A method for the economic evaluation of transport investments under demand uncertainty

Javier Campos (1)

Aday Hernández (2)

1 Associate Professor, University of Las Palmas de Gran Canaria, Spain. (jcampos@daea.ulpgc.es)

2 Associate Researcher, University of Las Palmas de Gran Canaria, Spain (ahernandezg@becarios.ulpgc.es)

Abstract. Although investment in major transport infrastructure (roads, rail, ports and airports) plays a crucial role within the logistic chain, most projects are so expensive that require public funding and support. Deciding what projects should be carried out then becomes a critical decision both in economic and political terms, particularly when demand uncertainty is quite relevant. This paper builds on standard cost-benefit analysis techniques and provides a model to perform economic evaluation of transport projects from their demand side. We illustrate the model with an example of a rail project, but our conclusions could be easily extended to other modes. For countries willing to expand their current transport infrastructure, our results could provide some of the answers to the main questions they are dealing with.

Keywords: Transport investment, economic evaluation, rail.

JEL classification**:** D61, L92, R42.

1. Introduction

Rail transport plays a very relevant role within the logistic chain in modern economies. This role is not limited to freight transport – a niche in which this mode has become more and more specialized in recent decades – but particularly on passenger transport over short and medium distances. High speed rail (HSR) is the riskiest bet most governments – in Europe, America and Asia – have recently taken in order to dramatically increase the mobility of people and liberate capacity on the conventional rail network. However, HSR projects are controversial and many doubts often arise about their social viability.

It is precisely this idea what justifies that the economic evaluation of public investment projects has become one of the fields of applied microeconomics which has gained larger relevance in the current context of budgetary constraints. Pressures to find the most efficient allocation of resources are increasingly being translated at every level of government into the need of selecting good projects and investing public money where its social return could be more rewarding. There exist several well-established techniques for conducting this assessment, but most of them simply try to compare the benefits that the society as a whole accrues from different types of public intervention in the markets, with the opportunity cost of the resources used to finance such interventions.

Transport markets make an especially fruitful area for all sorts of cost-benefit analyses (*CBA*), since measuring and giving money values to traffic flows, travel time and other transport costs seldom result as controversial as, for instance, evaluating the impact of health or environmental policies. The economic evaluation of any public intervention in transport markets particularly aims at quantifying in monetary terms the change in social welfare generated by this intervention. To evaluate a transport project is to identify, assess, aggregate and compare the costs and benefits generated by the project once discounted over time. These costs and benefits can be solely valued both from a financial point of view (just considering the revenues and costs generated by the project), or from a more general, social, point of view, which is the focus followed in this paper.

In the case of high-speed rail infrastructure and services, the main social benefits are primarily gained from time savings enjoyed by existing users, by users that switch in from other modes, and from the willingness to pay of the newly generated demand. Where appropriate, these benefits should also be weighed against those experienced by users of alternative transport modes, either because congestion (in roads or airports) is reduced and capacity is freed up, or because lives are saved (in roads) due to the deviation of road traffic. On the opposite side, the main social costs of *HSR* investments correspond to the expensive construction and maintenance costs of the infrastructure, the operation and maintenance of services provided over it, and other external costs (landscape effects, noise, pollution, etc.) whose components are often more difficult to quantify. If the benefits outweigh the costs, investment in high-speed rail is, in principle, socially desirable.

However, even a positive net present value does not preclude the possibility that there may be alternative projects that could provide a higher social benefit. When the amount of the investment is large enough – for example in the case of the European Structural and Cohesion Funds – the accuracy required when adopting decisions on particular projects is also larger. Although this is not a particular requirement for rail investment and our analysis could be easily extended to other infrastructure areas, the current worldwide expansion of *HSR* projects, jointly with the fact that most of these projects are very expensive and particularly uncertain, sometimes with dubious social returns in a 20-30 years horizon, all make of this sector a very interesting case study.

It is precisely the inevitable uncertainty associated with factors such as demand predictions or the future technology developments in the rail sector[1] what leads us to adopt in this paper an unconventional approach into cost-benefit analysis. Instead of conducting a standard assessment of a single high-speed line or corridor, using well estimated demand and cost data, we will follow and upside-down approach where demand uncertainty plays a central role. We will not simply compare (social) benefits and costs discounted (from an initial estimate of demand figures) to calculate a single value of a social net present value (*SNPV*). On the contrary, we will try to figure out what is the initial demand level that the project should have in order to provide a positive (expected) social return. Although this methodological approach is not completely new in the *CBA* literature, as it has been used, for example, in De Rus and Nombela (2007) and De Rus and Nash (2008), our contribution adds a larger role for uncertainty and explicitly shows that the reject/accept decision cannot be made based upon a deterministic *SNPV* but on a complete probability distribution of *SPNV* values. The main advantage of this methodology is that it internalizes and isolates most of the demand uncertainty in *HSR* projects, making it possible to determine, as a decision reference, the 'minimum demand threshold from which a project would be socially profitable'. If this minimum amount is not met, the society would gain more investing its resources on alternative projects.

After this introduction, the rest of this paper is structured as follows. In Section 2 the *project* (the hypothetical construction and operation of a new high-speed line, for example, in Morocco) is defined and the assessment model is formulated to calculate the value of the initial

[1] The MAGLEV (*magnetic levitation*) technology is increasingly viewed as the next standard for high speed surface transportation. Note that, if successful, all current investments on HSR could become obsolete in 10-20 years.

demand figures that guarantee a positive expected *SNPV*. Section 3 is then devoted to the practical implementation of this model in full detail and result analysis, while in Section 4 the main findings and lessons are discussed.

2. Project definition and assessment model

The economic appraisal of a rail investment project traditionally consists in comparing its discounted benefits and costs, by using – for example – the social net present value (*SNPV*) as the decision criterion. If there is uncertainty about the variables or parameters of the model, a sensitivity analysis is usually carried out *ex post*, showing different results under different scenarios. In this paper we will follow an inverse procedure: since the critical (uncertainty) variable is the demand, our objective will be to determine the threshold value of the initial demand that equals to zero the (expected) *SNPV*. Thus, our aim is to calculate 'the minimum level of traffic in the year of entry into service the new line that would guarantee a positive social return'. Firstly, we will begin with the technical definition of the project considering some reasonable assumptions about it in order to facilitate its assessment and secondly we will illustrate, step by step, the calculations to be done to produce the expected result.

2.1.Project definition

Our representative project consists in the construction and operation of a high-speed line of $\boldsymbol{L}$ km long. As shown in **Figure 1**, the society makes a gross investment equal to $\boldsymbol{GI_t}$ euros, which includes both the costs of planning and construction, during the construction period (between t = 0 and $t = T'$). During each of the years of operation of the line (between $t = T'+1$ and $t=T$), the project contributes annually to the society a change in the social net benefit (with respect to the situation without project) equal to $\boldsymbol{\Delta SB_t}$, which may be positive or negative. All these flows are valued at 31th December each year.

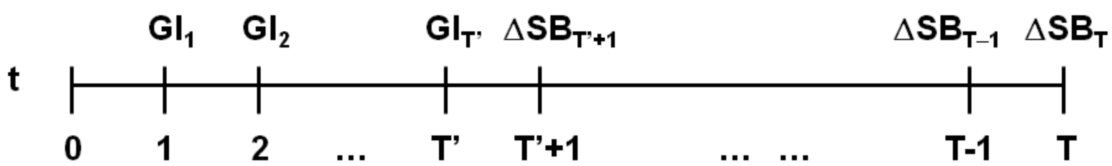

Figure 1. Project structure

Once the flows associated to the project are discounted with the interest rate $\boldsymbol{i}$, the formal expression of the social net present value at $t = 0$ is traditionally given by:

$$SNPV = -I_0 + \sum_{t=T'+1}^{T} \frac{\Delta SB_t}{(1+i)^t}, \tag{1}$$

where $\boldsymbol{I_0}$ summarizes, valued at $t = 0$, the initial investment net of its residual value ($\boldsymbol{RVI_T}$):[2]

$$I_0 = \sum_{t=0}^{T'} \frac{GI_t}{(1+i)^t} - \frac{RVI_T}{(1+i)^T} \tag{2}$$

On the other hand, the annual change in the net social benefit ($\boldsymbol{\Delta SB_t}$) can be decomposed into changes in consumers' surplus ($\boldsymbol{\Delta CS_t}$), changes in operators' (or producer's) surplus ($\boldsymbol{\Delta PS_t}$), changes in taxpayers' surplus ($\boldsymbol{\Delta GS_t}$) and changes in the indirect effects ($\boldsymbol{\Delta IE_t}$). However, to simplify our analysis we will only consider that the first two effects are relevant in our case, i.e. $\boldsymbol{\Delta GS_t = \Delta IE_t = 0}$, so that our society only includes transport users and transport producers:

$$\Delta SB_t = \Delta CS_t + \Delta PS_t \tag{3}$$

2.2. An initial benchmark: the analysis of a static model

To illustrate the calculations associated to the assessment model, we will proceed step by step, from a simple (static) framework to a dynamic one. Thus, let first assume that the project has a total length of one period: all investment takes place at $t = 0$ and the social costs and benefits associated to the operating period are valued at $t = 1$, i.e. $(T', T) = (0, 1)$. Under these conditions, it is immediate to verify that expression (1) becomes:

$$SNPV = -I_0 + \frac{\Delta CS_1 + \Delta PS_1}{(1+i)} \tag{4}$$

[2] Although it is not the most appropriate approach, we have considered that the residual value is just a percentage of the initial investment, in order to simplify the model.

2.2.1. Computing the (change in) consumers' surplus[3]

All the traffic in the new high speed line in period t = 1 comes from two possible sources of demand: the *diverted traffic* from existing modes, which will be generically denoted as: *airplane* (a), *bus* (b), *car* (c), or *conventional rail* (r),[4] or the newly *generated traffic*, by users who did not previously on this route.

<u>Diverted traffic</u>

In the initial situation *without* the project (denoted by superscript 0) the users' generalized cost of travel for each of the existing modes (m = a, b, c, r) is defined as:

$$g_m^0 = p_m^0 + v_m^0 \tau_m^0 + \varepsilon_m^0 \tag{5}$$

where:

- p_m^0 = monetary component of the cost in mode m (*without* project),
- v_m^0 = value of time in mode m (*without* project). Assuming that this value does not change with the project, we will simply denote it as v_m,
- τ_m^0 = total travel time in mode m (*without* project), and
- ε_m^0 = monetary valuation of the travel quality in mode m (*without* project).

In the situation *with* project, after the investment (denoted by superscript I), the change in the consumers' surplus of users diverted from other existing modes can be expressed as:[5]

$$\sum_m (g_m^0 - g_m^I) q_m^0, \tag{6}$$

where:

- q_m^0 = *HSR* trips made by travellers from other m modes.
- $g_m^I = p^I + v_m \tau^I + \varepsilon_m^I$ = generalized cost of travel at *HSR* for travellers form other modes.
- p^I = average fare of a *HSR* trip, τ^I is the average duration of that trip, and ε^I_m represents a monetary valuation of the *HSR* service quality, which is assumed close to zero.[6]

<u>Generated traffic</u>

The surplus associated with new trips (made by both old and new users) must be added to the previous expression. It is conventionally determined by:

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[3] From now on, to simplify the notation, subscript 1 is dropped.

[4] Conventional rail can be omitted when the project consists on the construction of a new line, where this mode did not previously exist.

[5] This expression, conventionally denominated 'rule of one half' in *CBA*, implicitly considers that the change in the social welfare of *each traveller* can be identified with the change that is produced in the *last traveller*.

[6] Alternatively, this valuation could be also incorporated to the value of travel time (v).

$$\sum_m \frac{1}{2}(g_m^0 - g_m^I)(q^I - q_m^0), \tag{7}$$

where q^I are total high-speed trips per year. These trips consist of the sum of all diverted demand from other modes *m*,

$Q^0 = \sum_m q_m^0$,

and the generated traffic, that we will simply estimate as a proportion (α) of the diverted traffic,

$$q^I - Q^0 = \alpha Q^0 = \alpha \sum_m q_m^0,$$

so that:

$$q^I = (1+\alpha)Q^0. \tag{8}$$

2.2.2. Computing the (change in) the operators' surplus

The change in producers' surplus is determined by the difference between the operators' income *with* and *without* project, and the operation and maintenance costs of the *HSR* line, plus avoidable costs associated with the reduction of service in each mode *m* (because of the traffic that is deviated to the high speed line):

$$\sum_m (p^I q^I - p_m^0 q_m^0 + C_m^0 - C^I), \tag{9}$$

where C_m^0 are the avoidable costs in mode *m* and C^I the operating and maintenance costs of the high-speed infrastructure.

In general, avoidable costs depend on the characteristics of each mode, the level of competition and the volume of diverted traffic. It is therefore possible to express them as:

$$C_m^0 = c_m q_m^0 \tag{10}$$

where c_m is the unit cost (per trip) saved in mode *m*, which we assume to remain unchanged after the project (compared to the situation *without* the project). Moreover, as an important simplification, we also assume that all operators in alternative transport modes obtain normal profits and all their costs are recoverable, allowing us to omit the calculation of surpluses in other modes different from *m*.

Therefore, operating and maintenance costs of a high-speed line could be expressed as:

$$C^I = I^M + c^A q^I + (c^O + c^M)N, \tag{11}$$

where:

- I^M = infrastructure maintenance costs (usually fixed in terms of total traffic),

- c^A = unit cost (per traveller) of acquisition of the rolling stock, net of its residual value,[7]
- c^O = unit operation cost (per train) of the rolling stock,
- c^M = unit maintenance cost (per train) of the rolling stock, and
- N = number of trains needed to satisfy the demand each year.

The number of trains in operation (N) is a crucial variable in order to determine the supply of transport services, since it changes as the demand does. To compute N, the capacity of trains (assumed to be constant) and the daily frequency of services (assumed to be homogeneous throughout the year) are required. For example, if $\overline{q}_e = \lambda \overline{q}$ is the effective average occupation of each train (where λ is the load factor and $\overline{q}$ is the number of seats) and H are the hours of operation per day,[8] then the number of daily services during a year in each direction is obtained from the ratio $(q^I/365)/\overline{q}_e$, so that the frequency (F) is:

$$F = \frac{((q^I/365)/\overline{q}_e)}{H}.$$

Thus, the number of trains needed to serve the annual demand of travellers q^I is given by $\tau^I F$, that is, using expression (8):

$$N[q^I] = \frac{\tau^I}{365H\overline{q}_e} q^I = \frac{\tau^I}{365H\overline{q}_e}(1+\alpha)Q^0 = N[Q^0]. \qquad (12)$$

2.2.3. Computing the (change in) social surplus

According to (3), the change in the social benefit is determined by the sum of changes in the surpluses of consumers and producers, i.e. the sum of (6), (7) and (9):

$$\sum_m (g_m^0 - g_m^I) q_m^0 + \sum_m \frac{1}{2}(g_m^0 - g_m^I)(q^I - q_m^0) + \sum_m (p^I q^I - p_m^0 q_m^0 + C_m^0 - C^I) \qquad (13)$$

Expanding the first term of the previous expression yields:

$$\sum_m \left[(p_m^0 - p^I) + v_m(\tau_m^0 - \tau^I) \right] q_m^0,$$

where it is assumed, for the sake of simplicity, that the project does not significantly alter the monetary value of the quality associated to travel on different modes, i.e. $\sum_m (\varepsilon_m^0 - \varepsilon_m^1) = 0$.

[7] Although this cost should be formulated as a cost per train (equivalent to the acquisition price of each train), the difficulty to obtain real values of the acquisition price (which are directly negotiated with the producer and usually includes part of the maintenance costs) suggests the possibility of calculating through the cost per passenger what simplifies the calculus and could be interpreted as a sort of leasing.

[8] In this case, we consider $\overline{q}$ = 350, λ = 80% and H = 18. See Table 4 below.

Substituting the previous result in expression (13) and simplifying the outcome, the change in the net social benefit can be rewritten as:

$$\sum_m v_m(\tau_m^0 - \tau^I)q_m^0 + \sum_m \left[\frac{1}{2}(g_m^0 - g_m^I) + p^I\right](q^I - q_m^0) + \sum_m C_m^0 - C^I \, , \tag{14}$$

showing that this change has got three elements: time savings in the diverted traffic, the value of the new generated traffic and resource savings in the modes that lose traffic.

Finally, given that $\sum_m (q^I - q_m^0) = \alpha \sum_m q_m^0$ and developing the intermediate term in (14), the previous expression leads to:

$$\sum_m v_m(\tau_m^0 - \tau^I)q_m^0 + \alpha \sum_m \left[\frac{1}{2}(p_m^0 - p^I) + p^I\right]q_m^0 + \frac{\alpha}{2}\sum_m v_m(\tau_m^0 - \tau^I)q_m^0 + \sum_m C_m^0 - C^I \, ,$$

where, after incorporating the expressions of costs (10) and (11), together with (12), we finally obtain as a benchmark:

$$\begin{aligned} \Delta SB = \Delta CS + \Delta PS = \\ &= \left(1 + \frac{\alpha}{2}\right)\sum_m v_m(\tau_m^0 - \tau^I)q_m^0 + \\ &+ \left(\frac{\alpha}{2}\right)\sum_m (p_m^0 + p^I)q_m^0 + \\ &+ \sum_m c_m q_m^0 - \\ &- I^M - \left(c^A + \frac{(c^O + c^M)\tau^I}{365H\overline{q}_e}\right)(1+\alpha)\sum_m q_m^0 \end{aligned} \tag{15}$$

2.2.4. Finding the minimum demand threshold: SNPV=0

The last step of the calculations is to solve the equation *SPNV* = 0 using expressions (4) and (15). For a better understanding of the procedure, we first consider a simpler case (where the diverted traffic comes only from a mode) and then we later generalize this result. Thus, let us consider that there is only an alternative mode (e.g., the airplane, $m = a$). In this case, expression (15) simplifies to:

$$\begin{aligned} \Delta SB = (1 + \frac{\alpha}{2})v_a(\tau_a^0 - \tau^I)q_a^0 + \frac{\alpha}{2}(p_a^0 + p^I)q_a^0 + \\ + c_a q_a^0 - I^M - \left(c^A + \frac{(c^O + c^M)\tau^I}{365H\overline{q}_e}\right)(1+\alpha)q_a^0 \end{aligned}$$

According to (4), $SNPV = 0$ requires that $I_0(1+i) = \Delta SB$. Therefore, isolating q_a^0 from the previous expression, we easily obtain:

$$q_a^0 = \frac{I_0(1+i) + I^M}{(1+\frac{\alpha}{2})v_a(\tau_a^0 - \tau^I) + \frac{\alpha}{2}(p_a^0 + p^I) + c_a - (1+\alpha)\left(c^A + \frac{(c^O + c^M)\tau^I}{365H\overline{q}_e}\right)}, \tag{16}$$

where this value of q_a^0 determines the minimum value of the high-speed diverted traffic from the airplane that makes this project socially profitable. Note that, from q_a^0 we can immediately recover the volume of generated traffic (using the α parameter) and the total demand.

In the general case, with *m* alternative transport modes, the problem is to determine the value of $\sum_m q_m^0$ in (15) so that $I_0(1+i) = \Delta SB$. To get it, it is necessary to introduce some additional assumptions about the relation between different values of the diverted traffic, q_m^0, so the *m* values are reduced into just one.[9]

Among the different alternatives we might consider, for example that the diverted traffic can be expressed in relation to one of the modes. So, taking again the airplane (*a*) as the reference mode, we would have:

$$Q^0 = q_a^0 + q_b^0 + q_c^0 + q_f^0 = q_a^0 + \beta_b q_a^0 + \beta_c q_a^0 + \beta_f q_a^0 = (1 + \beta_b + \beta_c + \beta_f)q_a^0 \tag{17}$$

where the β parameters (that reflect the relation between different diverted traffics) can be determined endogenously in terms of the relative market share of each mode in relation to the high-speed rail mode. Using this procedure, the change in social welfare can be finally obtained as:

$$\begin{aligned}
\Delta SB &= \\
&= \left(1+\frac{\alpha}{2}\right)\left\{v_a(\tau_a^0 - \tau^I) + v_b(\tau_b^0 - \tau^I)\beta_b + v_c(\tau_c^0 - \tau^I)\beta_c + v_f(\tau_f^0 - \tau^I)\beta_f\right\}q_a^0 + \\
&+ \left(\frac{\alpha}{2}\right)\left\{(p_a^0 + p^I) + (p_b^0 + p^I)\beta_b + (p_c^0 + p^I)\beta_c + (p_f^0 + p^I)\beta_f\right\}q_a^0 + \\
&+ \left\{c_a + c_b\beta_b + c_c\beta_c + c_f\beta_f\right\}q_a^0 - \\
&- I^M - (1+\alpha)\left(c^A + \frac{(c^O + c^M)\tau^I}{365H\overline{q}_e}\right)(1 + \beta_b + \beta_c + \beta_f)q_a^0
\end{aligned}$$

and solving again $I_0(1+i) = \Delta SB$ we get:

[9] Alternatively, the problem would be unsolvable, since the expression $SNPV = 0$ would have infinite solutions.

$$q_a^0 = \left\{ I_0(1+i) + I^M \right\} \Bigg/ \left\{ \begin{array}{l} (1+\frac{\alpha}{2})\left[v_a(\tau_a^0 - \tau^I) + v_b(\tau_b^0 - \tau^I)\beta_b + v_c(\tau_c^0 - \tau^I)\beta_c + v_f(\tau_f^0 - \tau^I)\beta_f \right] \\ +\frac{\alpha}{2}\left[(p_a^0 + p^I) + (p_b^0 + p^I)\beta_b + (p_c^0 + p^I)\beta_c + (p_f^0 + p^I)\beta_f \right] + \\ \left[c_a + c_b\beta_b + c_c\beta_c + c_f\beta_f \right] - (1+\alpha)(c^A + \frac{(c^O + c^M)\tau^I}{365H\overline{q}_e}(1+\beta_b+\beta_c+\beta_f) \end{array} \right\}$$

whose interpretation is similar to that of expression (16).

2.3. The general model of *T* periods

After this simplified introduction, we will now generalise the procedure assuming that the change social benefit in (1) is distributed over *T* years. To repeat the same steps, we first introduce a time subscript *t* from expression (15) so that the change in social welfare in year *t* is given by:

$$\begin{aligned} \Delta SB_t = & \\ & = \left(1+\frac{\alpha}{2}\right)\sum_m v_m(\tau_m^0 - \tau^I)q_{mt}^0 + \\ & + \left(\frac{\alpha}{2}\right)\sum_m (p_m^0 + p^I)q_{mt}^0 + \\ & + \sum_m c_m q_{mt}^0 - \\ & - I^M - \left(c^A + \frac{(c^O + c^M)\tau^I}{365H\overline{q}_e}\right)(1+\alpha)\sum_m q_{mt}^0 \end{aligned}$$

The main simplifying assumption underlying this expression is that all the parameters of the model remain constant over time with the exception of traffic, which is assumed to grow at a constant rate (θ). Thus, q_{mt}^0 represents diverted traffic from mode *m* towards *HSR* in year *t*,

$$q_{mt+1}^0 = q_{mt}^0(1+\theta). \tag{18}$$

Therefore, it is immediate to obtain the following:

$$
\begin{aligned}
&\sum_{t=T'+1}^{T}\frac{\Delta SB_t}{(1+i)^t}= \\
&\quad=\left(1+\frac{\alpha}{2}\right)\left[\sum_m v_m(\tau_m^0-\tau^I)\sum_{t=T'+1}^{T}\frac{q_{mt}^0}{(1+i)^t}\right]+ \\
&\quad+\left(\frac{\alpha}{2}\right)\left[\sum_m (p_m^0+p^I)\sum_{t=T'+1}^{T}\frac{q_{mt}^0}{(1+i)^t}\right]+ \\
&\quad+\sum_m c_m\sum_{t=T'+1}^{T}\frac{q_{mt}^0}{(1+i)^t}- \\
&\quad-\sum_{t=T'+1}^{T}\frac{I^M}{(1+i)^t}- \\
&-(1+\alpha)\left(c^A+\frac{(c^O+c^M)\tau^I}{365H\overline{q}_e}\right)\sum_m\sum_{t=T'+1}^{T}\frac{q_{mt}^0}{(1+i)^t}
\end{aligned}
\qquad (19)
$$

where

$$
\sum_{t=T'+1}^{T}\frac{q_{mt}^0}{(1+i)^t}=\frac{q_{mT'+1}^0}{(1+i)^{T'+1}}\left[1+\left(\frac{1+\theta}{1+i}\right)+\left(\frac{1+\theta}{1+i}\right)^2+\ldots+\left(\frac{1+\theta}{1+i}\right)^{T-(T'+1)}\right]
$$

Note that this final expression is just a sum of terms of a geometric progression with common ratio (1+θ)/(1+i) so that we can rewrite it as:

$$
\sum_{t=T'+1}^{T}\frac{q_{mt}^0}{(1+i)^t}=\left[\frac{\left(\frac{1+\theta}{1+i}\right)^{T-T'-1}-1}{\left(\frac{1+\theta}{1+i}\right)-1}\right]\frac{q_{mT'+1}^0}{(1+i)^{T'+1}}=\left(\frac{(1+\theta)^{T-T'-1}-(1+i)^{T-T'-1}}{(\theta-i)(1+i)^{T-1}}\right)q_{mT'+1}^0=\gamma q_{mT'+1}^0
$$

and then replace it in (19).

Finally, from (1), we know that $I_0=\sum_{t=T'+1}^{T}\frac{\Delta SB_t}{(1+i)^t}$ must hold to guarantee that

SNPV =0, i.e.:

$$
\begin{aligned}
I_0 = &\sum_{t=T'+1}^{T} \frac{\Delta SB_t}{(1+i)^t} = \\
&= \left(1+\frac{\alpha}{2}\right)\left[v_a(\tau_a^0-\tau^I)+v_b(\tau_b^0-\tau^I)\beta_b+v_c(\tau_c^0-\tau^I)\beta_c+v_f(\tau_f^0-\tau^I)\beta_f\right]\gamma q_{aT'+1}^0 + \\
&+\left(\frac{\alpha}{2}\right)\left[(p_a^0+p^I)+(p_b^0+p^I)\beta_b+(p_c^0+p^I)\beta_c+(p_f^0+p^I)\beta_f\right]\gamma q_{aT'+1}^0 + \\
&+\left[c_a+c_b\beta_b+c_c\beta_c+c_f\beta_f\right]\gamma q_{aT'+1}^0 - \\
&-\sum_{t=T'+1}^{T}\frac{I^M}{(1+i)^t} - \\
&-(1+\alpha)\left(c^A+\frac{(c^O+c^M)\tau^I}{365H\overline{q}_e}\right)(1+\beta_b+\beta_c+\beta_f)\gamma q_{aT'+1}^0
\end{aligned}
$$

Thus, solving for $q_{aT'+1}^0$, the value of the initial (first period of operation) demand (diverted from the airplane) that equals the social *NPV* to zero is given by:

$$
q_{aT'+1}^0 = \left\{ I_0 + \sum_{t=T'+1}^{T}\frac{I^M}{(1+i)^t} \right\} \Bigg/ \left\{ \begin{array}{l} (1+\frac{\alpha}{2})\left[v_a(\tau_a^0-\tau^I)+v_b(\tau_b^0-\tau^I)\beta_b+v_c(\tau_c^0-\tau^I)\beta_c+v_f(\tau_f^0-\tau^I)\beta_f\right]\gamma \\ +\frac{\alpha}{2}\left[(p_a^0+p^I)+(p_b^0+p^I)\beta_b+(p_c^0+p^I)\beta_c+(p_f^0+p^I)\beta_f\right]\gamma + \\ \left[c_a+c_b\beta_b+c_c\beta_c+c_f\beta_f\right]\gamma-(1+\alpha)\left(c^A+\frac{(c^O+c^M)\tau^I}{365H\overline{q}_e}\right)(1+\beta_b+\beta_c+\beta_f)\gamma \end{array} \right\}
$$

As discussed below, once this initial value is found, the calculation of total diverted demand, generated demand and all other variables of the model is immediate.

3. Model implementation and results analysis

Implementing the expressions just developed in the previous section and the formal calculation of the minimum demand thresholds that guarantee the social profitability of this *HSR* investment project requires an exogenous definition of the set of parameters that complete the model. These are mainly technical parameters related to producers' and consumers' costs and the specific characteristics of each project. Although the main point of this paper is a methodological one, the relevance of our simulation results will be highly conditioned by the plausibility of the reference values that we use to perform our simulations. Most of these come from other projects (see Campos and de Rus, 2009) and the authors' experience in analysing *HSR* markets (Campos, 2009).

3.1. Parameters

3.1.1. Modelling the producers' cost

In accordance to previous sections, our reference project is a high-speed line between two cities (non-stop) with a total length of 500 kilometres (**L**), whose life is estimated in 40 years (**T**), out of which the first five ones (**T'**) correspond to the planning and construction period. We assume that the same number of kilometres is built every year, so that the annual gross investment (GI_t) between $t = 0$ and $t =$ T' (valued at the end of each year) is given by:

$$GI_t = \frac{L}{T'} \cdot ckm,$$

where *ckm* is the construction cost per kilometre in euros. The value of this unit cost of construction varies across projects, because it is directly affected by terrain circumstances. Campos *et al.* (2008) use a database of over 160 high-speed rail projects around the world and obtain average values for the construction costs per country. In the case of Spain, these values range between 9 and 17.5 millions of euros per kilometre if costs of planning are included.

With respect to the residual value of the investment in infrastructure (RVI_T), we can simply consider that this is adequately represented by a proportion (δ =10%, for example) of the gross investment. Thus, the expression (2) for the initial investment would be:

$$I_0 = \sum_{t=0}^{T'} \frac{GI_t}{(1+i)^t} - \frac{\delta}{(1+i)^T}\left(\sum_{t=0}^{T'} \frac{GI_t}{(1+i)^t}\right) = \left(1 - \frac{\delta}{(1+i)^T}\right)\left(\sum_{t=0}^{T'} \frac{GI_t}{(1+i)^t}\right).$$

Once the infrastructure has been built, the provision of high-speed rail services involves two types of costs: those related to the maintenance of the infrastructure itself and those associated to the provision of the services (i.e., acquisition, operation and maintenance costs of rolling stock).

According to (11), annual maintenance costs of infrastructure are denoted by I^M which are considered independent of the traffic volume, because they only depend on the line length, $I^M = cmk^I \cdot L$, where cmk^I is the maintenance cost per kilometre. According to Campos *et al.* (2008), a reasonable value of this parameter for Spain would be around 35,000 euros per kilometre and year, making the annual cost for a line of 500 kilometres line around 17.5 million euros.

In the case of the acquisition costs of the rolling stock (c^A) raised in expression (11), it must be taken into account – as discussed in footnote 7 – that they are being considered the unit cost per traveller and not by train; therefore, it is not easy to obtain appropriate references on its value. In France, according to UIC data (UIC, 2005), there is reliable information about total acquisition values for different models of train (TGV *Réseau*, TGV *Dúplex*), these values are around 50,000 euros per seat, what implies that a train of 350 seats costs a minimum of 17 to 18 million euros. However, factors such as the inside design, technical specifications and other characteristics may change the price dramatically. Thus, and although the range of variation can be high, an initial estimation of the unit cost c^A, can be between 25 and 40 euros per passenger and year for an intensive use of between 300,000 and 500,000 passenger per train and year.

The estimation of unit costs for operation and maintenance of rolling stock is less difficult due to the existence of better information. Thus, Campos *et al.* (2008) shows that the average operative cost per seat is around 53,000 euros, with little dispersion between countries, so that the cost per a train of 350 seats (c^O) would be 18.55 million euros per year.[10] The equivalent figure for the maintenance costs (c^I) would be 1 million euros per train and year, assuming an average use intensity of 500,000 kilometres per year.

3.1.2. Modelling the users' cost

As discussed above, the users' generalized cost (g) includes the price of each trip (p), total travel time (τ) valued by each passenger and a set of additional factors (ε) globally related to the 'quality' of each mode, which will not be considered in this case. In principle, since our analysis is based on a hypothetical corridor it is difficult to estimate a value for the generalized cost; however, using as a reference information from Madrid-Barcelona corridor in Spain (620 km) and adjusting it to 500 km line, Table 1 shows reasonable estimates for p_m and p^I (*HSR*), taking into account differences in vehicle types.[11]

Mode	**Vehicle (Company)**	**Price (620 km)**	**Estimated price (500 km)**
Airplane (*a*)	Boeing 757 (IBERIA)	30 – 160 €	24 – 130 €
Bus (*b*)	Eurobus (ALSA)	25 – 45 €	20 – 36 €

[10] This value primarily includes labour costs and energy, as well as the proportion of the overall cost of administration and service management.
[11] Recall that, according to the avoidable costs assumption in (10) (i.e., all operators in alternative modes have normal profits in the corridor and all their costs are recoverable), we consider that $p_m = c_m$, i.e. a 100% degree of cost coverage in all the alternative modes.

Car (*c*)	Medium-sized car	85 € (*)	68.5 €
Conventional rail (*r*)	*Alvia Train* (RENFE)	60 – 100 €	48 – 80.5 €
High speed rail	*AVE Train* (RENFE)	70 – 150 €	56 – 121 €

Source: AENA (2006) and own elaboration. (*) Includes tolls and fuel consumption.

Table 1. Price estimates per mode (one way trip, 2006)

With respect to total travel time – including time spent in the vehicle, access time and waiting time – it can be estimated using a similar approach, although in this case we have in Table 2, more detailed information on several Spanish corridors and their exact travel time for different modes. This allows us to calculate in the last two rows, the average speed of each mode and extrapolate it to a line of 500 kilometres.[12]

Line [length]	AVE	Plane	Road*
Madrid - Granada [430 km]	3:25	2:37	4:18
Madrid - Malaga [540 km]	2:40	2:24	5:24
Madrid - Cadiz [660 km] (Jerez)	3:30	2:24	6:36
Madrid - Valencia [350 km]	1:40	2:14	3:30
Madrid - Alicante [420 km]	2:00	2:22	4:12
Madrid - Barcelona [620 km]	2:45	2:30	6:12
Madrid - Bilbao [395 km]	2:25	2:22	3:57
Madrid - A Coruña [600 km]	3:55	2:29	6:00
Madrid - Badajoz [390 km]	3:00	2:20	3:54
Average Speed (km/h)	**180 km /h**	**170 km /h**	**100 km /h**
Estimated time for 500 km	**2.77 hours**	**2.94 hours**	**5 hours**

Source: AENA (2006).

* In road transport (car) is assumed a constant speed of 100 km/h.

** An hour and a half is added to bus (6.5 hours).

*** Total time in AVE is multiplied by 1.5 times for conventional rail.

Table 2. Total travel time by mode: different corridors

[12] Although it is generally assumed that *HSR* services run at speeds exceeding 250 km/h, the average commercial speed is much lower because of intermediate stops and traffic restrictions. In the case of the airplane, we must include access time to the airport and hence, the average speed is further reduced.

Once the travel time for each mode has been estimated it is finally necessary to define the value of time (v_m) that will be used in the valuation of time savings from diverted traffic to *HSR*. Although the value of time is one of the critical parameters in the appraisal of any transport project, it cannot be obtained straightforwardly, because it depends on specific factors such as type of user, travel purpose (work, leisure,…), frequency, period of the day, year, etc. For this reason, and in order to simplify our analysis we initially consider that v_m is an average value, common to all transport modes and users and it has an (initial) constant value of €15 per hour. This simplification is removed later in order to introduce uncertainty in our model.

3.1.3. Demand parameters

The final set of parameters that are needed to solve model are those related to the demand characteristics. We must first determine what percentages of diverted traffic to *HSR* come from each alternative mode, i.e., the β-parameters in expression (17). For example in the Madrid-Seville corridor, the introduction of the high-speed rail in 1992 reduced the demand of air transport by 30-40%, decreasing the load factor and flight frequencies. The conventional rail transport was also affected by the introduction of new services (Madrid-Seville, Madrid-Malaga and Madrid-Cordoba), that were among the rail operator (RENFE) main lines before 1990. Today, these lines have lost most of its traffic, while the effects on the road transport have been less significant. Globally speaking, and taking a conservative approach using the data from other existing high-speed lines (Madrid-Saragossa or Madrid-Barcelona), it could be considered that diverted traffic ratios percentages may be safely given by 75% (from conventional rail to *HSR*), 20% (from airplane), 4% (from car users) and 1% (from bus passengers). Using these shares (s_m), and selecting the airplane as the reference mode, β_m parameters are determined by the ratio:

$$\beta_m = \frac{s_m}{s_a}.$$

With respect to the generated traffic, this is estimated – according to (8) – as a proportion of diverted traffic. In particular, we consider a reasonable α=0.10. Finally, the annual growth rate of demand (θ) is assumed constant throughout the life of the project, and equal to 3%. The following table summarizes the values assigned to the main parameters of the model.

Parameter	Notation	Value	Unit of measure
Line length	**L**	500	Kilometres
Last year of the construction of the project	**T'**	5	Year
Last year of the project	**T**	40	Year
Average capacity of each train	$\bar{q}$	350	Seats
Load factor	λ	80%	%
Hours of operation	**H**	18	Hours
Unit construction cost per kilometre	ckm	20,000,000	€ /km
Proportion of the residual value of the infrastructure	δ	10	%
Unit maintenance cost of the infrastructure	ckm^I	35,000	€ / km
Unit acquisition cost of the acquisition of rolling stock (per passenger)	c^A	30	€ / passenger
Unit operative cost of rolling stock (per train)	c^O	18,500,000	€ / train
Unit maintenance cost of rolling stock (per train)	c^I	1,000,000	€ / train
Average price of a high speed trip (one way)	p_I	88.5	€
Average price of a plane trip (one way)	p_a	77	€
Average price of a bus trip (one way)	p_b	28	€
Average price (operative cost) of a car trip (one way)	p_c	68.5	€
Average price of a conventional train trip (one way)	p_f	64.25	€
Avoidable average costs (plane)	c_a	77	€
Avoidable average costs (bus)	c_b	28	€
Avoidable average costs (car)	c_c	68.5	€
Avoidable average costs (conventional train)	c_f	64.25	€

Table 3. Summary of the values of the main parameters of the model

Parameter	**Notation**	**Value**	**Unit of measure**
Total travel time on high speed rail	τ^{I}	2.77	Hours
Total travel time by plane	τ_{a}	2.94	Hours
Total travel time by bus	τ_{b}	6.5	Hours
Total travel time by car	τ_{c}	5.0	Hours
Total travel time on conventional rail	τ_{f}	4.15	Hours
Value of time (high speed rail)	v^{I}	15	€ / hour
Value of time (plane)	v_{a}	15	€ / hour
Value of time (bus)	v_{b}	15	€ / hour
Value of time (car)	v_{c}	15	€ / hour
Value of time (conventional train)	v_{f}	15	€ / hour
Diverted traffic from plane	s_{a}	20	%
Diverted traffic from bus	s_{b}	1	%
Diverted traffic from car	s_{c}	4	%
Diverted traffic from conventional rail	s_{f}	75	%
Ratio of generated traffic with respect to diverted traffic	α	10	%
Annual rate of growth of demand	θ	3	%

Table 3. Summary of the values of the main parameters of the model (cont.)

3.2. Evaluation results

3.2.1. Calculating the initial demand thresholds

From the values of the parameters in Table 3 it is straightforward to compute the expressions derived in Section 2 using a standard worksheet. In particular, with the proposed values and a discount rate of 5% we get the following results with respect to the initial demand (when it starts the operation period $t = 6$) that at least guarantees a *SNPV* equal to zero.

Diverted traffic:	16,702,817 passengers
from the airplane:	3,340,563 passengers
from the bus:	167,028 passengers
from the car:	668,113 passengers
from the conventional train:	12,527,112 passengers
Generated traffic:	1,670,282 passengers
Total required demand:	18,373,098 passengers

Table 4. First year demand requirement for a socially profitable HSR line

These figures show that if the total annual demand in the first year is less than 18.3 million of passengers, the project will not be socially profitable. It is obvious that this is just an approximate figure conditioned by the assumptions about the parameters of the model. However, from a methodological point of view our analysis still remains useful because it provides a simple procedure to classify and rank different project alternatives in the 2009-2020 horizon, according to the expected demand.

Results in Table 4 are changed if the reference parameters do so. For example, if we modify the assumptions with respect to the origin of the diverted traffic – assuming, for example, that *HSR* captures most of diverted traffic from air transport (95%) and road transport shares remain the same (car, 4%; bus, 1%),[13] the total minimum demand threshold would increase to 21.7 millions of passengers, out of which 18.7 million would come from the airplane. This increase is due to the reduction of the time savings: given the existence of less time savings in the airplane than in the conventional rail it would be necessary to attract a larger number of travellers to offset the social costs of the project.

Similarly, it is possible to make different types of sensitivity analysis on the model parameters, some of which are summarized in the following table.

[13] This would be the case of a high-speed line built on a new route where conventional rail did not previously exist.

	Diverted traffic	**Generated traffic**	**Total demand**
Initial situation	16,702,817	1,670,282	**18,373,098**
Increase of train capacity ($\overline{q}$ = 450 seats)	13,284,484	1,328,448	**14,612,932**
Reduction of the load factor (λ = 60%)	27,202,245	2,720,225	**29,922,470**
Increase of the construction (*ckm* = 30 mill.)	24,840,191	2,484,019	**27,324,210**
Reduction of the construction cost (*ckm* = 15 mill.)	12,634,130	1,263,413	**13,897,543**
Reduction of the acquisition cost of trains (c^A = 15 €/ pas.)	10,494,766	1,049,477	**11,544,243**
Increase in the value of time (v = 30 €/h)	9,971,601	997,160	**10,968,761**
Reduction of the demand rate of growth (θ= 1%)	21,873,643	2,187,364	**24,061,007**

Table 5. Sensitivity analysis of the model results

3.2.2. A step further: the model under uncertainty

Although the sensitivity analysis procedure is fairly standard, the usefulness of the results in Table 5 is limited because they are built upon a *ceteris paribus* approach. Only one parameter is changed in each case whereas the rest remain unchanged. What happens when the project is simultaneously affected by several sources of uncertainty? In this case, an alternative approach consists in identifying the parameters and variables in Table 3 whose exact values are unknown by the analyst and model them through explicit probability distributions (normal, uniform, triangular, etc.) depending on the known range of values. Under this approach, the expressions of the *SNPV* used in Section 2 should be now viewed as the *expected value* of the *SNPV*. The initial demand threshold is also a random variable and, therefore, the results in Tables 4 and 5 can be given in terms of probability distributions.

Just to illustrate these ideas, consider for example the case of the value of time (*VoT*). As noted above this is a critical variable in the project appraisal literature. However, in most cases its specific value is very difficult to determine, either because of lack of information about the current and future users (a detailed survey could be carried out, but this is very expensive and often unpractical) or because the transposition of values from other (previous) projects is always imperfect. In any case, we can now consider that, instead of setting a deterministic value (€15, according to Table 3), the *VoT* is distributed between €5 and €30 according to a triangular probability distribution. After this, and using a suitable worksheet, the calculations in our model can be repeated several times to obtain the probability distribution of the initial demand.

Figure 1 shows this probability distribution, obtained after 5,000 iterations in the computations of the previous model using @RISK software. As it can be seen, the average value approximates to the one obtained in the first row of Table 4 although it does not exactly coincide because this figure is the result of a simulation process. The interpretation of the figure is immediate: to guarantee a *SNPV* > 0 our project should attract a minimum number of passengers during the first year of between 12.5 and 25.9 million. This result is valid with a probability of 89.5%. Interestingly, note that there are no limits to introduce additional sources of uncertainty in the model and even that correlations between those sources could be properly taken into account.

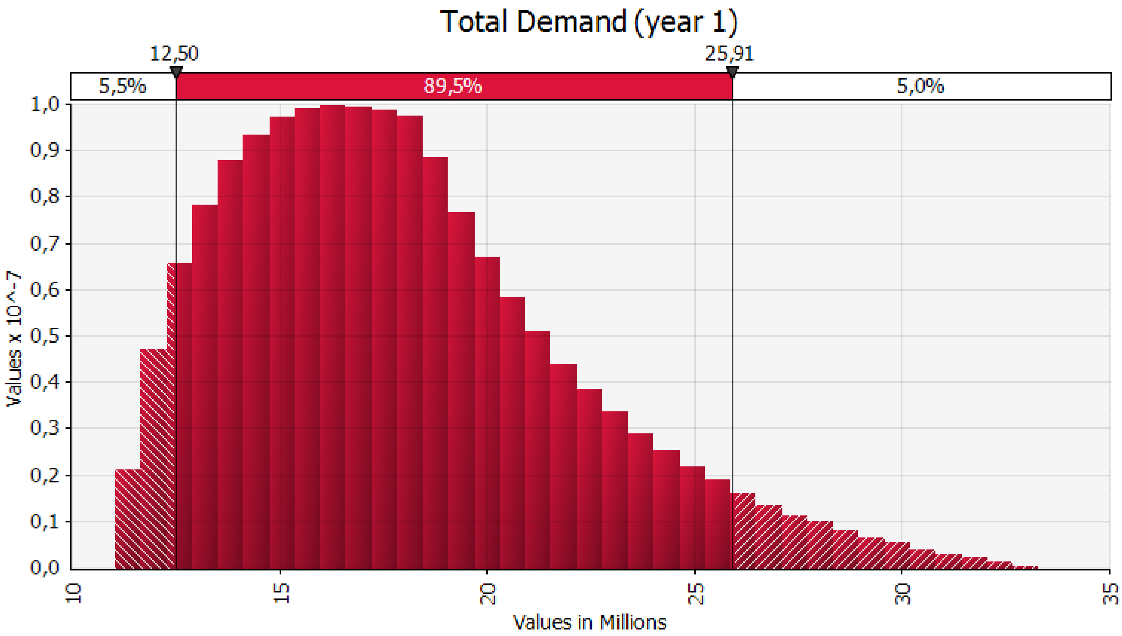

Figure 1. Probability distribution of the initial demand (total)

From a methodological point of view, the utility of this approach is self-evident: the decision of accepting or rejecting a particular investment project is carried out taking into account the demand uncertainty and other sources of uncertainty simultaneously, involving a margin of error into the decision that can be set *ex–ante* by the analyst. Ultimately, it is a more complex approach to *CBA*, but also more realistic.

4. Conclusion

High-speed rail is widely reckoned as one of the most significant technological breakthroughs in passenger transportation nowadays, but building, maintaining and operating *HSR* lines is very expensive and their potential benefits are always subject to great deal of uncertainty, particularly on the demand side. In this context, the aim of this paper has been to extend received *CBA* methodology in order to develop some new procedures to detect the circumstances under which such proposals might be socially worthwhile.

Our approach departs from traditional *CBA* but changes its perspective: since demand uncertainty is the critical variable to accept or reject most rail projects, we transform the traditional *SNPV* > 0 acceptance criterion into a 'demand-driven criteria' and thus obtain different values for this critical demand under alternative simulated scenarios. What is wanted is to select (or rank) projects according to their real demand, finding the minimum traffic threshold (in the year of entry into service) which guarantees a positive social profitability. To achieve this goal we defined a reference hypothetical project that involved the construction and operation of a high-speed (new route or improvement of an existing conventional line). From here, and expanding in full detail the traditional the expression of social NPV we derived an assessment model that allows us to obtain that minimum demand threshold.

Under the appropriate simplifying assumptions, this model can be easily implemented (and suitably changed, if needed) according to the analyst's needs. It is basically a methodological tool to provide a quick reference regarding the size of the corridors where *HSR* projects are socially viable or not. Our results show, just as an example, that under reasonable assumptions extracted from previous experiences the minimum demand necessary to ensure a positive social return can be placed around 18.3 million passengers (in the first year), a figure that is substantially higher than any of the projects currently discussed in Spain (or even in Morocco). However, the relevance of this exercise does not lie in this value, but into the methodology itself. A particularly important additional element that is also worth noticing here is the possibility of introducing several sources of uncertainty in the estimation of demand thresholds, which is a novelty with respect to previous literature.

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