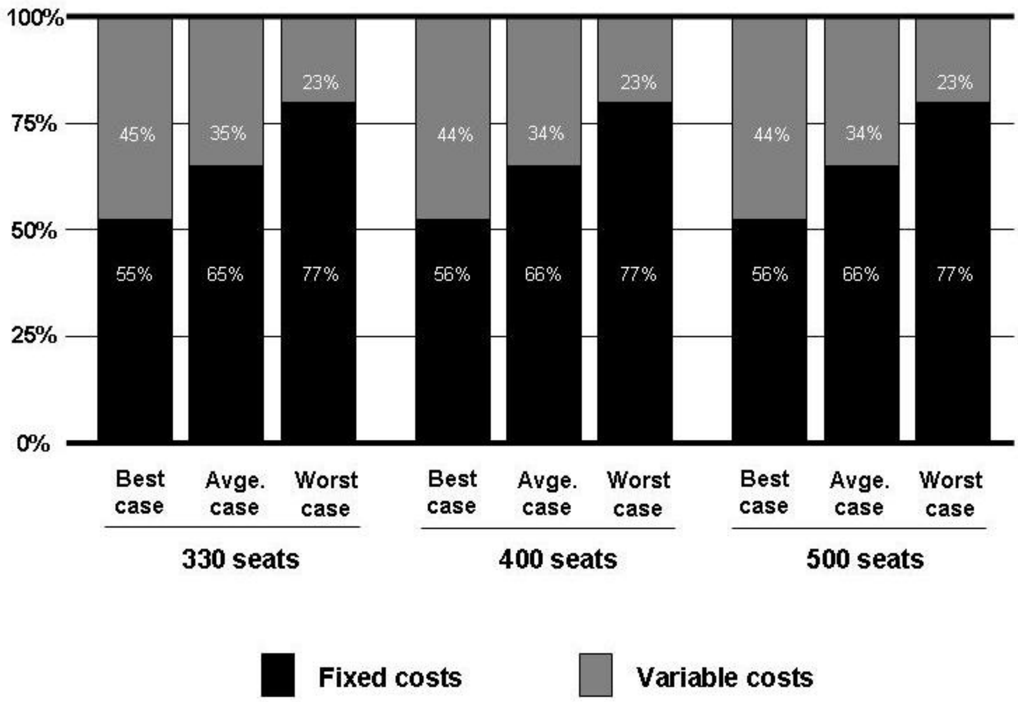


**Figure 2.14. NPV cost distribution depending on line length**