LCC APPROACH FOR HIGH-SPEED BALLASTLESS TRACKS

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PREFACE

The first academic semester of 2014, I took a course in KTH-Stockholm related to railways, led by Anders Lindahl, which I enjoyed largely due to the teacher's implication on it. At the same time, I chose a high-speed platform design as final master degree project in The Polytechnic University of Madrid which I carried out during 2014-15. Thus, I decided to tell my project to Anders in order to look for a Master's thesis in the same field. Moreover he introduced me to Michael Than, an engineer from Sweco company, who found me a place to sit in the company and also helped me in the costs data compilation and gave me advices from his large experience. Anders has been constantly helping and encouraging me through meetings and corrections whenever he was. I would like to thank them for their time and knowledge shared with me.

The development of this research has not been an easy path due to mostly the difficulty to obtain reliable data. Furthermore, as this research contains an economic base and a method used in the Spanish project I would like to thank for their technical help both to my Spanish supervisor, Ricardo Lorenzale, and to my uncle, Ildefonso González.

Finally, singular thanks to my family for their economic support and understanding during my studies but especially during these last two years in Stockholm.

Stockholm, August 2015

Irene Serrano

ABSTRACT

An approach of life cycle cost analysis (LCCA) for high-speed ballastless tracks in Spain is carried out in this document based on an approximation of the present value behaviour through the Electre II Multi criteria method. A review of other LCC researches has been done analysing their results in order to adapt previous experimental tracks costs to the present study which is focused on construction and maintenance costs in Spain. Even though several ballastless systems are introduced and analysed in terms of costs, and environmental impacts; only four of them are deeply compared with ballasted tracks: Japanese Shinkansen, Rheda 2000, EDILON embedded rail system and LVT. The comparisons are established using ratios (ballastless/ballasted track costs) instead of total costs due to their lack of validation among countries and years. Furthermore, two case studies have been presented: one using 3% as discount rate which favours ballastless choice and another using 6% which in contrast, favours the traditional option. Last chapter aims to compare results from the presented method with proper present value calculations during 60 years in the Ballasted Madrid-Seville line (Spain).

El presente documento recoge un análisis del coste de ciclo de vida en vías en placa para alta velocidad aplicado a España. Este análisis se basa en la aproximación del comportamiento del valor actual (VA) de estas vías en comparación con las vías tradicionales de balasto a lo largo de 60 años y mediante su similitud con un método multicriterio en el que se asignan pesos a distintas variables, Electre II. Se han tenido en cuenta estrictamente costes de construcción y mantenimiento de la vía japonesa Shinkansen, EDILON carril embebido, LVT y Rheda 2000. Costes de vías de alta velocidad de todo el mundo han sido la base de este estudio adaptando los datos para territorio español. Cabe remarcar, que se ha trabajado con ratios de costes (vía en placa/vía de balasto) y no se han utilizado costes totales por su poca validez para comparar entre países y en el tiempo distintos tipos de vía. Además, la comparación se ha llevado a cabo con dos tasa de descuento para estudiar su influencia, 3% que da resultados beneficiando a la vía en placa y 6% que beneficia a la vía en balasto.

En el último capítulo, se ha querido contrastar los resultados de VA usando los ratios aproximados de costes obtenidos durante el estudio y los VA más exactos con ayuda de Excel de la línea Madrid-Sevilla (España).

CONTENT LIST

GLOSSARY

ASL Asphalt Supportive Layer

BB Slab Track Belfour Beatty
"Balfour Beatty Rail has developed the Embedded Rail System (BBERS) to improve rail performance and reduce life cycle costs. The system is suitable for all traffic, from high speed, heavy freight, to metros or light rail" (Balfour Beatty , n.d.)

CENIT Centro de Investigación del Transporte (Transport Investigation Centre)

CSL Concrete Supportive Layer

FPL Frost Protection Layer

FST Floating Slab Track
A floating slab track is a track system constituted of a reinforced concrete slab supported by a resilient layer (D2S International, n.d.).

HBL Hydraulically-bonded layer

HSR High Speed Railway

IM Infrastructure Manager

LCA Life Cycle Assessment
Life Cycle Assessment (LCA) is a "tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle" (United Nations Environment Programme, n.d.)

LCC   Life Cycle Cost
LCC is an "Economic assessment of an item, system or facility and competing design alternatives considering all significant costs over the economic life, expressed in terms of equivalent currency unit" (Stephen & Dell'Isola, 1995)

LCCA Life Cycle Cost Analysis
Life-Cycle Cost Analysis is a process for evaluating the total economic flows of a project by analyzing initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs over the life of the project (Federal HIghway Administration, n.d.)

MCA Multi-criteria Analysis

Multi-criteria decision-making methods is "a branch of research models that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems" (Wang, et al., 2010).

MGT Million Gross Tonnes

NPV Net Present Value
Net Present Value is "a measure of discounted cash inflow to present cash outflow to determine whether a prospective investment will be profitable" (Free dictionary, n.d.)

PCA Portland Cement Association
The Portland Cement Association (PCA) is "a powerful and vocal advocate for sustainability, jobs creation, economic growth, infrastructure investment, and overall innovation and excellence in construction throughout the U.S. " (Portland Cement Association, n.d.)

RAMS Reliability, Availability, Maintenance and Security

RCRS Reinforced Concrete Roadbed Slab
The RCRS is "a current version of slab track for at-grade application. Since 1990, the RCRS system has undergone experimental testing and monitoring and has been used on the Hokuriku Shinkansen line" (N. Bilow, et al., n.d.)

UIC
European gauge or standard gauge.

1. INTRODUCTION

1.1   BACKGROUND

It was in 1925 when a train needed to pass through a tunnel in Japan or when high speed trains (220 km/h) started to be designed around 1964, when an innovative track composition (slab track) was thought for these new requirements. Slab track provides a system with a composition made of a continuous layer or isolated blocks of concrete or asphalt instead of using ballast. Although those might be the upper layers, elastic and dampening materials are placed below to obtain suitable results. The main goal of this system is the no need of maintenance at all remaining the same dynamic behaviour as ballasted tracks which directly implies a higher availability of tracks. Furthermore, ballastless tracks contribute to increase security avoiding the interaction of ballast between wheel-rail (churning).

Currently, the positive Japanese experience of slab tracks, the need for more tunnels in high-speed lines and the urge to save the environment drive us to take into account the use and research of slab tracks. As an example of this, in Germany there are 7,400 km of slab tracks already built; 2,700 km in Japan; in Taiwan 700 km for high-speed lines and in Malmö (Sweden) 12 km.

However, a careful and detailed life cycle cost analysis (LCCA) must be done in order to achieve a suitable balance between investment and maintenance due to large differences in costs between both systems.

LCC is defined as an "economic assessment of an item, system or facility and competing design alternatives considering all significant costs over the economic life, expressed in terms of equivalent currency units" (Stephen & Dell'Isola, 1995). Researches from all over the world have been comparing ballasted and ballastless tracks in terms of costs obtaining often wide and opposite range of results.

Although ballastless tracks have been introduced as one system, there are certainly many different ways to combine concrete or asphalt with elastic materials in order to be able to adapt a track to specific soil conditions achieving similar results. Examples of different slab track systems are: Rheda, Shinkansen, Bögl, LVT or Edilon. Then, more difficulties arise in this choice due to the fact of lack of experience in most of them and high production costs.

Recent research has recommended further studies in ballastless systems especially in their structural stability, their maintenance need and overall their cost analysis in order to develop it efficiently (Michas, 2012).

1.2   PURPOSE

The purpose of this research is to provide decision-makers with a new and simple approach of life cycle cost analysis in order to facilitate future developments towards decreasing costs in high-speed railways.

1.3   AIM OF THE STUDY

This report aims to compare different slab track systems for high-speed lines such as: EDILON embedded rail system, Shinkansen, Rheda and LVT in terms of LCC. It is an analysis of construction and maintenance costs behaviour during 60 years-life of a railway track based on previous experience. Besides, the influence of environmental impact from each system is evaluated as well as the influence of the chosen discount rate.

Last chapter contains a practical comparison in the Madrid-Seville line between approximated present value based on the method of this report and exact calculations.

1.4   METHOD

LCCA is approached in this report with an adapted cost-benefit method, Present Value. An approximation of Present Value calculations has been carried out through the Multi Criteria Analysis steps of Electre II method. Fixed total costs are not used in this research. Instead, the relation between ballastless and ballasted track costs is used for the study.

1.5   REQUIREMENTS, CONDITIONS AND LIMITATIONS

✓ One ballastless track cycle of 60 years is used for this study which is also two ballasted track cycles. Thus, construction costs are added once for the first type of track and twice for the ballasted one regardless construction costs in year 60.

✓ This study is closer to double passenger tracks than freight and passenger ones due to the fact of experimental data are from those kinds of tracks. Besides the application shown in last chapter is also a passenger line exclusively.

✓ Results from this study are suitable for speed between 200 and 300 km/h.

✓ Among the two factors stated to have more influence when choosing a track, traffic tonnage and maintenance strategy, maintenance strategy is the one which has been taken into account in the report. Traffic tonnage data from experience has not been compiled (CEDEX, 2009).

Railway field involves great number of activities, materials, companies and countries which make tremendous hard to compile information and even more to achieve conclusions (Figure 1). Therefore, the limitations of this report are summarized as follow:

- Only construction and maintenance costs are part of this study. The costs ratios used in the research are subjective but based on experience. Even though the data are often 20-25 years old and prices have varied since that moment, the advantage of using ratios is mainly that costs variations such as inflation or different prices among countries influence technically equally to both terms of the equation (ballasted and ballastless track costs).
- Maintenance costs are not taken into account per year in the approximated method. Instead, they are once located during 60 years depending on the maintenance rates of the systems. This approximation might vary the results as the last chapter shows from the practical comparison in Madrid-Seville line but it has thought to be accurate enough to use it for the study.
- No economic benefits are included in the study.
- No financial strategies are taken into account since they influence equally to any track.
- The study includes two cases of discount rate, 3% and 6%, which are two extremes but it does not include anyone between them.
- The steps of Electre II Method have been used to develop the study. Nevertheless, the scoring and weighting step does not fulfil rigorously a multi criteria analysis. It has been decided by the author in order to be closer to the Present Value calculations.
- Neither sensitivity analysis nor Monte Carlo simulation has been carried out although they are recommended to approach unknown parameters (Flanagan & Norman, 1983).
- No differentiation among costs in tunnels, earthworks or viaducts has been done in the present research. It is assumed that depending on the type of ballastless track used, the conditions are more or less suitable. As well, the ratios presented might vary greatly overall in earthworks for ballastless tracks.

Furthermore, the main limitation has been the lack of unicity of the data from experience.

It is clear that the regulations, land cost, labour cost or laws are very different from a country to another. This fact makes a huge disadvantage when comparing projects in terms of costs, especially in the railway industry. The first step to try to fix this problem is to be aware on how and how much those differences influence in total costs. Some requirements when doing a proper LCCA are (Gleave, 2004):

- Normally, financing costs and rolling stock are not included. However and according with Steer Davies project, management and station costs should be included.
- It is of great importance differences in land costs among the countries. For example, southern European lands are cheaper than Nordic countries, UK or Japan. Meanwhile this seems to have big impact in costs, land costs are only 5% of the construction costs.

- Regulations and approval processes differ also adding some difficulties in countries for instance UK or Germany but Spain.
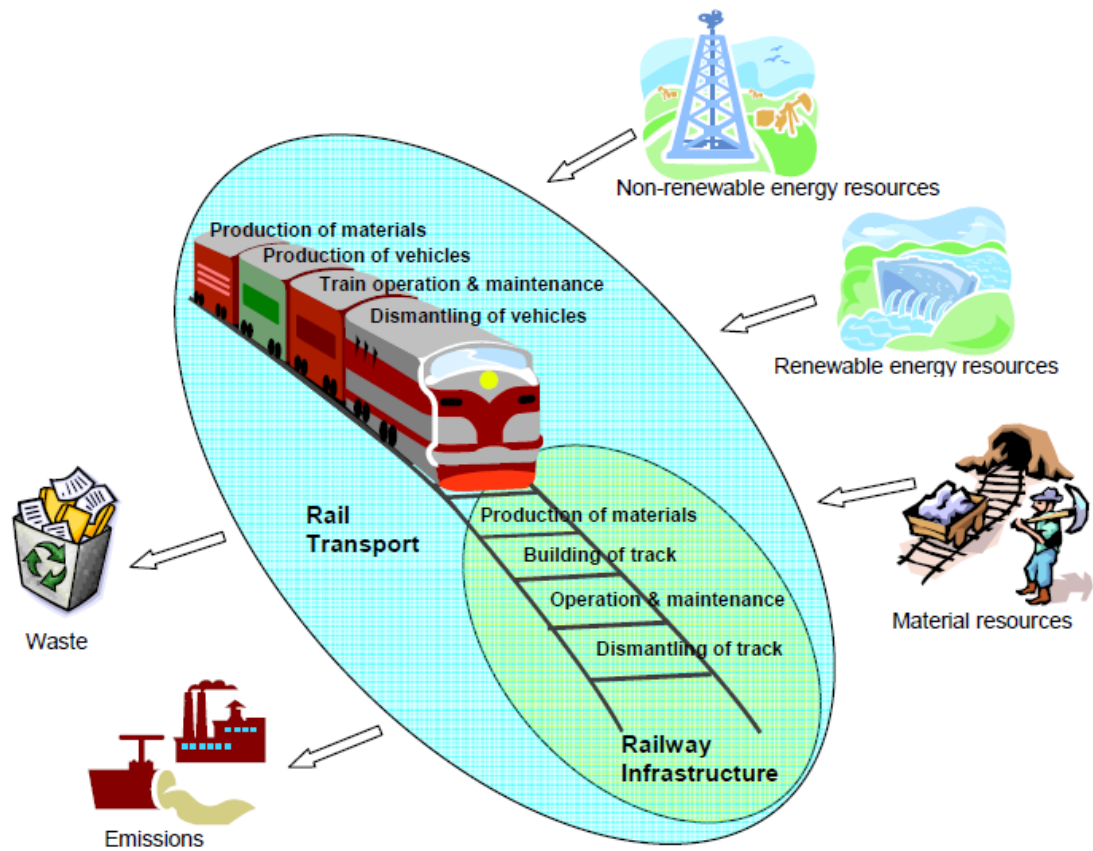

Figure 1. Fields influencing railway industry (Stripple & Uppenberg, 2010)

2. LITERATURE REVIEW

Most of the researches that have been carried out refer to general features of slab track comparing to ballasted track. There is a wide range of opinions, data and conclusions that often differ depending on who is the researcher or the outcome for. Hence, reviewed researches have been compiled in this chapter in order to give an idea of the current situation concerning life cycle cost analysis in the railway industry.

❖ LCC studies

A study supported by UIC and Esveld, which includes different kinds of slab track compared with ballasted track, states the difficulty of taking a broad view of conclusions in the costs field. There are too many variations and also difficulties to transform for example track availability into economical units or influence of social policies. Due to this fact, the study is only a guidance of costs.

In one hand, a first conclusion is that installation of slab track on earthworks is much more expensive than in tunnels. Actually, there is a large range since slab track earthworks costs might vary between 1.3 and 3 times more expensive than ballasted being reduced that range in tunnel installation from 1.1 to 1.5 (REN, et al., 2008).
Same source states that especially in tunnels the fact of larger transversal section in ballasted tracks can raise the price of the track to 50% as well as other extra requirement such as under-ballast mat to obtain the suitable elasticity or measures for noise vibration. Moreover, if a tunnel track design is decided from the beginning to be slab track it will be even cheaper due to that special alignment features are taken into account that benefit ballastless use.

On the other hand regarding maintenance costs, the authors state that factors such as tonnage, speed and the maintenance approach to achieve high reliability, availability and security (RAMS) are the key points influencing the costs. Hence, no specifications are given due to these big uncertainties (UIC , 2002).

Based on these assumptions, which they were applied to the HSL-S line (Netherlands), the following results were obtained. They are also showed graphically in Figure 2 (Esveld, 1999):

- ERS-INT, (Embedded Rail System integrated into the concrete substructure) was obtained to be the cheapest system both in initial costs and annual costs including construction, maintenance and additional costs. Approximated values of its construction and maintenance costs have been used in the present study.

- Rheda system appeared to be the most expensive concerning initial investment as well as traditional ballasted track for HS concerning annual costs. Approximated values of construction and maintenance costs have been also used in the present study.
- A range of between 15-20 years was suggested for the ballastless costs to be equal to the ballasted ones.
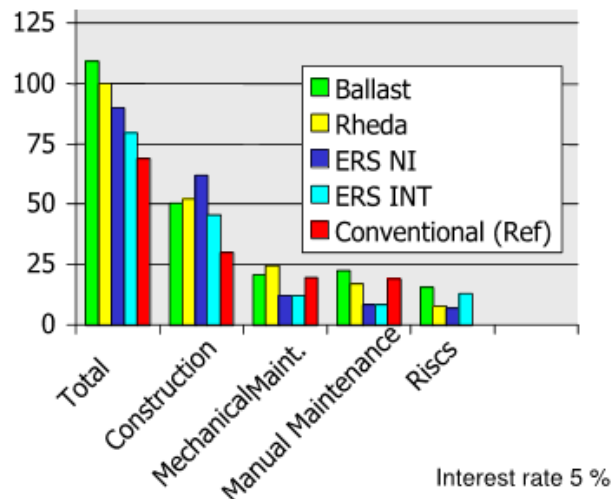

Figure 2. NPV analysis in EUR/m excluding the concrete slab (Esveld, 1999)

Especial attention has to be paid to the interest rate that has been used (5%) due to the fact that it makes a remarkable difference in present value calculations as it is explained in the following chapter. This interest rate is rather high so it favours beforehand ballastless tracks results.

Furthermore, it is interesting that Miodrag (Budisa, n.d.) bears out through the graph below that ERS-INT is also the cheapest concerning construction costs (exclud. the concrete slab) including in his study the Shinkansen model and Belfour Beatty (BB) Slab Track whose annual costs are equal to ERS-INT though (Figure 3).

Cost estimate	Construction	Annual Cost
▪ Conventional ballasted track	USD 1,037	USD 125
▪ Wide Tie	USD 1,195	USD 102
▪ Sinkansen	USD 1,345	USD 114
▪ Edilon	USD 1,315	USD 114
▪ Rheda	USD 1,315	USD 114
▪ Balfour Beatty	USD 1,400	USD 91
▪ Slab track ERS Integrated	USD 943	USD 91

Figure 3. Summary of costs for the superstructure, excluding the concrete slab in USD/yd (Budisa, n.d.)

According to a research carried out by The Delft University of Technology, 3 km test-track ERS system installed in Netherlands required 20% fewer costs than the traditional ballasted track. Although this data has not been taken into account in this study since it concerns to a single track and excludes the subgrade and ground stabilization works, the figure below shows the results from this research which could be interesting for the reader. The final conclusions from this report are as follow (ZOETEMAN & ESVELD, n.d.):

✓ Construction costs for ERS were 40% higher than ballasted track.
✓ The total discounted life cycle cost calculated for ERS was 20% lower than the ballasted track (no specification of discount rate).
✓ Rail renewal was not needed in the time of the analysis.
✓ Inspection and rail grinding costs are not included.
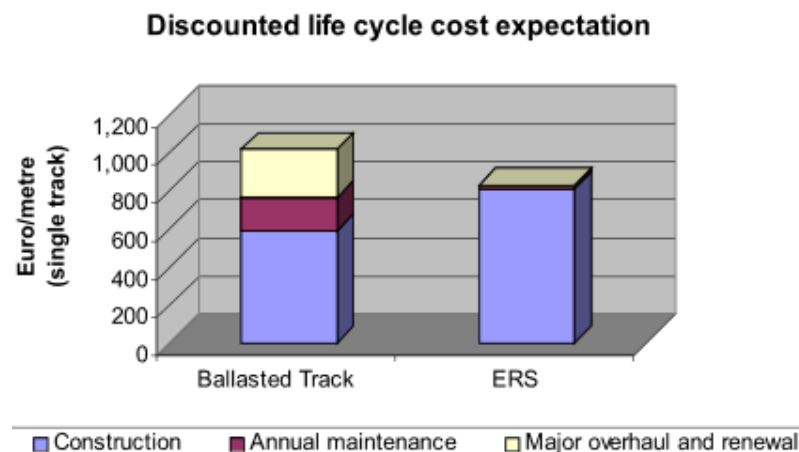
Figure 4. Outcome from the analysis in HSL-S (ZOETEMAN & ESVELD, n.d.)

A LCC study carried out by PCA using EcoSlab computer program aimed to compare two kinds of track structure: Direct Fixation Slab Track (DFST) and Independent Dual Block Track (IDBT) or LVT with conventional ballasted track for high-speed. Three prototypes were used varying freight volume and speed passenger trains and differences in the outcome have been found as follow (Kondapalli & Bilow, 2008):

✓ A ratio of 1.1 was achieved comparing ballasted track and slab track construction cost per mile (=1.6093 km). This ratio includes a moderate subgrade preparation.
✓ Only 0.38 of the labor force costs of ballasted track were needed for the slab track per mile (=1.6093 km).
✓ Costs for rail replacement, tie installation, fastener replacement (5.846 slab track more expensive), tie abrasion repair, rail grinding etc…are also included in the study but these specific results are out of the limits of this research.

Conclusions from this study hold that through identifying and quantifying the major variables, accurate present value calculations can be obtained. Furthermore the following results were obtained through a sensitivity analysis:

✓ The net benefit of slab track is linearly related to an increase of traffic tonnage. Particularly, if the tonnage is decreased by 8%, the net benefit of slab track is assumed to decrease by 5%.
✓ A slab track life increase up to 40 years is expected to involve an increase in the net benefits.

In Figure 5, the result of a prototype which mix moderate freight and 200 MPH (321.86 Km/h) passenger trains is shown using EcoSlab. This prototype is the one which has obtained the highest savings in terms of life cycle costs (11%) comparing with others situations that involves less speed or only freight.

Numerical results from this study have not been considered in this report since they are general to any slab track.
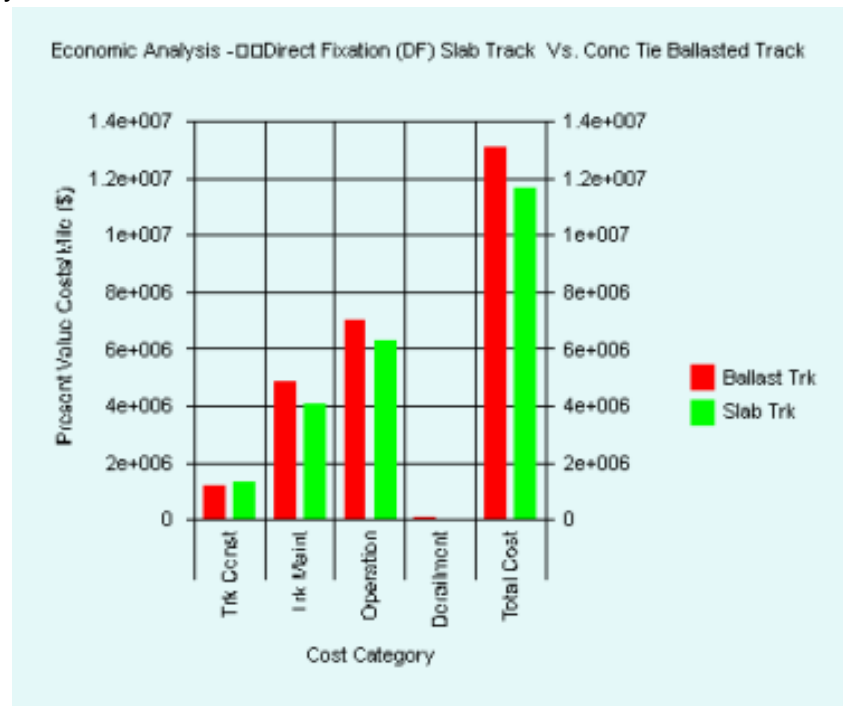
Figure 5. Results from PCA study. Direct Fixation Slab Track vs. Ballasted track (Kondapalli & Bilow, 2008)

An important Spanish research has been reviewed which was carried out by CENIT (The Innovation Transport Center). The research focuses on the analysis of the costs both in high-speed ballasted and slab tracks in the mid-long term. It is divided in four parts as follows:

- The first chapter contains a complete analysis of the construction costs of a new ballasted and ballastless track including also data from different experiences in the

world which have been put together in the report as literature review (CEDEX, 2008a).
- The second chapter structure is similar to the first one with maintenance costs instead (CEDEX, 2008b).
- During the third and fourth chapter a method to analyse life cycle costs is developed. It aims to compare different parameters which differ from one structure track to another without obtaining exact costs. It is important to denote that the research has been made only for tracks supporting passenger trains (CEDEX, 2009).

Relevant conclusions that have been found which involve all kinds of ballastless tracks for passenger lines are (CEDEX, 2009):

- Although the financial strategy is crucial in order to lower the construction costs, same strategy affects proportionally to both kinds of tracks. Therefore, it is not a distinct parameter. Due to this fact, the construction costs can be added in year 0 of the analysis. This assumption has been used for the PV approach in this report.
- Regarding maintenance costs in high-speed lines, the most influence factor were predicted to be the traffic volume on it and the maintenance strategy. However, factors such as maximum speed, axle-load, or length of a tunnel do not make difference among different structures.
- There is a lack of data in terms of material renewal which definitely implies change in costs.
- There is a need of continuously revising data since the costs and ratios might change by the years.
- There are many variables which are complex to measure such as availability, possibility of using the same track for future improvements and the well-known variety and controversial data.

The research concludes suggesting the Figure 6 which shows that depending on the gross ton/day a track has to support, there is higher or lower probability to success choosing ballastless or ballasted track. Different colours in Figure 6 mean:

- VP Esc 1 (blue line): it represents the worst scenery for ballastless track
- VP Esc 2 (yellow line): it represents the best scenery for ballastless track
- VB Esc 1 (red line): it represents the best scenery for ballasted track
- VB Esc 2 (green line): it represents the worst scenery for ballasted track

Then according with the conclusions of the study and with Figure 6, table 1 represents with numbers the same results.
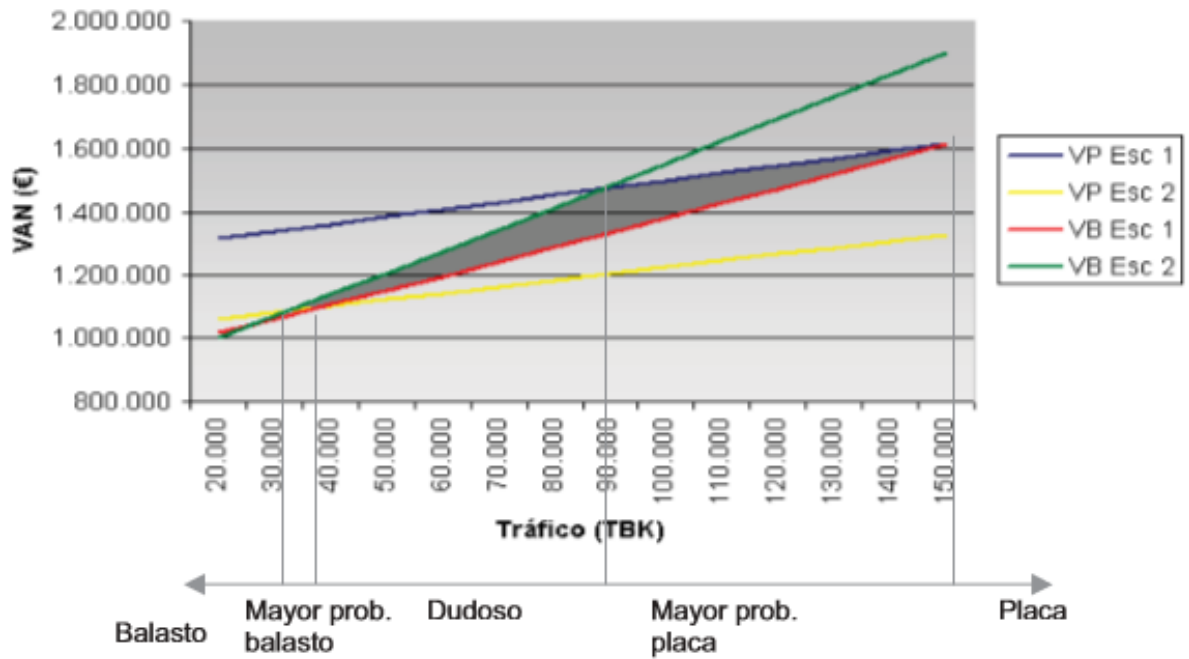
Figure 6. Conclusions from the research. Present Value (€) - gross tonnes /day (CEDEX, 2009)

Gross tonnes/day	Track structure suggested
< 32,000	Ballasted
32,000 - 40,000	Higher probability for ballasted
40,000 - 90,000	Doubtless
90,000 - 150,000	Higher probability for ballastless
> 150,000	Ballastless

Table 1. Results from the research (CEDEX, 2009)

To conclude this section, a recent research carried out by several Spanish companies has stated that during the first 26 years of a railway life the ballasted option is the cheapest. This research belongs to The Fastrack Project which is an on-going ballastless track development in Spain. Due to the fact that there is no experience of this type of track, it has not been included in this report with numbers but with its description and features in chapter 4. The following conclusions are given by its LCC study (Fastrack,e, 2013):

- The Fastrack rail would be the best option from the 27thyear regarding long-term life costs.
- Rheda system is more expensive during the construction phase of the track than Fastrack.
- LVT is cheaper than Rheda, Fastrack and ballasted track but its features are rather different from the rest.

❖ Other related studies

Lichtberger states in The Track Compendium that investment costs for any ballastless track should not be more than 30% higher than the ballasted ones excluding Rheda system which has longer experience being often its construction costs around 50% higher or even more. Furthermore, the advantages of ballasted track are the improvements related to the automatized operation for maintenance. In conclusion, the author highlights that the use of slab track is required only for special situations such as heavy load railways, high traffic or tunnels since the construction costs on earthworks increase to 2-2.5 times in slab tracks (Lichtberger, 2011).

These conclusions are also supported by a PCA research (Kucera & Bilow, 2002) which states that a target of 1.3 times the cost of traditional tracks construction can be built. Indeed, it gives an example of it in U.S where a target of 1.278 has been achieved. Moreover, maintenance costs of slab track are estimated to be only 0.2 times the ballasted ones in the same country on heavy tonnage routes including train delays and reroutes and excluding tie replacement in ballasted tracks. These apparently competitive costs reach same PV than ballasted tracks in 8 years. The original costs in the report are given in $/miles.

A research made in The Polytechnic University of Catalonia (Spain), which focuses on describing deeply and technically each slab track structure, uses a MCA to compare Edilon and Rheda system in two specific locations in Spain. The conclusions of the report are (Cortina, 2013):

- It is suggested a general used of slab track when a high-speed train up to 300 km/h is being designed.
- A detailed life cycle cost analysis is suggested for lines whose speed remains between 200 km/h and 300 km/h. Within this analysis, factors such as commercial speed, traffic volume, technical parameters and the quality of available ballast are suggested to be aware of. Furthermore, constructions costs, maintenance costs, renewal costs, savings and extra costs must be included as it was expected.
- Systems such as Rheda 2000, which have two elastic levels and concrete sleepers, might be better for high traffic volumes or freight and passengers lines.

- More elastic levels are often needed in order to decrease noises and vibrations being in that case systems like LVT or Edilon more appropriate. However, their construction is more complex.
- Although prefabricated concrete slabs have higher initial costs, they have a large experience for speeds up to 300 km/h.
- Embedded Rail Structures allow vehicles on them and less height of the superstructure is needed but they are not suitable for high traffic volumes.
- The author suggests the use of comparison matrixes in the first stages of the design using weighting criteria in order to analyse the best choice for a project.
- Improvements in the ballastless production and construction process have been obtained in the high-speed line Barcelona-French border where three slab track kilometers (Rheda, Edilon) have been constructed in 3 months including all geometric details.

Another project which has a great importance is INNOTRACK which was founded by the EC commission. Its main goal is to create a global European approach in track infrastructure to low both investment and maintenance costs in the rail sector, especially to low 30% LCC. This approach is being carried out bringing together the main issues influencing LCC from infrastructure managers (IM) and industry suppliers. Furthermore, the project highlights the importance of a European work as one. Some conclusions that can be advised from this program are as follow (INNOTRACK, 2010b):

- The installation phase is the one holding more possibilities to save costs.
- INNOTRACK has developed two superstructure improvements: The Two Layers Steel Track and Embedded Rail Slab Track (BB ERS) which have been analysed in terms of both technical and economical features being the results specified in the suitable section of this report for the second type. A 30% savings are hypothetically possible with BB ERS track system (Figure 8) for certain tonnages as the previous CENIT research suggests too. After LCC calculations, 20% reduction was obtained for annual traffic of 55 MGT (Million Gross Tones)/year.
- The Two Layers Steel Track has not been included in this report due to the lack of experimental data and previous researches. This new approach can achieve savings mainly in switches and crossings in terms of delay costs. However, it involves an increase in material costs of 15% of the track total costs.

Figure 7. The Two Layers Steel Track construction (INNOTRACK, 2010b)

Figure 8. BB ERS example in UK (INNOTRACK, 2010b)

- INNOTRACK through Bankverket (Sweden) has analysed the savings that can be achieved in the relation between IM and suppliers. This situation has changed lately becoming a knowledge-trade between them in order to meet suitable requirements (Figure 9). This situation implies savings in cost comparing with a situation in which the lack of knowledge was present (Figure 10).
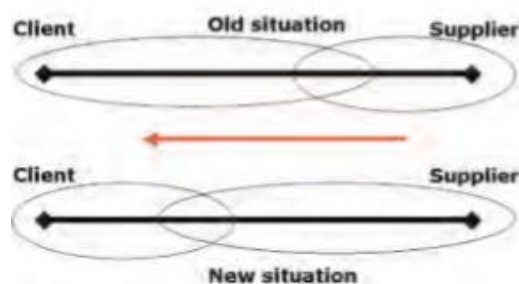

Figure 9. Evolution of the relation between IMs and suppliers

Figure 10. No matched relation between IMs and suppliers

- INNOTRACK has established a harmonized LCC calculation method at European level, which aims to identify cost drivers, assess the track components and modules, and also to make cross-country comparisons. This model bases decisions on the connection between RAMS performance and resulting LCC. Figure 11 illustrates the process that INNOTRACK suggests for new developments.
- The program used to perform LCCA has been D-LCC.
- A model for LCC calculation suggested is shown in Figure 12 for each element of the infrastructure.
- The NPV method has been chosen in the analysis which is the basis of the method used in the present study.
- The discount rate has a great impact on the calculation as the Figure 13 shows. According to the conclusions of the research, when comparing two alternatives with large different initial costs (ballasted vs ballastless tracks) the chosen discount rate is mostly the key for the decisions. Besides, only if in the first years there is a large reduction in maintenance costs, the higher investment will be balanced with a high discount rate (6%).
- INNOTRACK calculations were made using a 4-5% discount rate.
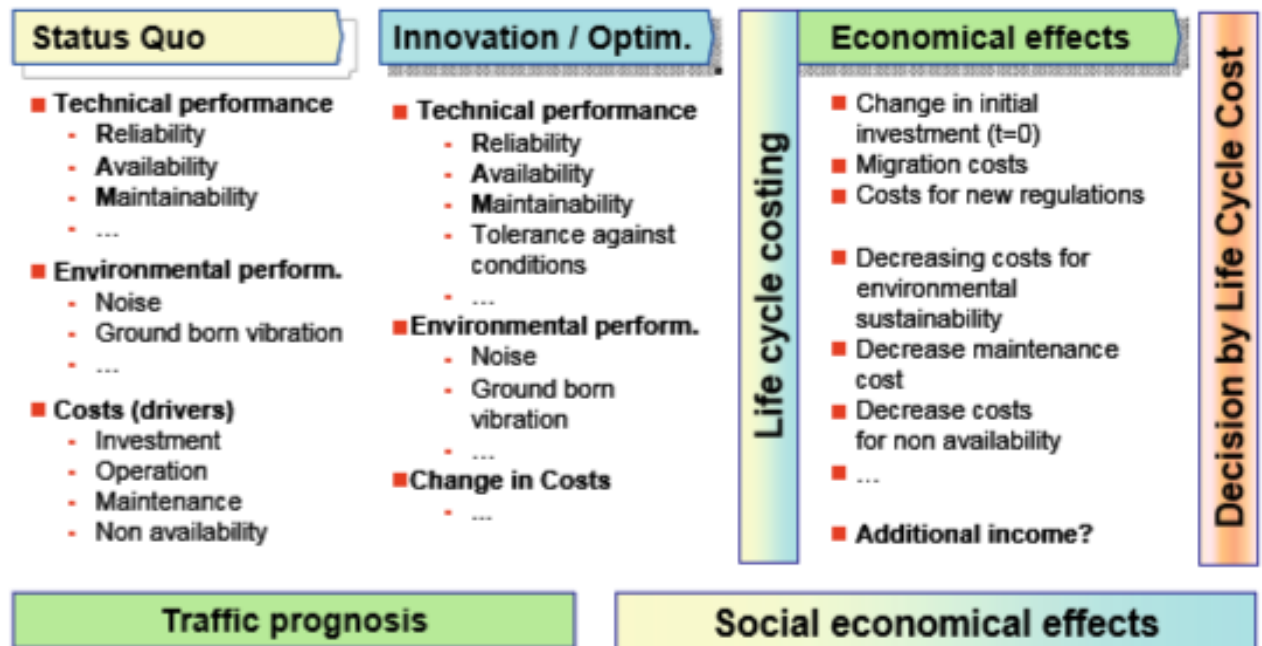
Figure 11. RAMS-LCC model proposed (INNOTRACK, 2010b)
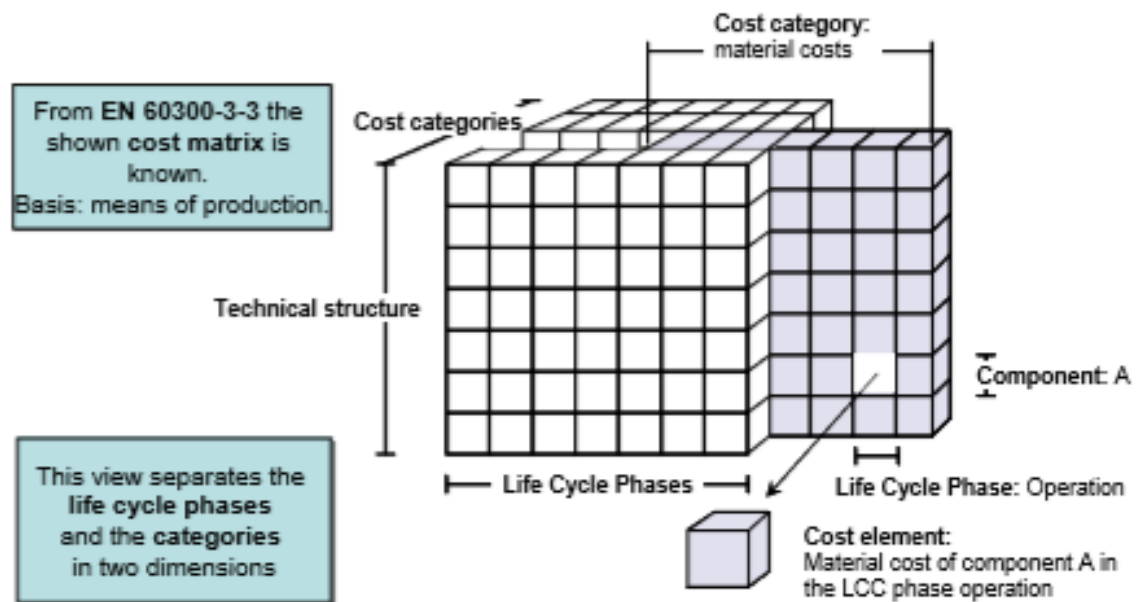
Figure 12. Dimensional costs matrix for LCC (element cost calculation) (INNOTRACK, 2010b)
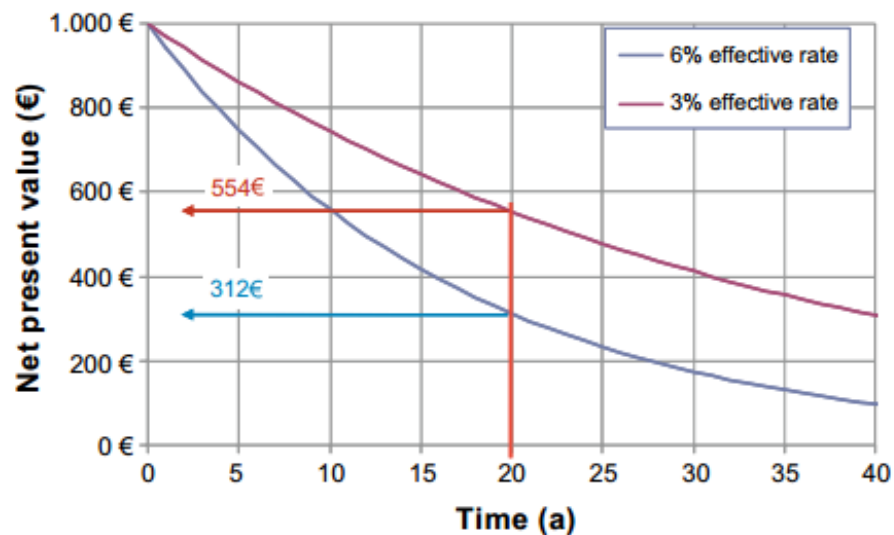
Figure 13. Cash-flow calculations with different discount rates

- The importance of feedback between suppliers and IMs is once again shown in Figure 14. It is also a confirmation of the method that has been used in the present study which values stronger the costs in early phases of life cycle.
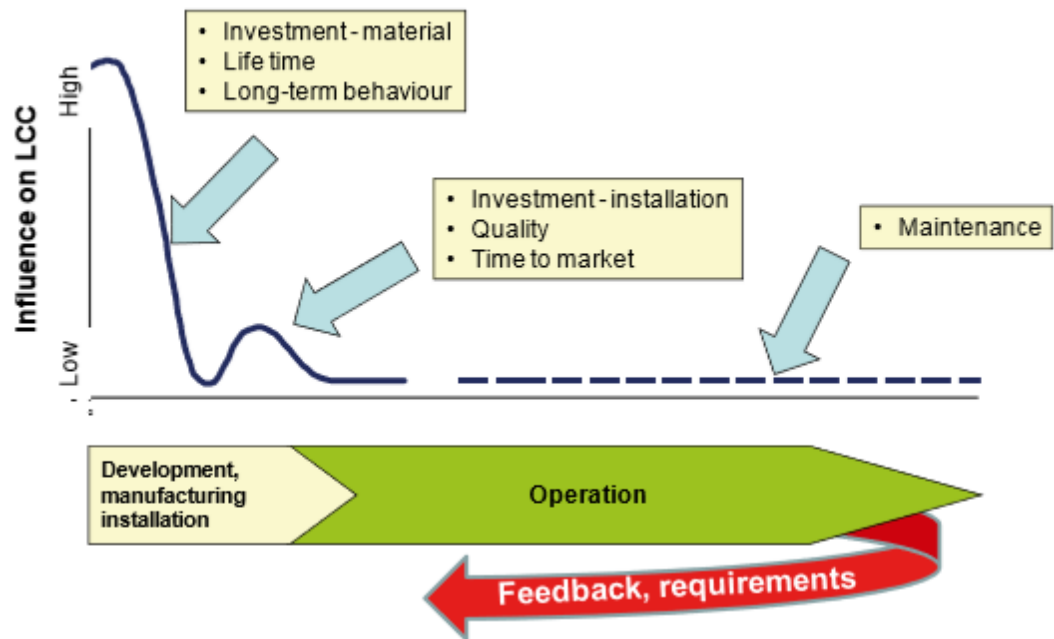
Figure 14. Key phases for reducing LCC

The research concludes highlighting the complex process that is to achieve deep knowledge of RAMS and LCC variables at European level. However, a guideline has been given in the report without having obtained the initial aim of the project.

To conclude and according to a research in Madrid Metro (no high-speed), the main factors that point toward the choice of the track structure are related to the local soil conditions, labour costs, construction costs, subgrade quality and also the conditions during the construction (ZOETEMAN & ESVELD, n.d.). This study analyses ballasted track and Edilon blocks system. The following considerations were taken into account for it:

✓ The PV calculation for ballasted track and Edilon blocks system took place during 50 years.
✓ The discount rate was 5%.
✓ The use of Edilon system gave at least a 10% reduction in the LCC regardless the inflation.

To conclude, a recent research by Esveld et al. probes into soil improvements and slab bending stiffness increment in order to progress ballastless high-speed tracks performance. Therefore, it is suggested both to limit minimum subsoil stiffness and to maximize the width in the slab-soil contact (Steenberger, et al., 2007).

3. METHODOLOGY FOR LCCA

To decide which kind of track will be constructed in a new high-speed line implies a specific analysis regarding factors such as: number and type of superstructures, features and quality of the soil, weather of the area or maximum speed among others. As it has been introduced before, the discussion about to construct ballasted or ballastless tracks has been on for many years. In the present research, an extra discussion is added regarding different kinds of ballastless tracks which most of them fulfil same requirements but the prices might vary significantly. Hence, the need of an analysis in terms of life costs is clearly the goal.

The following three analyses are suggested by The Polytechnic University of Barcelona (Cortina, 2013) in order to compare ballasted and ballastless tracks:

- Costs of construction and maintenance of both systems.
- Quality of ballast that will be used and its life span.
- Effects of ballast churning (from maximum speed about 280 km/h).

This research focuses on the first analysis in order to determine where the main costs of each system are set and then, compare them considering two discount rates. Chosen discount rate has definitely a big influence so two extreme cases are developed to be able to analyse the difference.

Moreover, the decision of the track system and LCCA must be done in the first stages since the design of the track depends on it; slab tracks allow smaller radii and cambers. However, more uniformity on the profile must be achieved in order to diminish embankment to not overpass 7-9 meters (Melis, 2006).

The methodology that has been followed in this report is a comparison of construction and maintenance costs in ballasted and ballastless systems using an approximation of Present Value behaviour through the Multi Criteria Analysis steps of Electre II method.

3.1 INTRODUCTION TO LCC TERM

A life cycle cost analysis (LCCA) is not a new tool under development. It has been used for many years in fields which need high investments at the beginning of an asset´s life. Therefore, the higher the investment is the more accurate and important the LCCA must be. Regarding slab track field, this statement is fulfilled due to the fact of high investments that these systems involve. Moreover, slab tracks often do not allow further modifications concerning its design once it has been already built up and finished.

Hence, a life cycle assessment tool (LCAT) should be carried out in order to achieve suitable resolutions by the decision-makers. LCCA is especially useful when there are different methods which are valid for same requirements but initial costs and operational costs vary.

LCC is defined as *"an economic assessment of an item, system or facility and competing design alternatives considering all significant costs over the economic life, expressed in terms of equivalent currency units"* (Stephen & Dell'Isola, 1995).

The ultimate goal of a LCCA is to find the best way to balance investment and maintenance. In Figure 15, a classification of Whole Life Costs (WLC) is shown which includes incomes and other costs that are out of the goals of this study but they might give an idea of the components of a LCC.

There are several techniques to carry out a LCC depending on the goal of the analysis. Generally, monetary valuations are normally assessed through one of these techniques (Department for communities and local government: London, 2009):

- Financial analysis which focuses on how the impact of an option influence in the financial costs and revenues.
- Cost-effectiveness analysis which assesses a project with alternative options but the ultimate goal cannot be monetary-valued.
- Cost-benefit analysis (CBA) which is widely used and is based on a calculation of benefits and costs during the life time of the asset. This analysis also converts non-monetary terms such as environmental costs or society costs into monetary and familiar numbers with which a whole project can be assessed. Furthermore, it takes into account the value of money in time since future expected payments or revenues are discount (Net Present Value method). However, CBA has also limitations in terms of no consideration of impacts interaction or no agreement in the method to convert non-monetary costs into monetary ones.

The limitations of CBA analysis are tangible in the infrastructure field since environmental costs have great consequences and no general valuation is accepted. The present study belongs to the railway industry which means that each of these costs and benefits are assumed by different companies or organisms. This fact makes very difficult and laborious the collection of data in order to carry out a LCCA involving with high level of uncertainty with which the infrastructure manager has to handle through a sensitivity analysis for instance.
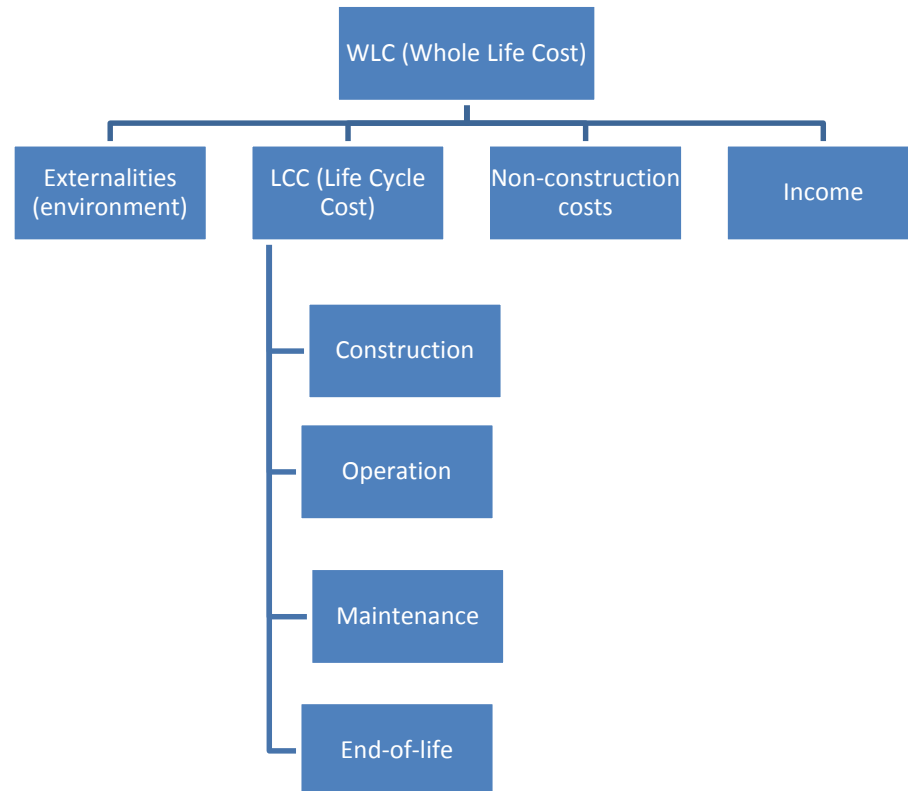
Figure 15. WLC depending on the type of costs. Source. ISO 15686-514

3.2   COST-BENEFIT ANALYSIS. PRESENT VALUE FORMULA

Exact and rigorous Life Cycle Cost calculations can be approached with different methods as it has been introduced in the beginning of this section in order to assess monetary valuations. One of these methods is the Net Present Value (NPV) method which discounts with a discount rate, gains and losses by the time. Although it is a cost-benefit analysis, it is often used to know the present value of either benefits or costs separately. Actually, when only the costs are taken into account in the PV calculations a LCCA is obtained. Decision-makers must pay especial attention to the sign of the calculations. While in a CBA the higher NPV is, the more benefits are expected, in a PV only in term of costs the higher the PV is the more expensive the project is estimated due to a (-) in the formula. Henceforth, this research uses this formulation since only costs are included.

Even though PV formula is basic, long-term projects require the use of programs in order to get good accuracy. The formula shown in (1) is suitable for a CBA.

$$NPV = PV \ (benefits) - PV \ (costs) \quad (1)$$

If only the costs have influence in the study (2) and (3) are used instead:

$$Present \ Value \ (PV) = PV \ (costs) \quad (2)$$

$$PV \ (costs) = \sum \frac{C_i}{(1+r)^n} \quad (3)$$

Where:

- C_i are the i costs included in the calculation
- r is the discount rate which it depends on the country mainly but also on the type of project and risk of it. It will be discussed in the following point.
- n accounts for the periods included in the analysis. Normally, it is calculated in years-unit so n are the number of the year analysed.

Once the PV formula is familiar to us, some properties of the formula are important to remind:

✓ The closer in time a cost is from now, the more influence has in the PV total calculation due to the factor n. The following example is useful to understand it properly:

If a costs of 1000 € is has to be paid next year with a 3% as discount rate , the present value of that payment now is (4)

$$PV \ (1000€ \ cost \ in \ year \ 1) = \frac{1000}{(1+0.03)^1} = 970.87 \ € \quad (4)$$

If the same payment with same conditions has to be done in 2020, equation (5) shows the difference as:

$$PV \ (1000€ \ cost \ in \ year \ 5) = \frac{1000}{(1+0.03)^5} = 862.61 \ € \quad (5)$$

Thus, it is clear that the further in time a cost is located, less value or colloquially "less importance" has in the present moment. Practically, it makes sense since that money can be invested until the moment of the payment. Hence, a double investment can happen in the same period of time.

Present value calculations give apparently an objective idea and basis of the investment needed for a project. Nevertheless, infrastructure and especially in railway field the costs from different slab tracks to be added in the formula are neither fixed nor robust nor

consistent. That is the reason of why many contradictions can be found in this field in term of construction or maintenance costs. Then, numerically and accurate calculations are completely useless in conditions that were not a specific project and location.

To avoid these limitations but also adding their own ones, an approximation of each term of the PV formula is the tool chosen to analyse the behaviour of the ballastless tracks costs included in the present report (6). The process of adding the terms of the equation is compared with a MCA being the terms the criteria of the project. Hence, the steps of a general MCA are used here to approach the behaviour of PV. The criteria are weighted with a factor which represents the distance in time from now to the moment of the payment as exactly the formula involves.

$$PV \ of \ ballastless \ type \ i \ in \ the \ MCA = k_1 * S_1 + \ k_2 * S_2 + \ k_3 * S_3 \ ... \ (6)$$

Where:

- K_j are the weighting factors which fulfil that $k_1 > k_2 > k_3$...

$$kj = \frac{1}{(1+r)^n} \ (7)$$

Initially, K_j are part of the formula of Simple Present Value (3). Nevertheless, maintenance costs are going to be represented in this report each year of the life cost by a percentage of the ballasted maintenance costs between 0 and 1. This means that there is a constant flow (cost) each year of the life period analysed which is represented with the following equation and same meaning than the previous one of Simple PV:

$$PV \ of \ a \ constant \ flow \ (costs) = \sum C_i * \left[1 - \frac{(1+r)^{-n}}{r} \right] \ (8)$$

Therefore, the K_j are instead as equation 9 shows and indeed they are going to be used in this report as:

$$kj = \ 1 - \frac{(1+r)^{-n}}{r} \ (9)$$

- Sj represent the costs (C_i) themselves in the cardinal scale (scoring) which has no meaning out of this analysis.

This formulation is further explained in the next chapter.

3.3   DISCOUNT RATE APPROACH

The discount rate (r) is "*the interest rate at which an agent discounts future events in preferences in a multi-period model*" (Dictionary, n.d.).

As it has been introduced in the literature review chapter, the discount rate has a great impact on the results of any present value calculation.

According to the INNOTRACK research conclusions, when comparing two alternatives with large different initial costs (ballasted vs ballastless tracks) the chosen discount rate is mostly the key for the decisions. Hence, the trick is that there is no method to select a suitable discount rate rather than experience due to its complexity. Depending on the authority, company or country different discount rates are chosen for infrastructure projects as the figure 16 represents (INNOTRACK, 2010b).

The influence of a low discount rate in LCC calculations makes impact in favour alternatives with low capital costs, short life cycle and high maintenance costs (ballasted track). On the other hand, high discount rate influences positively the ballastless choice which includes higher capital costs, longer life cycle and lower maintenance costs (Figure 17) (INNOTRACK, 2010b). This statement is based on achieving the lowest PV possible through minimize each PV formula component or shortening the life of the asset. Only the first option is applied since a 60 years period has been decided for this study. This decision is due to the fact of being a complete cycle of a ballastless track and two times the cycle for a standard ballasted track.

BV	4.0 %	
DB	5.9 %	For infrastructure
NR	6.5 %	
ProRail	4.0 %	
Public investor	≅ 4.0 %	
Private investor	5.0 % ++	Depending on risk
InnoTrack	≅ 4-5 %	For comparison

Figure 16. Discount rates used by different investors and IMs (INNOTRACK, 2010b)

Indeed focusing on minimizing each component of the formula, for fixed costs the discount rate plays the main role. As Figure 17 represents, the higher the discount rate is the more favourable low investment asset is. Furthermore, Figure 17 represents the different evolution of the NPV in a reference system (blue line), which can be approached as ballasted system, and in an innovative system (red line), which can be approached as slab track system, varying the discount rate. 4% seems to favour equally both alternatives.
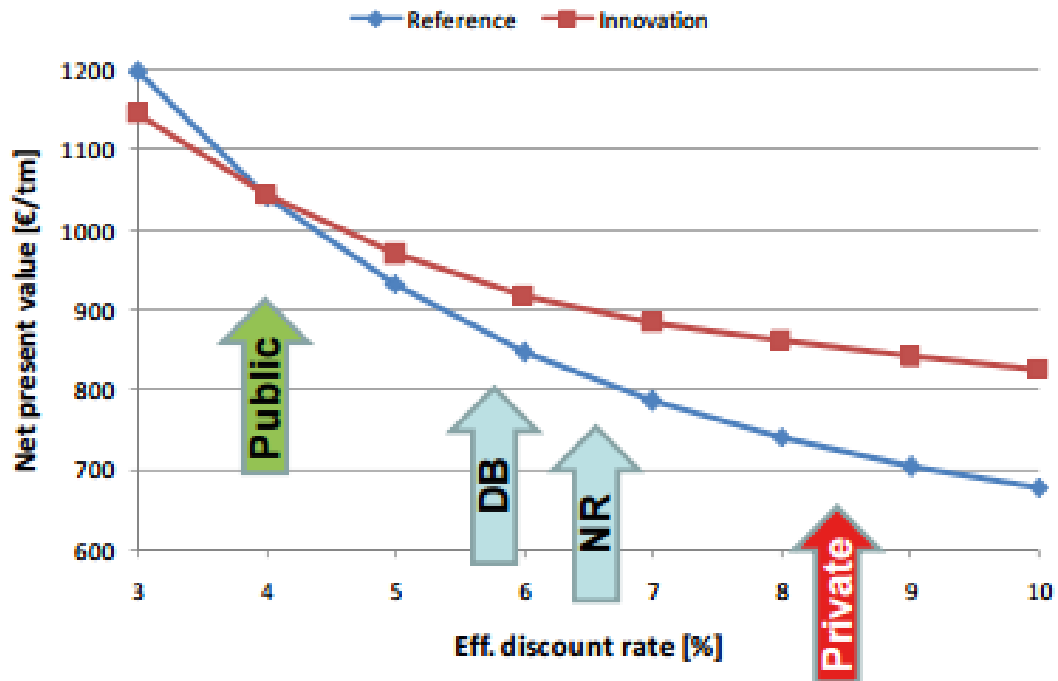
Figure 17. Influence of discount rate on NPV (INNOTRACK, 2010b)

3.4   METHODOLOGY USED IN A MULTI-CRITERIA ANALYSIS. ELECTRE II

Multi-criteria methods are largely used in project assessment through scoring the project's solutions against a group of criteria. Generally, criteria are weighted in order to give preference depending on the decision-maker's goal. The steps of a general MCA are explained in the present chapter as well as their application on this research. MCA techniques can be used to:

- Identify a single most preferred option
- Rank options
- Short-list a limited number of options for subsequent detailed appraisal
- Distinguish acceptable from unacceptable possibilities.

When a decision-making process is chosen to be studied, numerous and different methods might be used. ELECTRE method (Elimination Et (and) Choice Translating Reality) was introduced by Bernad Roy (1968-1991) in order to face existing problems in decision-making methods. In this report, the case of ranking options is thought to be suitable using Electre II method.

One limitation of MCA is that it cannot show that an action adds more to welfare than it detracts. Unlike CBA, there is no explicit rationale or necessity for a Pareto Improvement

rule that benefits should exceed costs. Thus in MCA, as is also the case with cost effectiveness analysis, the 'best' option can be inconsistent with improving welfare, so doing nothing could in principle be preferable.

The steps to follow according with a manual for multi-criteria analysis are named below and described further in following chapters (Department for communities and local government: London, 2009):

1. Establish the goal and objectives of the MCA. This step includes the identification of decision-makers and other key players such as technical experts, infrastructure managers (IMs) or previous researches.
2. Identify the options included in the analysis.
3. Identify the criteria according to the goals of the analysis that have been set in step 1. The selected criteria must be of notable difference among the options so concerning this study common features of ballastless tracks are avoided.
4. Describe the performance of each option against the criteria including score this performance.
    a) Description of the consequences in the options-criteria relation.
    b) Score the options against the criteria bearing in mind the consistency of the scores. The coefficients S_j represent this step.
5. 'Weighting'. Decide weights for each of the criteria regarding their relative influence in the studied process. Concerning this study, the coefficients k_i are the weights.
6. Combine the weights and scores for each of the options to obtain the results.
7. Examine the results.
8. Conduct a sensitivity analysis of the results to change scores or weights if needed. Besides, have into consideration other analysis and options that could improve the results until a final result will be chosen. This step is part of the limitations of the present study.

3.4.1   Objectives and decision-makers of a MCA

The ultimate end of every multi-criteria analysis is to facilitate the decision-making process through an analysis wide enough to obtain conclusions as closer as they could be to the complex reality is. In terms of the present document:

✓ A cost comparison analysis of different ballastless tracks is intended.
✓ A better understanding of where the main costs of a ballastless track are settled is also the purpose of the analysis. Thus, improvements to reduce them could be developed in the future.
✓ Analyse the influence of high and low discount rate.

The best decisions come often from a mix of several persons and not only from one expertise. Thus, key players or stakeholders are the ones who take part in the multi-criteria analysis or decision-making process such as consulting or construction

companies and the government. Therefore, stakeholders are a very important part in the railway industry overall because it works with long-terms decisions. Decision-makers in the railway industry were traditionally the administration organism of a country but recently these decisions are being privatized. In both cases, infrastructure managers are the head of the decisions. However, in order to have information as reliable as possible to take suitable resolutions, expertise in the subject matter, people with knowledge even other previous researches are also involved in the decision-making process as key players.

3.4.2   Identifying the options included in the analysis

This step is decided after having limited accurately the objectives to be achieved with the analysis. Although sometimes the options are not clear when a project is going to be carried out it is better to spend time on it. They are the main part of the analysis since actually they are the direct result of the project to be constructed. The options analysed in the present report are:

- Ballasted track for high-speed railways
- Ballastless track (Shinkansen, EDILON, Rheda 2000 and LVT)

3.4.3   Identifying the criteria

In a LCCA, criteria are the costs included on it. Thus, it is in this part where the limitations have to be decided. Depending on time resources or on the goals to achieve, costs included are selected. Concerning this study the following costs are included:

- Owner costs (Co). Construction costs (Co_1) + maintenance costs (Co_2). Maintenance costs include inspections, repair and upgrading but no operation.
- Society costs (Cs) include only environmental impacts. Those impacts are analysed in the report but they are not part of the results.

Other costs and benefits are out of the limitations of the research due to either be common to all track systems as the user costs or due to lack of data as disposal costs.
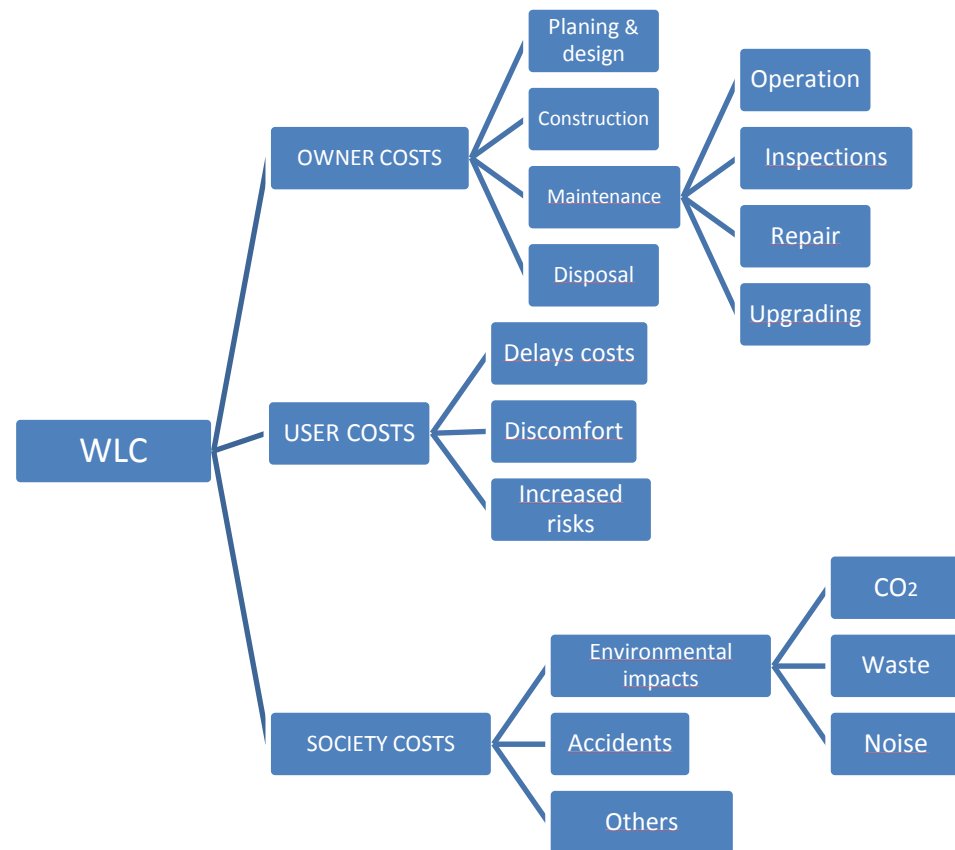
Figure 18. WLC depending on the costs holders. Source (ETSI PROJECT, 2007)

3.4.4   Scoring the options against the criteria

After having well defined both criteria and options of the project, the next step is to assess and judge each option against each criterion. The result is a performance or impacts matrix.

This step is the first judgement in the analysis and as it has been shown before, objective and subjective decisions have been separated. The scoring part is an objective action since normally exact and numerical quantities are calculated in a life cycle cost. Thus, there is no doubt when those quantities are scored. Firstly, an overview of the maximum and minimum quantities of the performance is needed in order to decide a cardinal scale to score them. In this MCA, the costs data are not numerical data but ratios of ballastless tracks costs divided by the ballasted ones. Hence, the neutral point is 1 when the price of the ballastless track is the same than the ballasted; being for example 2 double expensive for the ballastless or 0.5 half of the tradicional track costs. A cardinal scale between 0 and 9 is chosen which relates 0 with ratio 0 and 9 with ratio 3.

- Construction costs (Co_1). The ratios vary between 1 (price ballastless = price ballasted) and a limit of 3 that is established for this analysis. These ratios are identified with a score as the picture shows below between 3 and 9. Thus each increase of 0.1 in the ratio is scored with +0.3 in the cardinal scale in the MCA.
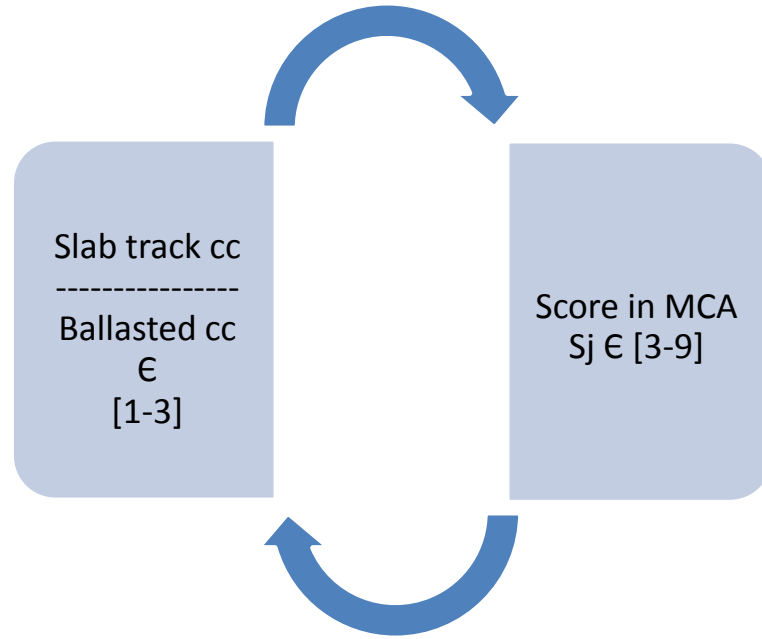
Figure 19. Conversion ratios-score in MCA. Construction costs

It is important to denote that the cardinal scale used is a decreasing scale which means that the higher the punctuation is the more expensive and the worse in terms of costs becomes.

- Maintenance costs (Co_2) represent the strength of ballastless systems being lower than the costs which ballasted tracks require. In order to keep the same formulation than is used in construction costs, ratios comparing slab track costs over ballasted cost are used. However, the ranges of those ratios vary from 1 (same maintenance cost than ballasted track) to a limit situation of 0 which would mean that no maintenance is required in the system. The picture below shows a graphical explanation of the conversion to the MCA cardinal scale in the range of 0 to 3.
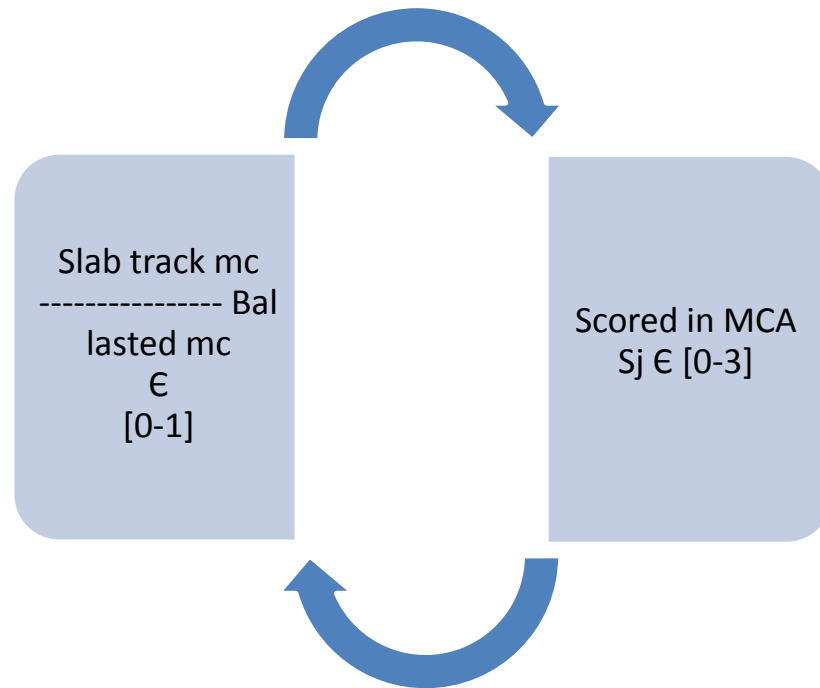
Figure 20. Conversion ratios-score in MCA. Maintenance costs

As it has been explained, the sub-criteria of maintenance costs are inspections, repair and upgrading. In spite of the fact that they require different degrees of interventions involving their own costs, stakeholders normally provide maintenance information as one section without diving into sub-criteria. Different maintenance needs are taken into account when adding the cost in the PV formula (8) during the 60 years life cycle. It is explained in the weighting criteria section.

- Environmental impacts (Cs) are part of the society costs regarding the WLC classification. Infrastructures works and specially transportation influences deeply to the environmental and mostly in a negative way. Thus, it is of great importance the analysis of the consequences caused by transport infrastructure. In order to have a real knowledge about these consequences in a project when decisions have to be taken, they must be added into calculations such as PV. Apparently, there are no problems to do it until equanimity in the input data is required. When it happens, decision-makers realize that there is no general method to convert environmental effects into monetary units to be compared with investment, maintenance costs or personal costs. Therefore it is in this point when a multi-criteria analysis might be the best tool to get closer to quantitative and qualitative measures.

Concerning this research, noise and vibrations impacts are studied since they are different from one track to another. However, those impacts are not converted into monetary units due to lack of method and time resources. Other environmental effects are common to all kinds of tracks though.

3.4.5 Weighting criteria

In the weighting step, the decision-maker or normally a group of them have influence through providing some criteria with preference regarding the purpose of the analysis. Therefore in principle, it is a subjective process in which expertise without a stake in the outcome of the analysis should take part to avoid bias. The way to proceed includes meetings face to face to discuss the weights and find out the best consensus among the individual views of the stakeholders.

However, weighting process in this MCA analysis varies its features being less subjective due to the k_j meaning. As it has been explained in the previous section and equation 9 shows, k_j factors represent the high or low influence of costs in the PV calculations concerning their distance in time but also the crucial influence of the discount rate.
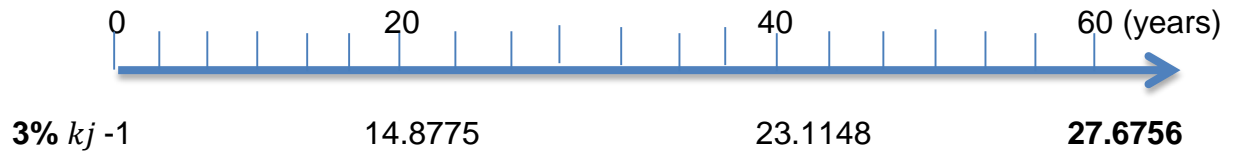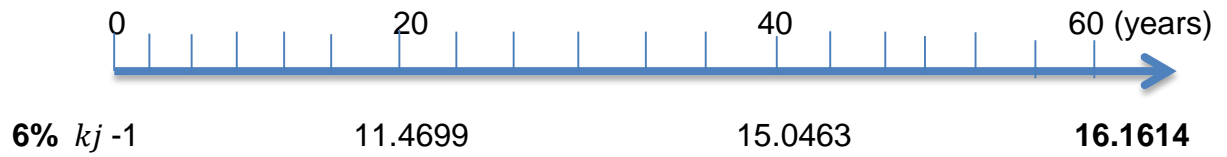
$$kj = 1 - \frac{(1 + r)^{-n}}{r} \ (9)$$

As only construction and maintenance costs are included, only K_1 and K_2 have presence in the PV approximation.

⇨ K_1 represents the factor which discounts the construction costs. As it has been denoted, these costs are discounted in year 0 due to the non-influence of financial strategies. Then, this means that $K_1 = 1$ for any discount rate used.

⇨ K_2 represents the factor which discounts the maintenance costs during the 60 years asset life. The maintenance costs are disposed in one constant number/ratio since they are results from previous researches or from fabricant data. These costs are equally divided during the 60 years. Although in normal conditions, the first 20-30 years there is no need of maintenance in ballastless sytem as this is a comparison among ballastless systems there is no influence on it.

Moreover, the selection of the discount rate influences the results as it has been explained before. In order to compare the differences on the results, two case-studies have been carried out using 6% and 3% as discount rate, extremely high and low respectively.
The following graphs show the kj within a period time of 60 years both with the high and the low discount rate used for the calculations. They have been calculated with the help of Excel.

0	20	40	60 (years)

6% kj -1   11.4699   15.0463   **16.1614**

0	20	40	60 (years)

3% kj -1   14.8775   23.1148   **27.6756**

4. APPROXIMATED PRESENT VALUE BEHAVIOUR

This chapter aims to develop a ballastless tracks comparison in order to propose an appraisal especially in terms of costs during their life time. A multi-criteria method is used following the methodology exposed in the previous chapter which was considered to be the most suitable for this research. It has not been possible to get a rigorous comparison since as it is developed during this chapter; cost analysis has a high dependence on each specific project as well as several uncertain factors which are carefully explained too. Indeed, this is the main disadvantage when general knowledge is being seeking regarding rail industry.

4.1 OBJECTIVES AND DECISION-MAKERS OF THE MCA

✓ A simple cost comparison analysis of different ballastless tracks is intended.
✓ A better understanding of where the main costs of a ballastless track are settled is also the purpose of the analysis. Thus, improvements to reduce them could be developed in the future.
✓ Analyse the influence of high or low discount rate

In the research the following key players have taken part providing information:

- JAPANESE SHINKANSEN
- EDILON ERS
- SONEVILLE LVT
- PCA
- TIFSA
- CENIT (Transport Investigation Centre)
- FASTRACK

4.2 IDENTIFYING THE OPTIONS INCLUDED IN THE MCA

4.2.1 State-of-art

Slab track provides a system with a composition made of a continuous layer or isolated blocks of concrete or asphalt instead of using ballast (Figure 21 and **Table 2**). Although those might be the upper layers, elastic and dampening materials are placed below to obtain suitable results. The main goal of this system is the no need of maintenance at all remaining the same dynamic behaviour as ballasted tracks which directly implies a

higher availability of tracks. Furthermore, ballastless tracks contribute to increase security avoiding the interaction of ballast between wheel-rail (churning). This interaction often takes part in trains with speeds higher than 300 km/h (CEDEX, 2008b).

Without being general, the use of ballastless tracks in tunnels is often a good decision due to the fact of the great savings in height that can be achieved, up to 900 mm over the head of the rail.

Table **3** shows the km constructed around the world of ballastless tracks in tunnel, earthworks and viaducts currently.

Before sorting out each type of ballastless track, a general description of their superstructure is carrying out to clarify concepts (Escolano, 1998).

- Platform. It is the element which the superstructure is laid on. It is composed likely by three layers: subsoil, protective layer of the subsoil and frost protective layer (FPL).
- Sill. It is located just above the platform. It can be made of either a hydraulically bonded layer (HBL) or a concrete sill with or without reinforcement.
- Slab. It is made of asphalt or reinforced concrete being specific in each type. The construction method can be bottom-up or up-down.
- Fasteners. They depend on the slab track system. Moreover they absorb most of the elastic deformations of the track as well as they can be adjust due to settlements or maintenance in a range of -4 mm to +20 mm in elevational profile and ±5 mm in plan profile.
- Long welding rod.
- Extra elements for noise isolation in order to achieve same results than ballasted tracks. The reduction is around 5 dB (depending on the ballastless system)

Spanish experience on ballastless tracks started also at the end of the 70s as in other European countries. The first system to be used between Madrid and Barcelona was PACT (Paved Concrete Track) which was imported from Britain but it had to be removed in 1992 due to continuous maintenance problems. In the same year, EDILON system was decided to be installed in Atocha station (Madrid) as well as STEDEF system was installed in several tunnels and viaducts. Nevertheless, all those ballastless tracks were not for high-speed lines that started in 1992 between Madrid and Seville.

The first ballastless system used in Spain for high-speed was BBEST (Balfour Beaty) for trains running up to 240 km/h in 2000 (Cortina, 2013). Three years later, a trial section in The Mediterranean Corridor was constructed to prove six types of ballastless systems: Rheda, Rheda Dywidag, Stedef, Getrac, ATD and EDILON.

	Ballast Construction	Slab Tracks

Superstructure	◆ Rails
	◆ Rail fastening
	◆ Rail Support by Sleepers:
	  - Normal transverse beams
	  - Innovative solutions as frame or ladder
	
	◆ Ballast
		◆ Rails
		◆ Rail fastening
		◆ Rail Support:
		  - Discrete with sleepers or support points
		  - Continuous support with embedded or clamped rails
		◆ CSL or ASL
		◆ HBL

Substructure	◆ Upper non-bonded supportive layer, possibly as frost protection layer (FPL) ◆ Lower non-bonded supportive layer: Earth works with compressed or improved embankment or cut formation ◆ Foundation possibly compressed	◆ Upper non-bonded supported layer: frost protection layer (FPL) ◆ Lower non-bonded supportive layer: Earth works with compressed or improved embankment or cut formation ◆ Foundation possibly compressed

Figure 21. Features ballasted and ballastless tracks (Quante, 2001)

Since that moment, ballastless systems have been used several times in Spanish high-speed lines mainly in long tunnels (> 1,500 m.) using mostly Rheda 2000 and EDILON. Perthus tunnel is an example of the use of Rheda 2000 as Figure 22 shows below. While Rheda 2000 has been the most extended ballastless system in the country for high-speed tracks, EDILON has had always successful results in stations such as Atocha, Toledo or Sants (Bercelona). Recently, LVT system has been installed in a tunnel (400 m.) in the line Barcelona-French border which was opened in 2013.

Ballastless Track Systems					
Discrete Rail Support				**Continuous Rail Support**	
With Sleepers or Blocks encased in concrete	Sleepers on Top of Asphalt-Concrete Roadbed	Prefabricated Concrete Slabs	Monolithic Designs	Embedded Rail Structure (ERS)	Clamped and Continuously Supported Rail
Rheda	ATD	Shinkansen	Lawn Track (Rasengleis)	Deck Track	Cocon Track
Rheda-Berlin	BTD	Bögl	FFC	INFUNDO - Edilon	ERL
Rheda 2000	SATO	ÖBB-Porr	Hochtief	BBERS	Vanguard
Züblin	FFYS	IPA	BES		KES
Stedef	GETRAC		BTE-BWG/HILTI		SFF
SONNEVILLE-LVT	WALTER		PACT		Saargummi
Heitkamp					
SBV					
WALO					

Table 2. Ballastless track systems (Lichtberger, 2011)

Figure 22. Perthus tunnel. Rheda 2000. Image from Sener Company

45

Slab Track Design	Country of design	Total construction (km)
Bögl	Germany	4391
Shinkansen	Japan	3044
Rheda	Germany	2205
Sonnevile-LVT	Swiss	1031
Züblin	Germany	606
Stedef	France	334
Infundo-Edilon	Netherlands	211
ÖBB-Porr	Austria	122,2
IPA	Italy	100
PACT	UK	95,4
SATO	Germany	35,8
FFYS	Germany	33,1
BTD	Germany	32
ATD	Germany	31,7
Getrac	Germany	15,3
Walter	Germany	9,4
FFC	Germany	1
Heitkamp	Germany	0,39
BTE	Germany	0,39
BES	Germany	0,39
Lawn Track/Rasengleis	Germany	0,39
Hochtief	Austria	0,39
Deck Track	Netherlands	0,2

Table 3. Ballastless constructions around the world (Michas, 2012)

4.2.2   Types of slab track included in the MCA

SHINKANSEN SYSTEM (JAPAN)

The first high-speed line of the world was built in Japan between Tokyo and Shin-Osaka (552.6 km) in 1964. As it can be seen in Figure 23, it is called *Tokaido Shinkansen*. It is a ballasted track in which The JNR (Japanese National Railway) could afford neither high quality materials nor suitable terrain treatments for its 250 km of embankments. These trains achieved a maximum speed of 210 km/h which has increased until 270 km/h nowadays (Wakuda, 1997). However, the ballast of Tokaido Shinkansen had to be changed after twelve years of service (1976). The works had placed during a period of five years with the costs associated. This early problem might explain that the 40% of maintenance costs in *Tokaido Shinkansen* are used for ballast maintenance. (Melis, 2006).

The second Shinkansen was *Sanyo* which connects Osaka with Okayama and Hakata (664 km in total) increasing the maximum speed to 260 km/h. The interesting part of this line concerning this research is the one between Okayama and Hakata which was designed as ballastless track and opened in 1975. It has to be noted that between Osaka and Hakata, 129 tunnels were built due to the irregular topography (Melis, 2006).

After a ballasted and a partly ballasted Shinkansen; a third Shinkansen, *Tohoku*, was opened as a complete slab track line in 1982 since it has only 27 km out of 496 km of ballasted track. It linked Omiya and Morioka until 2002 when a connection between Morioka and Hachinohe was added. Currently, its speed is 275 km/h. Besides, *Shinkansen Joetsu* was first opened also in 1982, which includes long tunnels and simple structures using slab track mostly. It runs between Omiya and Niigata (303.6 km). Regarding those lines success, more Shinkansen such as *Hokuriku/Nagano* or *Kyushu* were constructed using the same model of slab track which comprises to limit embankments to 9 meters and vertical settlements to 30 mm. From Figure 27, it can be seen that the dominant superstructures in Shinkansen lines are tunnels (Melis, 2006).

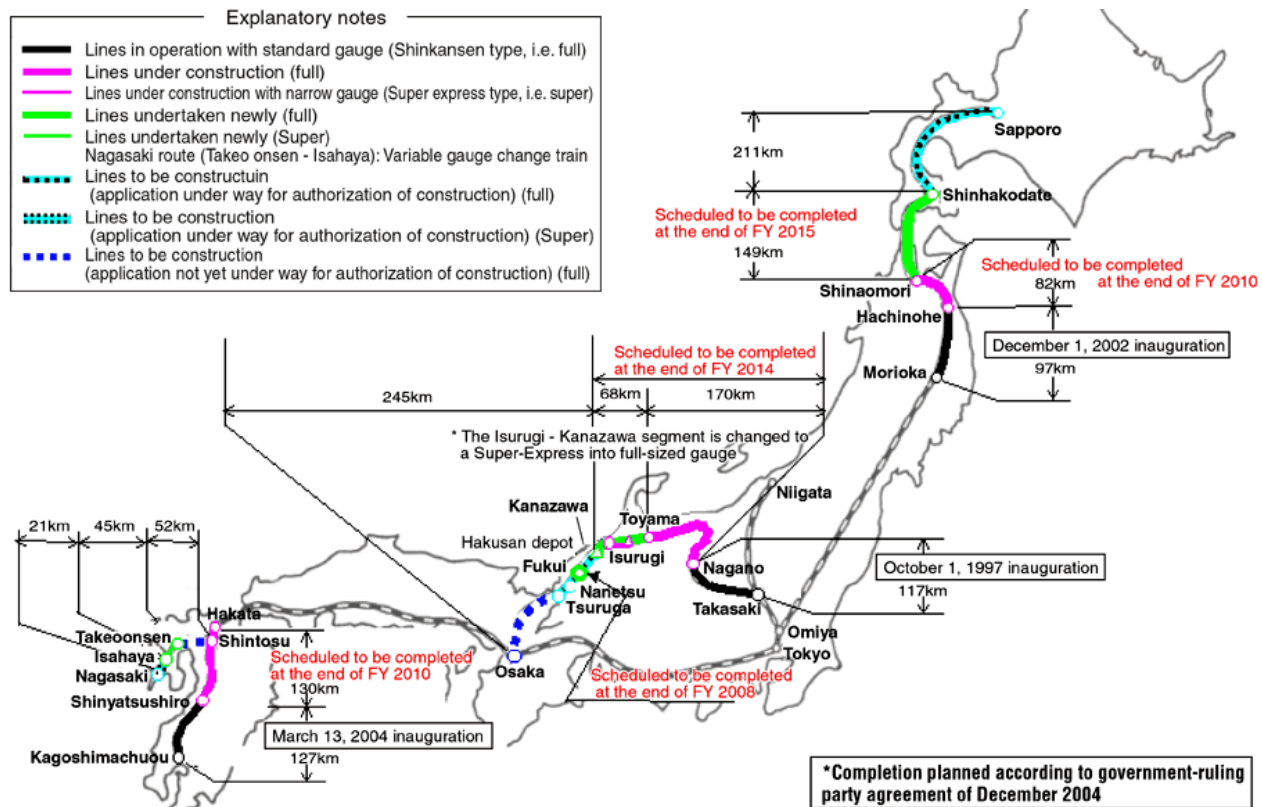**Figure 23. High-speed lines in Japan. (Guide of Japan, n.d.)**

Figure 24. Current status of Shinkansen lines (Ministry of Land, Infrastructure and Transport of Japan, 2010)

The Japanese ballastless track is called *slab track* and is made of prefabricated concrete slabs which are set on a layer of cement mortar and asphalt. This kind of ballastless track has two elastic levels, one between the rail and the slab and other one between the slab and the mortar. To avoid transversal or longitudinal displacements of the slabs, concrete retainers are located every 5 meters. Slabs used in slab tracks are either reinforced or prestressed concrete. Figure 25 and Figure 26 show the Shinkansen track including its measures and the elements is made of.

The steps that must be followed for the construction phase are: fabrication and transportation the concrete slabs to the work area, cement layer execution, concrete retainers setting, slabs fixation and finally asphalt layer spill (CEDEX, 2008a).

Far from Japan, in Spain, a research project started in 2008 following the goal of analysing deeper the Japanese system in order to be able to install it there based on its success in Japan. The responsible for the SULABU project were contacted to know in which phase was the project in March 2015 but they did not give much information but the project is now in stand-by (Alarcón, 2008).

Concerning the loading in this system, Shinkansen tracks carried 10-15 MGT/year of both passengers and freight in 1990 (N. Bilow, et al., n.d.).
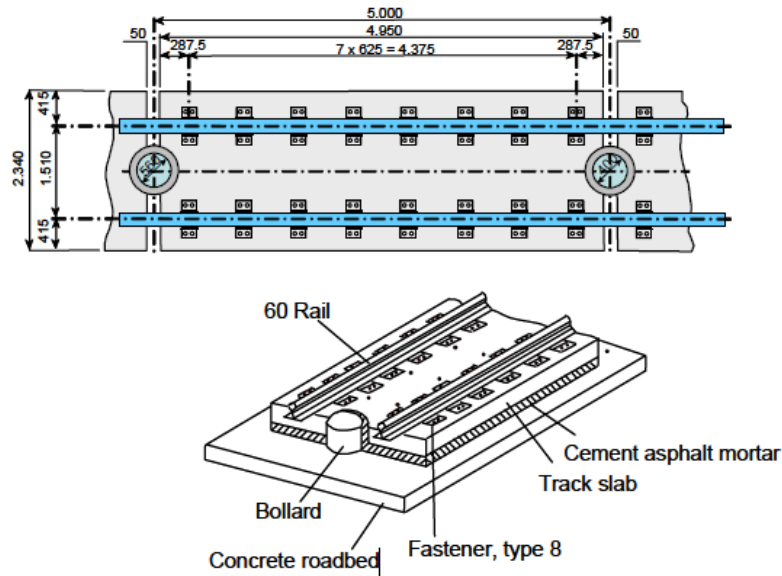
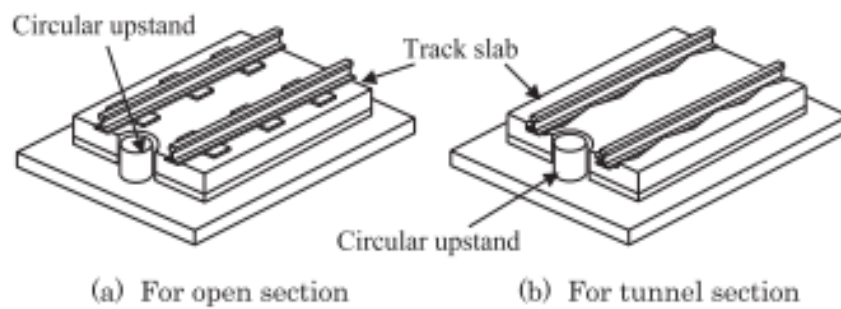**Figure 25. Shinkansen slab** (Esveld, 2003)

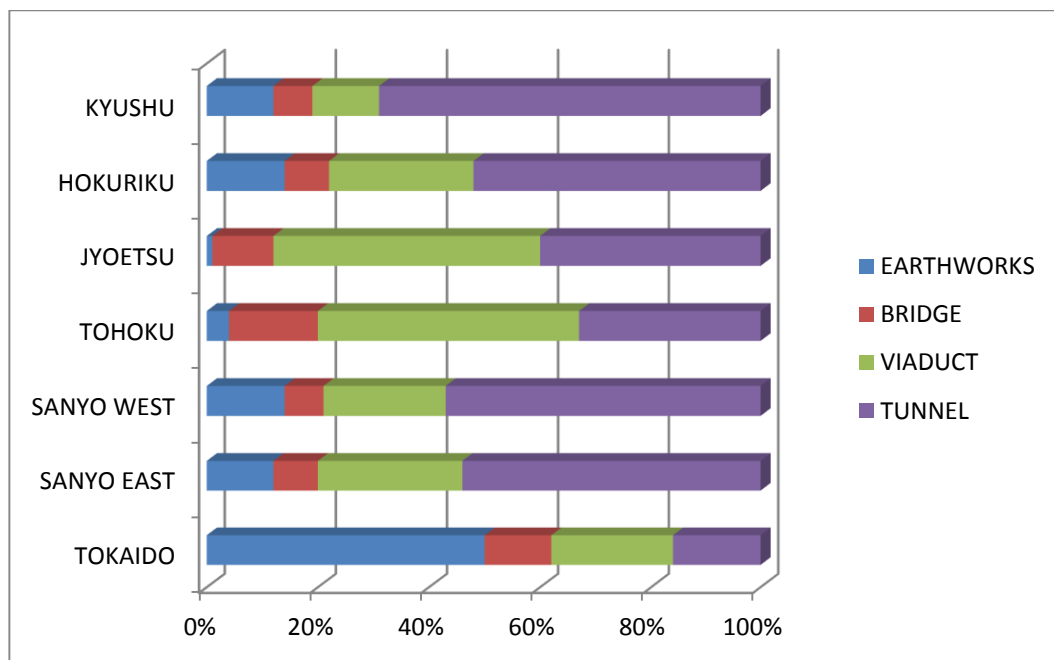**Figure 26. Shinkansen track elements (Ando, et al., 2001)**

Figure 27. Shinkansen infrastructures. Source of data: Railway Research Institute, Japan

LVT (Low Vibration Track)

The origin of LVT was a system composed by bi-block concrete sleepers for ballasted track (Stedef) in the 40´s which was improved for ballastless tracks in the 60´s (Figure 28). Afterwards, the booted single block system was developed and renamed as LVT as Figure 29 shows. Removing the tie-bar implied several advantages such as: increment of rubber boot depth, better behaviour of the track, better track geometry, better electrical insulation and easier track cleaning. The latest model of LVT is LVT HA (High Attenuation) which decreases the cost of mechanical vibration and noise emissions and it is presented in Figure 31 (Soneville AG, 2011).

Soneville AG became the licensor of all slab track components of the system in 1981 after having been developed by Roger Soneville. Currently and since 2009, Soneville AG works together with Vigier Rail AG which is in charge of several concrete rail products in the European market.

The first application of the system was in 1966 in the Botzberg tunnel (Switzerland) where the first variation was used. Nowadays, LVT is widely used in tunnels but also in viaducts and bridges on more than 900 km on track; for instance: underground in Barcelona and Rio de Janeiro, Eurotunnel and in the longest railway tunnel, Gotthard tunnel under construction in Switzerland. Furthermore, the first application in Spanish territory has been installed in the Barcelona-French border line.
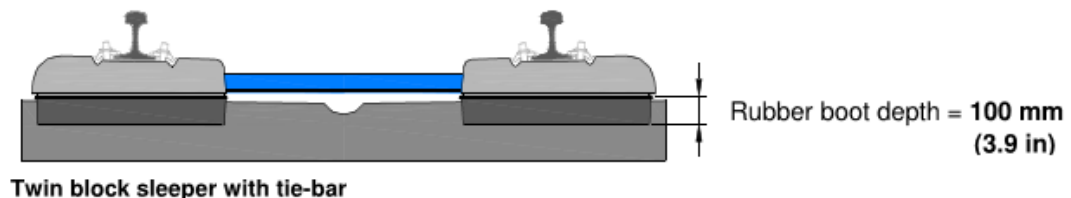

Rubber boot depth = **100 mm**
(3.9 in)

Twin block sleeper with tie-bar

Figure 28. First development of LVT in the 60s (Soneville AG, 2011)

Rubber boot depth = **153 mm**
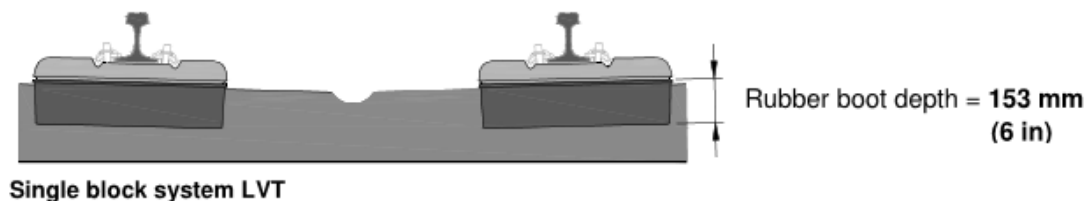**(6 in)**

Single block system LVT

Figure 29. Single block system LVT improvement (Soneville AG, 2011)

Regarding its technical description, it is made of two elastics levels being its main feature to dissipate vibrations and noises. Three parts can be distinguished in each block:

- Individual concrete block. Hard concrete blocks to provide the system with high resistance and durability. It restricts the geometrical tolerance.

- Resilient block pad. A pillow compounded of microcells of nitrogen spread on an elastomeric matrix. The loads of the traffic are spread on this pillow which also varies the density of microcells depending on the loads level.
- Rubber boot. A durable elastic box which involves the block without friction neither with the block nor with the slab. It is also adaptable to the vertical movements of the blocks.
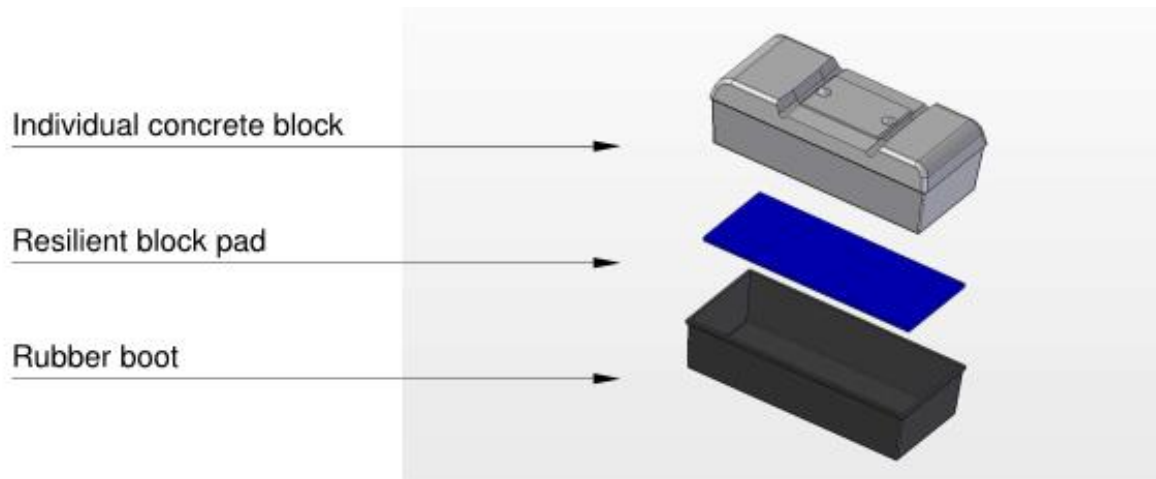

Figure 30. Technical description LVT system (Soneville AG, 2011)

LVT system uses a top-down construction which guarantees an accurate precision in the track geometry.

Concerning the loading, LVT seems to be able to support heavy haul as for instance the Eurotunnel supports 117.8 MGT/year being the busiest tunnel in Europe (Soneville AG, 2011).
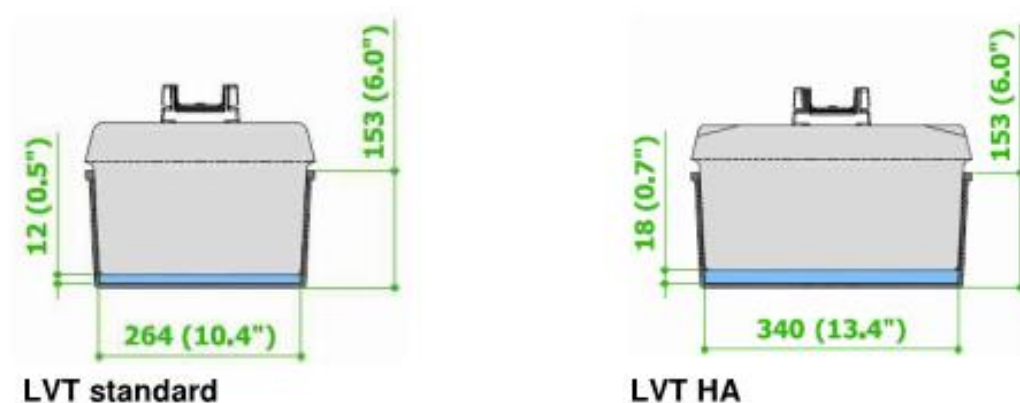

Figure 31. Different wide in LVT systems (Soneville AG, 2011)

EDILON SYSTEM (NETHERLANDS)

Edilon system belongs to Embedded Rail Structures (ERS) which is based on a continuous elastically supported rail. According to Esveld, the whole rail except of its head is surrounded by an elastic compound such as Corkelast. The Corkelast is fixed typically into a concrete slab as the Figure 33 shows or into asphalt in a recent development called ERIA.

Edilon ERS was introduced in the 70´s in Netherlands as the first ballastless system but it was not until 1976 when it was first used for high-speed lines. The INFUNDO system is a further development of EDILON which shares same features with. Currently, it is used in other countries (Madrid Metro-Spain/Light Rail) and also for v≥300 km/h in high-speed lines such as: 7% of Barcelona-French border track and 100 km in HS (Netherlands) (CEDEX, 2008a).

One of the main advantages that ballastless tracks involve is the constant vertical stiffness. Trains running in old ballasted tracks suffer a high stiffness difference when they cross through transitions from or to tunnels, bridges or hard soils. Hence, the concrete slab in ballastless constructions maintains high stiffness along the track and then smooth and faster movement might occur. Sleepered track have been analysed so far which even providing with more constant vertical stiffness than ballasted track, they vary it due to the rail support consisting of discrete points (Esveld, 2003). However, continuous rail offers the following advantages:

- Complete vertical constant stiffness
- Section height savings
- Noise, pollution and vibrations reductions.
- Better rail fatigues performance with high traffic/loading (ZOETEMAN & ESVELD, n.d.)
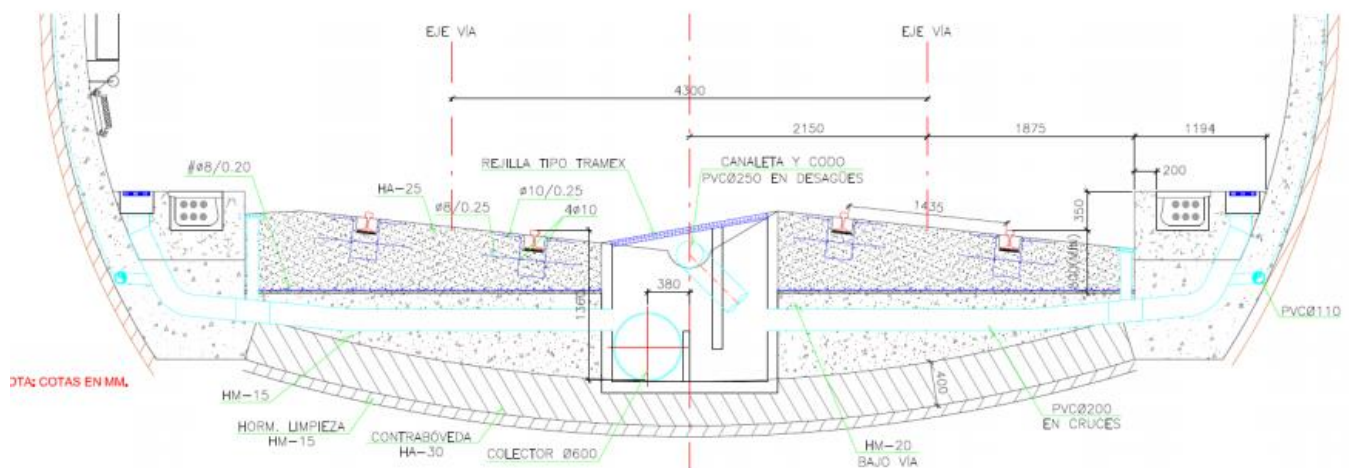- Increased life span (ZOETEMAN & ESVELD, n.d.)

Figure 32. EDILON section in HSR Barcelona-French Border. (Cortina, 2013)

Although the advantages are of great importance, Corkelast is an expensive material, special machinery is also needed for construction and repairing mistakes in alignment is difficult or impossible due to top-down construction method. Developments from the original Edilon system have taken place recently which includes lower noise and less quantity of polyurethane (CEDEX, 2008a).
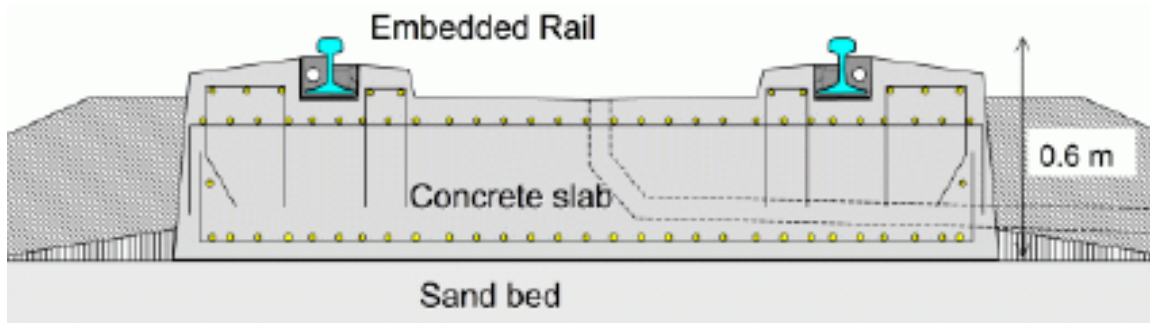

Figure 33. Embedded rail construction EDILON (Esveld, 2003)

Indeed, the features of embedded rail systems generate an interesting background to analyse their costs during their life span but especially during the constructions phase since the alignment cannot be modified.

RHEDA 2000 (GERMANY)

As its name means, Rheda 2000 is a development from a ballastless track which was first used in Rheda station (Lower Saxony, Germany) from Bielefeld to Hamm in 1972. The system includes a track panel made of rails connected by elastic fastenings to sleepers. Moreover, a reinforced concrete slab stands above the supporting layers and below the panel. However, different improvements have been incorporated from the classic Rheda section to the latest Rheda 2000 as Figure 34 shows. For instance, in Rheda 2000 one concrete supporting layer replaced the gaping between the old trough and the concrete track-supporting layer. Also monoblock sleepers were substituted by bi-block sleepers in order to improve the bond between the concrete and them (Kleeberg, 2009).

The great advantage of Rheda 2000 lies behind its simple construction with the no need of special machinery being any construction company able to build it.

A new improvement of Rheda 2000 includes a no reinforced concrete slab with controlled crack formation (Figure 36). Thus, improvements in term of costs, simplification of electromagnetic fields, and better adaptation to soil conditions are achieved when reinforcement is avoided (Kleeberg, 2009).
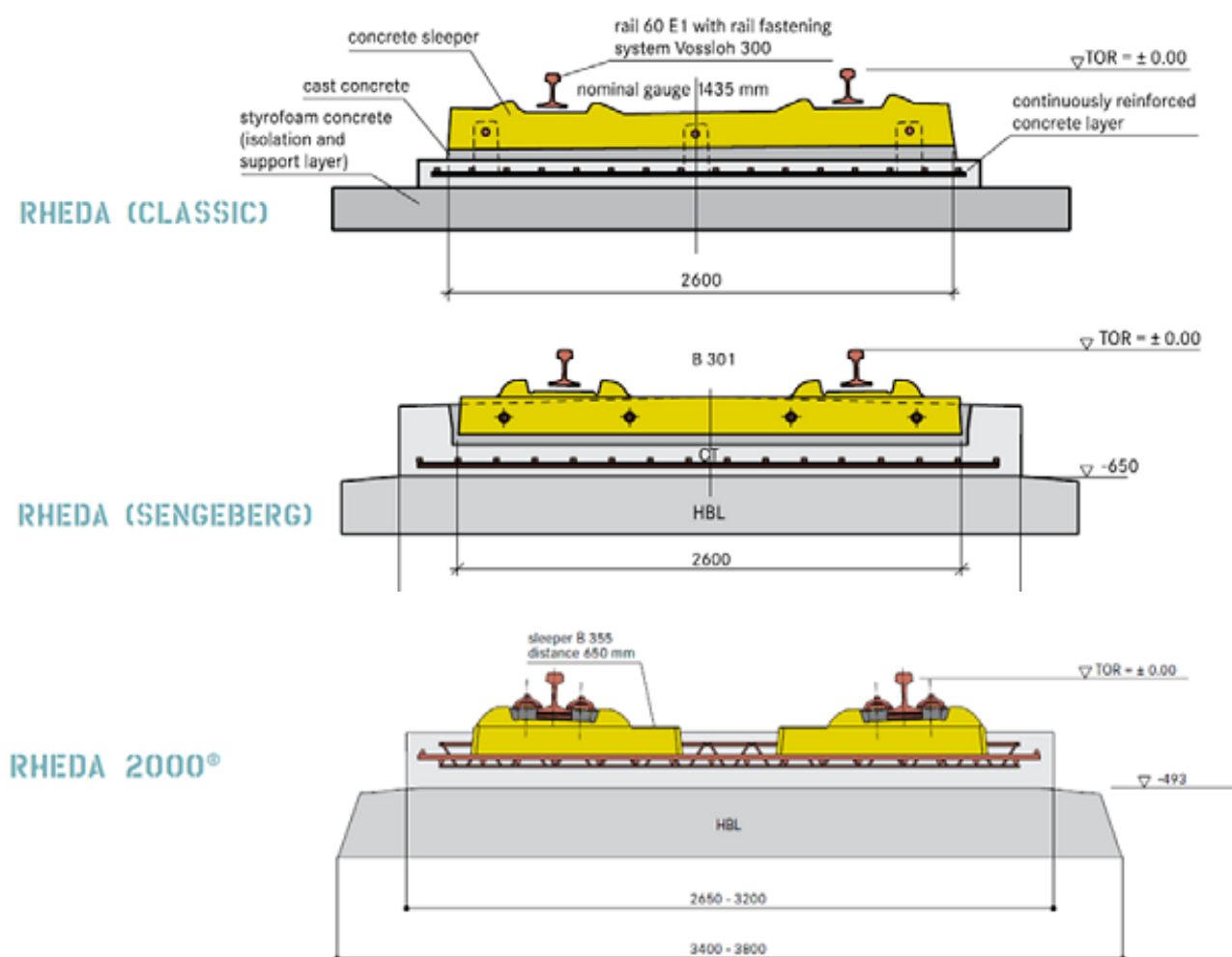
Figure 34. Developments of Rheda (Kleeberg, 2009)

Figure 35. Rheda structure (Esveld, 1999)

Figure 36. Rheda 2000 with controlled crack formation (Kleeberg, 2009)

As Rheda 2000 system has been used in more than 10 countries and in 2,205 km only in Germany, it has large experience on its behaviour and consequently large potential for future developments (Michas, 2012). Especially in Spain, it has been used in trial sections and in several tunnels for instance in the line Barcelona-French border (Figure 22).

FASTRACK (SPAIN)

Fastrack is an on-going development of a new ballastless track which was born in Spain. The project has been developed during 2013 and 2014 among 6 companies seeking to achieve a national competitive product in order to not depend on foreign patents in the future and to decrease the life cycle costs. As there is no experience of this system, no real results can be added to this report.
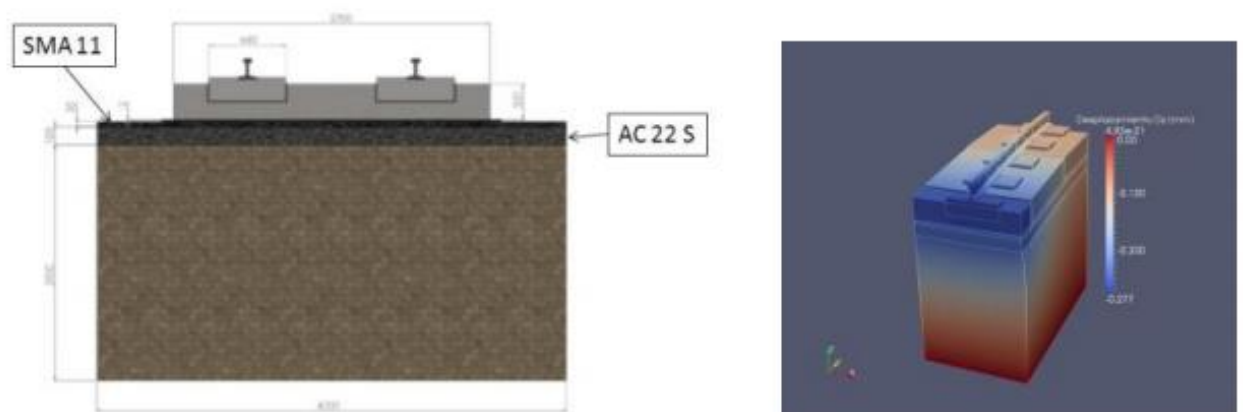
Figure 37. Fastrack section (Fastrack,b, 2013)

The components of a Fastrack section are:

- Two layers of bituminous agglomerate, SMA 11 and AC 22 S. SMA 11 is sustainable bituminous agglomerate used especially on high capacity roads and AC 22 S is hot bituminous agglomerate (SMA, n.d.).
- Concrete slab made with HA-25 and BS-400. Its appearance can be seen in Figure 38.
- Concrete retainers are needed to avoid horizontal or vertical deformations.
- Attenuation pads composed by two layers (Figure 40).

A graphically description of its construction method can be followed in Figure 41.
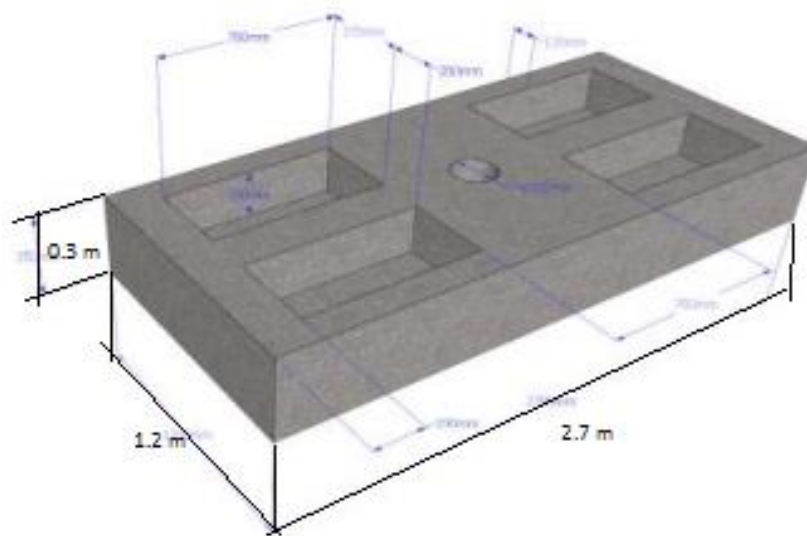
Figure 38. Fastrack concrete slab dimensions (Fastrack,c, 2013)

Figure 39. Concrete retainer (Fastrack,c, 2013)
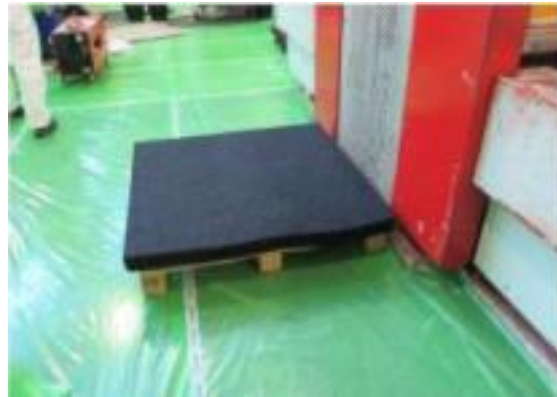
Figure 40. Example of attenuation pads

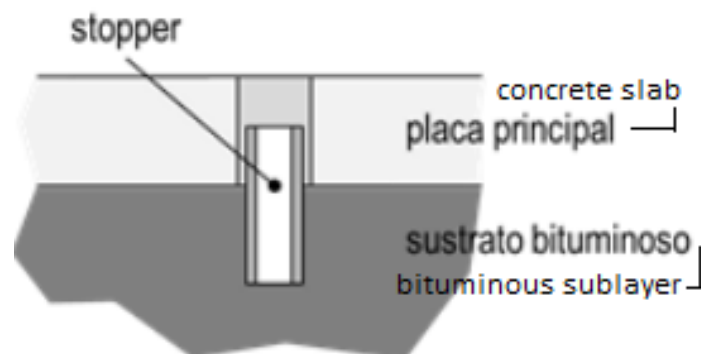**Figure 41. Construction phases (Fastrack,d, 2013)**

ZÜBLIN SYSTEM (GERMANY)

The Züblin system was developed late 70s in Germany. Initially, the sleepers were cast into the concrete slab through vibration as Rheda system. In the latest development of the Züblin

system, the concrete sleepers are connected by steel lattice trusses (Figure 42). This system has been used on 460 km in China (2005) and on 606 km in Germany as Table **3** shows (Züblin, n.d.).
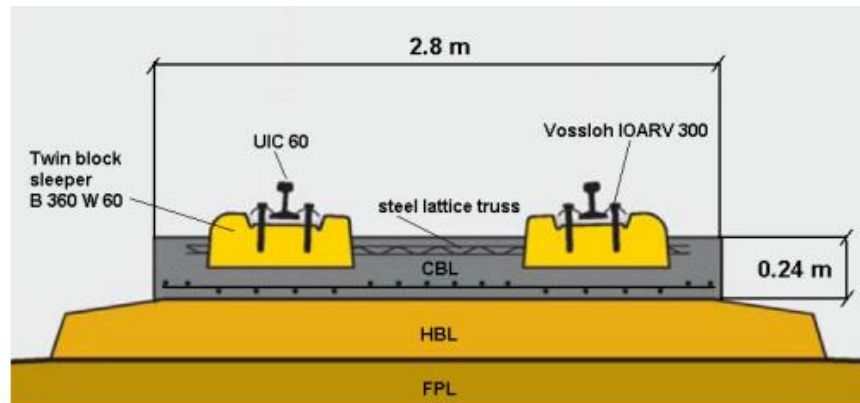
Figure 42. Latest development of Züblin system (Züblin, n.d.)

One of the advantages of this system is the purpose which was developed for, height corrections up to 50 mm. Moreover, the installation of the system is high automatized. However, it has not been taken into account in the research due to the lack of experimental data.
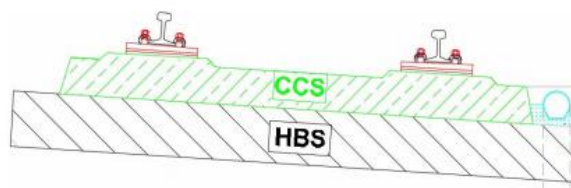
Figure 43. Example of Züblin system in Waghäusel (Germany) (Mörscher, n.d.)

IPA SYSTEM (ITALY)

IPA system (Industria Prefabbricati e Affini) has its roots in the Japanese system. Hence, this system is made of rectangular concrete slabs which are pre-stressed both in

longitudinal and cross directions. The slabs rest on a first layer of cement-asphalt which provides them with elasticity and irregularities compensation. A concrete layer is set below it.

It was first used in Italy in the late 80s between Udine-Tarviso being the first European line over 200 km/h (CEDEX, 2008a). Nevertheless, this system has not been included in the research due to lack of experimental data.
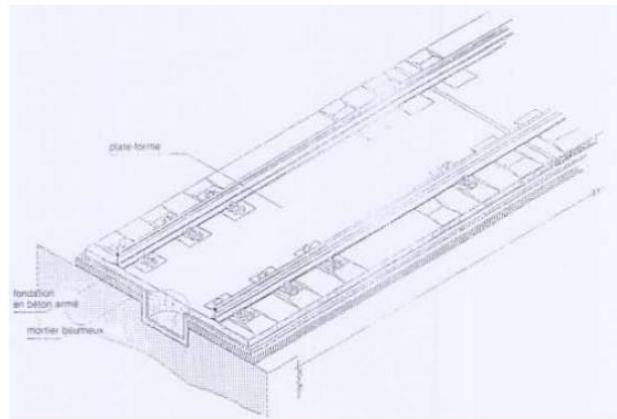
Figure 44. IPA system (Focacci, 1990)

4.3   IDENTIFY THE CRITERIA OF THE MCA
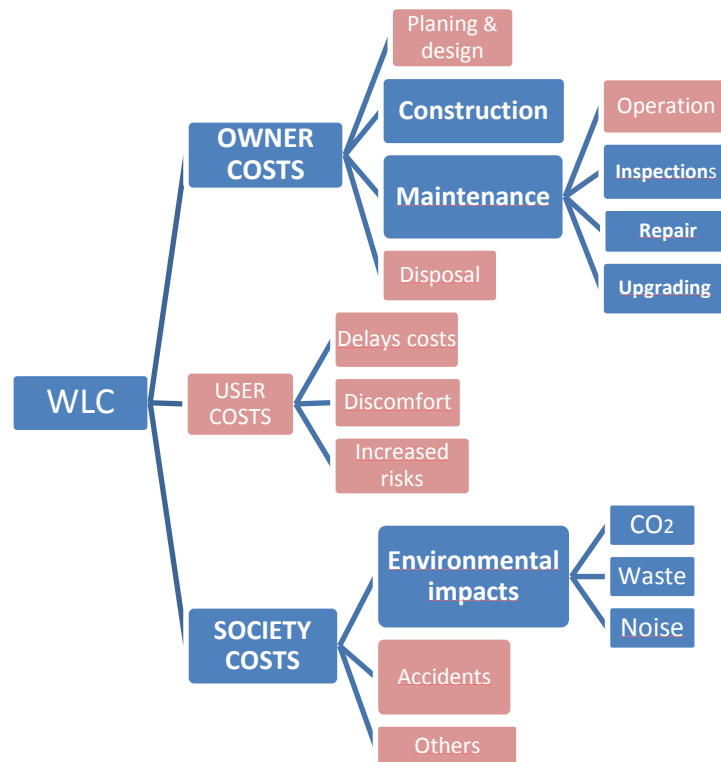
Figure 45. Criteria selected for the MCA

As it has been introduced in the previous chapter, some of the costs that are part of a whole life cycle analysis are not included in this study. Figure 45 shows the selected criteria included graphically in blue colour.

4.4   SCORING THE OPTIONS AGAINST CRITERIA

Following the methodology of the MCA, a performance matrix is the main input data which is likewise objective since information from the stakeholders have been used. Thus, a performance matrix is made through scoring the options included in the study (ballastless tracks) against the selected criteria (types of costs). In this step, constructions and maintenance costs are treated individually and environmental impacts are analysed without taking part of the numerical results. The ratios are varied based on the country and the experience to finally use ratios applied to Spanish territory.

4.4.1   Construction costs (Co_1)

Before going deeper into the construction costs of each system, some differences among the systems have to be explained when costs are analysed. Due to the fact that each system has its own features, details of what the costs include must be specified concerning the superstructure (Figure 46).

	High-speed ballasted track	Shinkansen	LVT	EDILON	Rheda 2000
Rails	x	x	x	x	x
Fasteners	x	x	x		x
Bonding material				x	
Sleepers	x				x
Ballast	x				
Prefabricated concrete slab		x	x		
Concrete slab "on-site"				x	x
Bituminous subgrade		x			
Non bituminous subgrade	x	x	x	x	x

Figure 46. Cost sections depending on the system. Data from: (CEDEX, 2008a)

Furthermore, there are other costs related with the superstructure indirectly which vary with the system too. These sections are summarized as follow without taking part of the present research:

- Ballastless constructions require more subgrade stabilization works.
- Ballastless constructions adapt better to the soil and allow smaller radii (Tifsa, 1999) (Estradé, 2000).
- Ballastless constructions allow height reductions in tunnel sections as well as lighter viaducts (Estradé, 2000).
- Generally, ballastless solutions involve more vibrations and noise which need of special system to reduce them.
- Superficial drainage is required by ballastless system instead of deep drainage from ballasted tracks.
- Need of transition zones between ballasted and ballastless areas.

SHINKANSEN SYSTEM (JAPAN)

The cost indices during the construction of the *Sanyo Shinkansen* (1975) were between 1.3-1.5 times the construction costs of ballasted track in the same line. As Figure 27 shows, 129 tunnels were constructed in the second Shinkansen not being a priori these indices accurate for earthworks (Melis, 2006)

Tohoku Shinkansen, which has fewer kilometers of embankments than Sanyo, needed also 1.3 times more inversion than if it would have been constructed all as ballasted track (Miura & Hideyuki, 1998).

Regarding newer construction of the Japanese system, Table 4 shows construction indices of the *Hokuriku Shinkansen* which vary importantly depending on the slab type. The first two rows are frame-shape slab tracks (Figure 47) which are supposed to reduce even more the construction costs being about 8 to 14% cheaper than earlier slab track constructions costs. There are 130 km of this kind of slab in *Hokuriku Shinkansen* tunnels where it has been achieved a range from 1.1 to 1.6 times more expensive slab track construction comparing with those constructed with ballasted track A. However, special ballasted track B or C* had to be used due to atmospheric conditions rising the price of this traditional construction (Ando, et al., 2001).

In the *Kusyhu Shinkansen*, construction costs decreased in JPY 1bn (approx. 7,679,772.99€) due to frame-shaped slab construction mostly but also due to improvements in the shot concrete quality in tunnels. Moreover, the used of a permeable roadbed in tunnels affected by geological difficulties (Figure 48), contributed to the reduction of JPY 2bn (approx. 15,359,545.98 €) in terms of construction costs. (Centre for Mega projects in transport and development, n.d.)

Table 4. Construction costs ratio in Hokuriku Shinkansen (Ando, et al., 2001).

TRACK TYPE IN HOKURIKU SHINKANSEN	COST INDEX	NOTES
J-Slab track AF 55T	0.92-1.19	Tunnels and viaducts
J-Slab track AF 57	0.86-1.12	Tunnels
Ordinary Slab Track A-55 M	1.00-1.30	Viaduct in warm areas
Slab track A-55C (prestressed)	1.10-1.43	Viaduct in cold areas
Slab track A-55 MN	1.16-1.51	Viaduct in warm areas
Slab track A-55CN (prestressed)	1.26-1.64	Viaduct in cold areas
Ballasted track A	0.77-1.00	
Ballasted track B	1.03-1.34	V≥160 km/h + snowed area
Ballasted track C	0.84-1.10	
Ballasted track C *	1.11-1.44	V≥160 km/h + snowed area

Figure 47. Frame-shape slab / plate slab
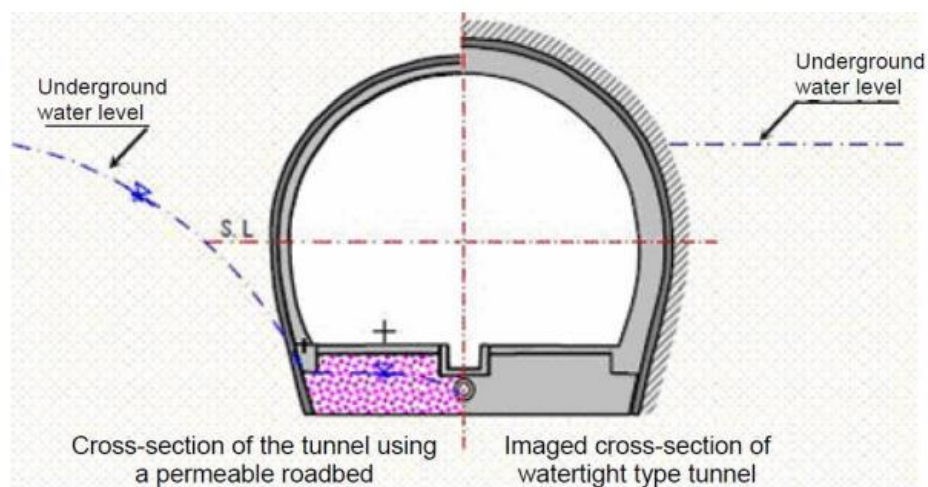
Figure 48. Comparison in tunnel sections. Shinkansen (Centre for Mega projects in transport and development, n.d.)

After the developments made in the following years especially for earthworks slabs (Reinforced Asphalt slab, RA and Reinforced Concrete Roadbed Slab, RCRS) which were tested in a few kilometres *in The Hokuriku, Tohoku and Kyushu*; The Japan Railway Construction Public Corporation stated that construction costs in cuts and embankments were 1.18 and 1.24 times the ballasted track costs respectively including typical subgrade (Ando, et al., 2001).

Even though a ratio of 1.1 was achieved in tunnel construction costs, 1.3 would be a robust value for scoring in the MCA (Table 5) in Japanese territory in order to be preventive since no more researches have been found to support it. However, a ratio of 1.5 has been thought to be a possible value in Spanish territory due to no general automatized production process is established. No references support this decision being only a subjective increment in costs from the author. This index includes slab construction and subgrade stabilization but no specifications have been found regarding fasteners, rails, labour and material costs.
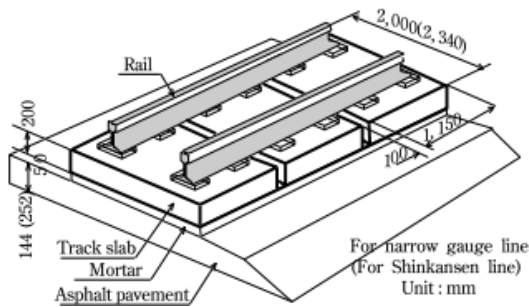
Figure 49. RA-Slab track
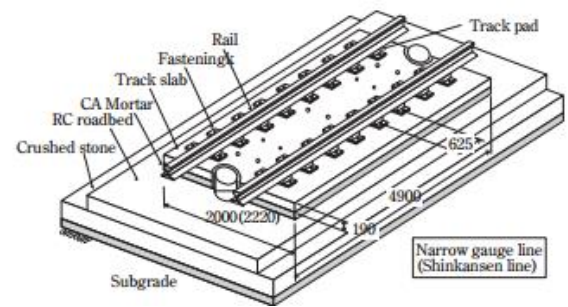
Figure 50. RCRS-Slab track

OWNER COSTS (Co)	SHINKANSEN SYSTEM		
	RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Construction/Investment (Co$_1$)	1.3 (1.5)	4.5	1.3 is a conservative value for Japan since 1.2 was achieved in The Hokoriku. 1.5 is used for Spain as a possible value.

Table 5. Conversion from construction costs ratio to MCA score in Shinkansen system

LVT (Low Vibration Track-Switzerland)

A study carried out by PCA (Portland Cement Association) which was part of the slab track market development program initiated in 2001 reports that:

- 100 miles or 160.934 km of LVT system have 28% (1.28) higher construction costs than ballasted track. This data includes subgrade stabilization, reinforced concrete slab, block ties, fasteners and rail using 2007 U.S. prices for labour and material and also 8% for contractor overhead and profit (PCA, Portland Cement Association, 2008).

A lower ratio of 1.25 was obtained from LVT track works in Lantau and Airport Railway line with the difference of the exclusion of subballast layer but including all components above that level (MTR, 2000).

A ratio of 1.3 for Spain (Table 6) has been thought to be possible due to the fact of having short experience using LVT but being LVT spread out in the world. LVT has been used in Spain for the first time in the Montcada tunnel in the Barcelona-French Border line (2013).

OWNER COSTS (Co)	LVT SYSTEM		
	RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Construction/Investment (Co_1)	1.28 (1.3)	3.9	1.28 is a conservative value since 1.25 was achieved. 1.3 is used for Spain as a possible value

Table 6. Conversion from construction costs ratio to MCA score in LVT system

EDILON SYSTEM (NETHERLANDS)

The study carried out for the High-Speed Line South (Netherlands), which was introduced in the Literature Review chapter, compares two kinds of embedded rail structures with a ballasted track for high-speed. One of them is not integrated into the concrete substructure (NI) and the other one is integrate into it (INT). Furthermore, improvements in ERS NI are possible involving 30% costs reduction if industrial machinery and processes are applied. This analysis obtained the following results regarding the exclusion of concrete slab cost using 5% as discount rate and being the costs units EUR/m/year (Esveld, 1999):

- A ratio of 1.2 was obtained when comparing ERS NI with the ballasted track.
- A ratio of 0.86 was obtained when comparing ERS NI (optimized) with the ballasted track.
- A ratio of 0.91 was obtained when comparing ERS INT with the ballasted track.

For the MCA, a ratio of 1.2 has been chosen (Table 7) since it is a conservative data due to the exclusion of the concrete slab and the influence in favour of ballastless track of 5% discount rate.

Furthermore, EDILON has been installed in tunnels recently in Spain increasing the experience of this system in the country and then lowing the prices in the production stage overall.

OWNER COSTS (Co)	EDILON SYSTEM		
	RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Construction/Investment (Co_1)	1.2 (1.3)	3.9	It is conservative data suitable for Spain

Table 7. Conversion from construction costs ratio to MCA score in EDILON system

RHEDA 2000 (GERMANY)

Several researches have been done related to Rheda 2000 construction costs.
For the Köln/Rhein-Main line studies were done with data from the line Köln-Frankfurt both in Germany (Tifsa, 1999). The results of the study are shown in Table 8.

- Globally, double construction costs were applied when Köln/Rhein-Main was decided to be built with Rheda 2000.
- Rheda system (Heilit & Woerner) and ballast UIC 60 B70/W60 were used for the study. Ballastless track in earthworks needs more degree of precision but also less safety area (approx. 2.5 m) which could decrease construction costs 7.8%.

Same research (Tifsa) analysed the Madrid-Seville line which is ballasted track originally and also a trial section of Madrid-Barcelona line. Both were compared in terms of costs as if there were Rheda system. The data used was taken from the line Köln-Frankfurt that was also used for the Köln/Rhein-Main. It has to be said that there are big uncertainties taken those data since the conditions of those lines in Germany are not the same than in Spain. The Table 9 and Table 10 show the construction costs ratios for the superstructure (including concrete slab) from the results of those studies (Tifsa, 1999) and (Puebla, et al., 2000). All results double the price of Rheda system compared with the traditional option.

KÖLN-FRANKFURT	FEATURES	RATIO C.C. SLAB TRACK/BALLASTED TRACK
EARTHWORKS	Less safety area decreases costs in 7.8%	1.9
TUNNEL	If the assembly process is improved: 1.2. Savings in height only 10 cm	1.5
VIADUCT	/	3.8

Table 8. Ratio construction costs in the Köln-Frankfurt line (Germany) (Tifsa, 1999)

MADRID-SEVILLA	FEATURES	RATIO C.C. SLAB TRACK/BALLASTED TRACK
SECTION 1 (MADRID-GETAFE)	2.02% TUNNELS 28% URBAN AREA	2.05
SECTION 2 (GETAFE-CÓRDOBA)	2.1% VIADUCTS 5.1% TUNNELS 42% BUMPY PROFILE	2.018
SECTION 3 (CÓRDOBA-SEVILLA)	MORE BUMPY PROFILE	2.09

Table 9. Ratio construction costs in Madrid-Seville line (Spain). Data from Colonia-Frankfurt (Germany) (Tifsa, 1999) & (Puebla, et al., 2000)

MADRID-BARCELONA	RATIO C.C. SLAB TRACK/BALLASTED TRACK
TRIAL SECTION	2.11

Table 10. Ratio construction costs in Madrid-Barcelona line (Spain). Data from Köln-Frankfurt (Germany) (Tifsa, 1999) & (Puebla Contreras, et al., 2000)

From Esveld LCC studies in the HSL-S (Netherlands), the following conclusions for the superstructure have been taken excluding concrete slab costs:

- 1270 €/m of Rheda system was estimated to be the construction costs in prices from 1999.
- 1.27 is the ratio comparing Rheda and ballasted construction costs in this line.

According to another comparative study (Miarnau & López, 1999):

- A ratio of 2.37 was achieved comparing again Madrid-Seville line as if its superstructure was built with Rheda 2000 with 1997 prices (Table 11).
- A ratio of 1.243 was achieved in the line Manheim-Stuttgart (mainly tunnel, Germany).
- The highest ratio was obtained in France. Rheda system was stated to be 2.86 times more expensive in this country.

COUNTRY	BALLASTED TRACK (M€/100 KM)	RHEDA TRACK (M€/100 KM)
SPAIN	41.11	97.78
GERMANY	45.20	56.19
FRANCE	32.15	91.95

Table 11. Comparison of superstructure construction costs ballasted-Rheda track in different countries. Prices 1997 (Miarnau Montserrat & López Pita, 1999)

As it can be seen, Rheda 2000 construction costs ratios vary greatly among countries and sources of data.

Recently, a study for the Barcelona-French border line stated that EDILON and Rheda 2000 were not far between each other regarding constructions costs. That is the reason to have chosen a ratio of 1.5 (Table 12) instead of higher ratios expected by other sources for Spanish territory regarding the large experience on this system in the country (Cortina, 2013).

OWNER COSTS (Co)	RHEDA 2000 SYSTEM		
	RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Construction/Investment (Co$_1$)	2.37 (1.5)	4.5	Wide range of ratios. 1.5 is a suitable value for Spain

Table 12. Conversion from construction costs ratio to MCA score in RHEDA 2000 system

ZÜBLIN SYSTEM (GERMANY)

According to the comparative study of Miarnau Montserrat, Züblin system was also analysed in terms of construction costs in the line Mannheim-Stuttgart (Germany) taking into account maximum speed of 250 km/h, 85% of tunnels and 15% of viaducts. Hence, a ratio of 1.44 was obtained comparing Züblin and ballasted track (Miarnau & López, 1999).

This data has not been used in this report since there are no enough sources of data to be robust.

4.4.2   Maintenance costs (Co2)

SHINKANSEN SYSTEM (JAPAN)

The Japanese experience is the largest one being a useful tool to get an overview of the maintenance costs. *Sanyo and Tohoku* line are the oldest and obviously they have more data than the newest *Shinkansen*. However, the technology has improved and the ratios provided by the stakeholders might be better currently. In a report of 1992, Japan Railway Technical Service stated that slab track requires little maintenance in relation with niveling, alignment repairs and cracks in the asphalt or mortar layer.

Indeed, under the period 1975-1984 *Sanyo Shinkansen* was analysed given that niveling must be done each 40 years and fixation in the alignment each 24 years. On the other hand, the asphalt mortar needs some maintenance three times a year (CEDEX, 2008b). According to Melis, *Shinkansen* needs 25% of the maintenance required by a ballasted track. This data is also supported by other authors who specify that *Tohoku*'s maintenance costs ratio was 0.33 in 1994, *Sanyo*'s ratio was 0.20 in 1994 and the same *Sanyo Shinkansen's* ratio increased to 0.25 in 2001 (Ando, et al., 2001). Hence, a ratio of 0.27 has been chosen as robust input data to represent the maintenance ratio in the MCA either for tunnels, earthworks or viaducts in Spain (Table 13). The ratio has been increased since the lowest maintenance ratio happened only in Japan. Figure 51 shows graphically that tamping was reduced compared with ballasted tracks as well as levelling overall in the 80s and 90s.

However, maintenance costs in earthworks are directly related with the quality of the soil and geological properties which they must be notable good to achieve low costs. Therefore, final settlements are fixed to be less than 30 mm as well as a well performed distribution of loads on the slabs. These two conditions were tested in the RCRS slab for earthworks obtaining the expected results (Ando, et al., 2001).

There are some tips to point out when comparing Japanese slab track with French or Germany solutions in terms of maintenance features. There is no need of demolition when a renovation must be done being also faster due to high level of systematization (not in Spain). Furthermore, hardening time for asphalt mortar is only 24 hours which is much lower than several days for concrete one. Thus unserved line time is reduced comparing with other ballastless tracks solutions (Alarcón, 2008).
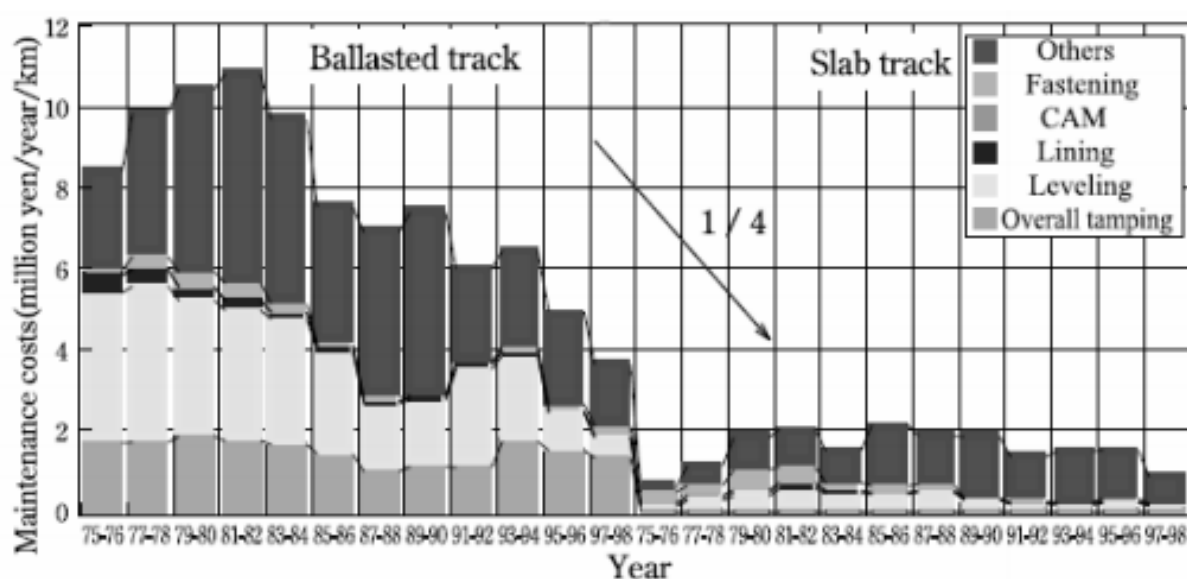
Figure 51. Comparison maintenance costs on tracks in Sanyo Shinkansen (Ando, et al., 2001).

The following table shows the conversion from the costs ratios to the score for the MCA analysis following the methodology explained in the previous and present chapter.

OWNER COSTS (Co)		SHINKANSEN SYSTEM		
		RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Maintenance (Co₂)	Inspection	0.25 (0.27)	0.81	Source: (Melis, 2006)
	Upgrading			
	Repairing			

Table 13. Conversion from maintenance costs ratio to MCA score in Shinkansen system

Previous life cycle studies of Japanese slab track have stated that a minimum of 12 years of commercial operation is needed to compensate the initial investment through lower maintenance as Figure 52 represents. Nevertheless, 10 years of amortization could be achieved if the load of the track is more than 12 Mio Gross tonnes/years (REN, et al., 2008).

Generally, the Japanese system gives good results due to the large mechanization existing nowadays in the country which could be improved in other countries such as Spain. However, some disadvantages that have been found in the *Shinkansen* performance are (N. Bilow, et al., n.d.):

- Minor cracks due to alkali-silica reaction and in cement asphalt mortar layers
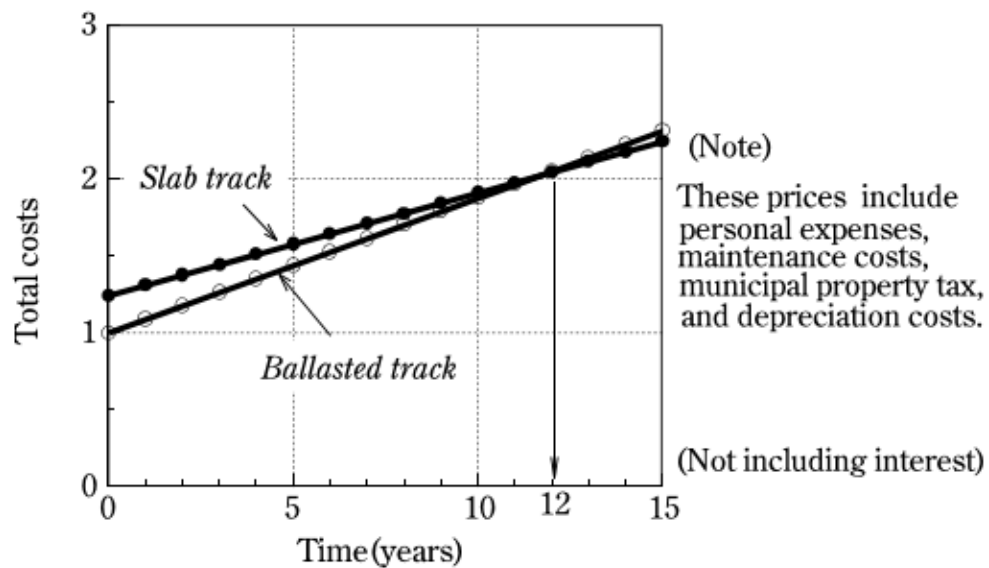- Some warping in the slabs in tunnels

Figure 52. Comparison in total costs between ballasted and ballastless track (Ando, et al., 2001)

LVT (Low Vibration Track)

Same study (PCA) that gave results for construction costs, added all the expenses of LVT system in a life cycle cost analysis which included the present value of maintenance, operating, derailment, and construction costs. The results showed that the total costs due to LVT installation are 8% less than the ballasted track costs. In Figure 53, the cost differences in each area are compared showing that the largest different between both systems is hold in the maintenance costs. As operation and derailment costs are out of the limitations of this study, a graphically approximation of the maintenance costs ratio has been used as follows:

⇨ 1.03e+007 M$ has been used as ballast track maintenance costs
⇨ 0.8e+007 M$ has been used as slab track maintenance costs
⇨ The result shows that slab track maintenance costs are 0.777 ballast maintenance costs.

From experience, LVT system has been used without any maintenance for 15 years in Switzerland. Moreover, its first development used in The Botzberg tunnel has needed no maintenance during its 50 years of life (Soneville AG, 2011). Although in Spain there is no experience due to the first section was installed in 2013, the comparative study made for Barcelona-French border line shows that LVT maintenance costs are in the same range than Rheda 2000 (Cortina, 2013).

Thus, a ratio of 0.8, which is supported graphically by Figure 53, has been decided to lower to 0.7 for the MCA due to the conclusion from the Spanish research (Table 14).

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OWNER COSTS (Co)		LVT SYSTEM		
		RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Maintenance (Co$_2$)	Inspection	0.8 (0.7)	2.1	0.7 is a suitable value for Spain.
	Upgrading			
	Repairing			

Table 14. Conversion from maintenance costs ratio to MCA score in LVT system
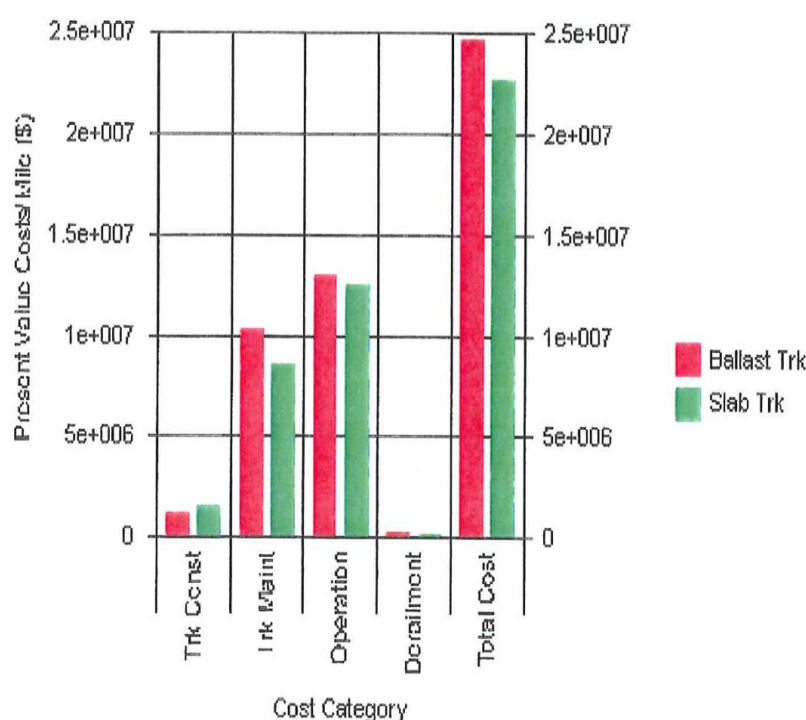
Figure 53. LCCA of LVT system (PCA, Portland Cement Association, 2008)

EDILON SYSTEM (NETHERLANDS)

From the same study used to estimate EDILON construction costs in Netherlands (Figure 2), it has been obtained an approximation ratio of global maintenance costs of 0.47 using as reference ERS NI and ballasted track in the NPV analysis (5% as discount rate). The approximations have been taken graphically and the data comes from Esveld LCC studies (Esveld, 1999):

- Mechanical maintenance: ERS-NI is 0,565 times cheaper than ballasted.
- Manual maintenance: ERS-NI is 0.375 times cheaper than ballasted.

Even though a value of 0.47 has been estimated for the MCA, it has been decided to increase the ratio to 0.5 for Spanish territory due to the conclusions obtained by the research from Barcelona-French border line as it is shown in Table 15.

EDILON system is considered to be the cheapest system comparing it with block systems and sleepered systems (Cortina, 2013).

OWNER COSTS (Co)		EDILON SYSTEM		
		RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Maintenance (Co$_2$)	Inspection	0.47 (0.5)	1.5	-
	Upgrading			
	Repairing			

Table 15. Conversion from maintenance costs ratio to MCA score in EDILON system

RHEDA 2000 (GERMANY)

From 1989 to 1994, maintenance costs in the Mannheim-Stuttgart line were analysed both with Rheda 2000 and with ballasted track obtaining that the slab track system cost on average 0.20 times the maintenance costs of ballasted track as Figure 54 y Figure 55 show below (REN, et al., 2008). Nevertheless, a lower ratio between 0.1-0.15 was proposed by Münchschwander for the line Berlin-Hannover (Germany) (Münchschwander, 1998/1999).

Concerning the famous Köln/Rhein-Main line (Germany), maintenance costs were found to be 30% higher than expected ones before its construction (Lichtberger, 2011).
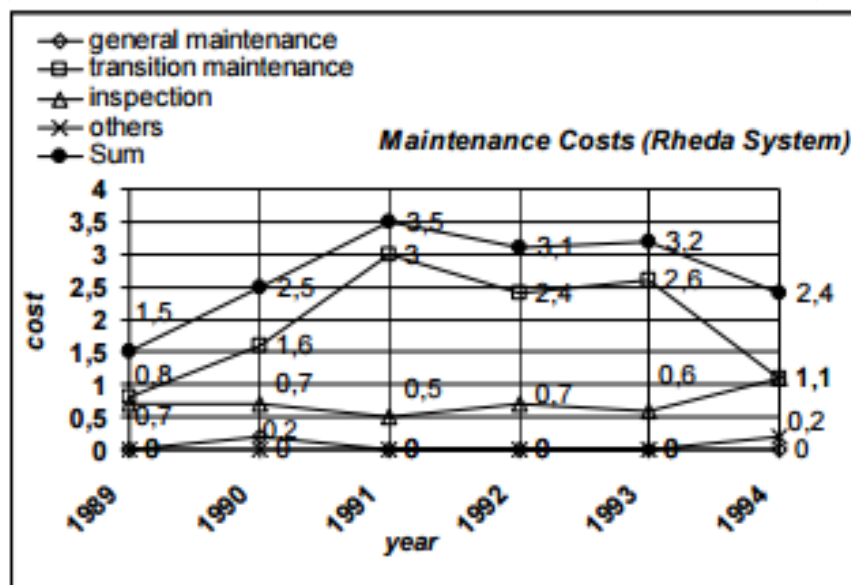

Figure 54. Maintenance costs of Rheda system in prices of 2008 (EUR/km). (REN, et al., 2008)
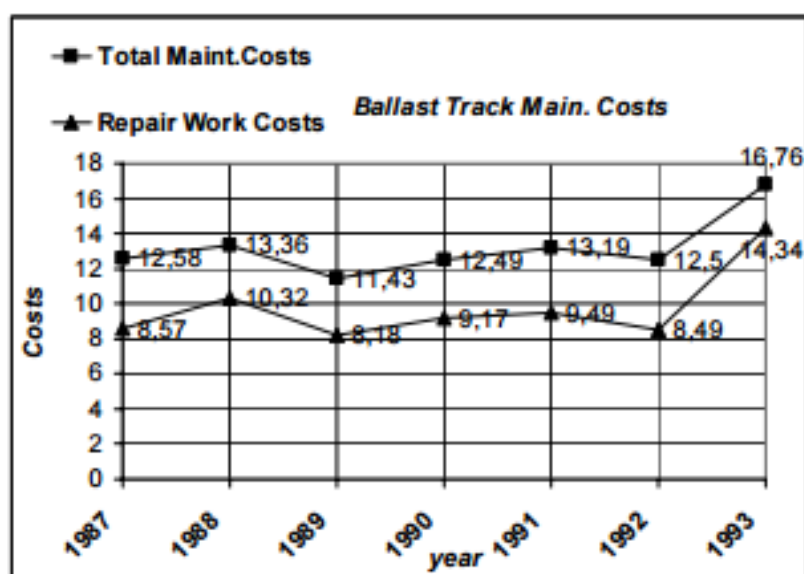
Figure 55. Maintenance costs of ballasted system in prices of 2008 (EUR/km). (REN, et al., 2008)

In the Madrid-Barcelona line, another study was carried out which applied a ratio much higher than the one found in the German line, ballastless maintenance costs were supposed to be 0.46 times lower than ballasted ones (Tifsa, 1999).

Furthermore, the conclusions from the study from Barcelona-French border agree with higher ratios similar to LVT maintenance costs. Thus, a ratio of 0.5 has been chosen as suitable for Spain and for this study concerning the MCA as the table below shows.

OWNER COSTS (Co)		RHEDA 2000 SYSTEM		
		RATIO SLAB TRACK /BALLASTED TRACK (SPAIN)	SCORE IN MCA	NOTES
Maintenance (C_{o2})	Inspection	0.46 (0.5)	1.5	0.5 is a conservative value for Spain
	Upgrading			
	Repairing			

Table 16. Conversion from maintenance costs ratio to MCA score in Rheda 2000 system

IPA SYSTEM (ITALY)

Other research which has not been included in the calculations due to lack of data is related to the Italian solution. The report concludes obtaining a range between 3-14% (0.03-0.14) concerning the savings achieved in maintenance costs by the ballastless Italian system compared with the traditional track in 1990. Therefore, those ratios are

the lowest of this report but the lack of more sources make them no robust (Focacci, 1990).

4.4.3   Environmental impacts evaluation (Cs)

As part of a railway track life cycle study, environmental impacts are important to be analysed. In this report, impacts which difference the tracks studied have been explained in this section. The impacts which vary depending on the type of track used are noise and vibrations mainly. Indeed, Figure 56 gives an idea of vibration values in a tunnel section when a train is passing through for different slab tracks. For instance, for low vibration values embedded slab track (FST) seems to have more vibrations. On the other hand, for high vibration values Rheda 2000 increases its vibration more than the rest of them.

<div align="center">SHINKANSEN SYSTEM (JAPAN)</div>

Previous researches have stated that the major environmental problems of *Shinkansen* system are related with the noise produced by the trains. Actually, the noise has great impact in the entrance and exits of tunnels which are also the most common type of structure in Japanese railways. As the speed of the train increases, the line-side noise of the trains has become also a problem since the 70s when the *Tohoku* and *Joetsu* were being built. However, this kind of issue is not precisely related with the track itself but with the type of structure designed especially in this case with the percentage of tunnelling required. The difference on noise emissions between ballasted and slab tracks are on average only 5 dB louder for slab tracks. For so, no special measures are normally taken for slab tracks (Ando, et al., 2001).
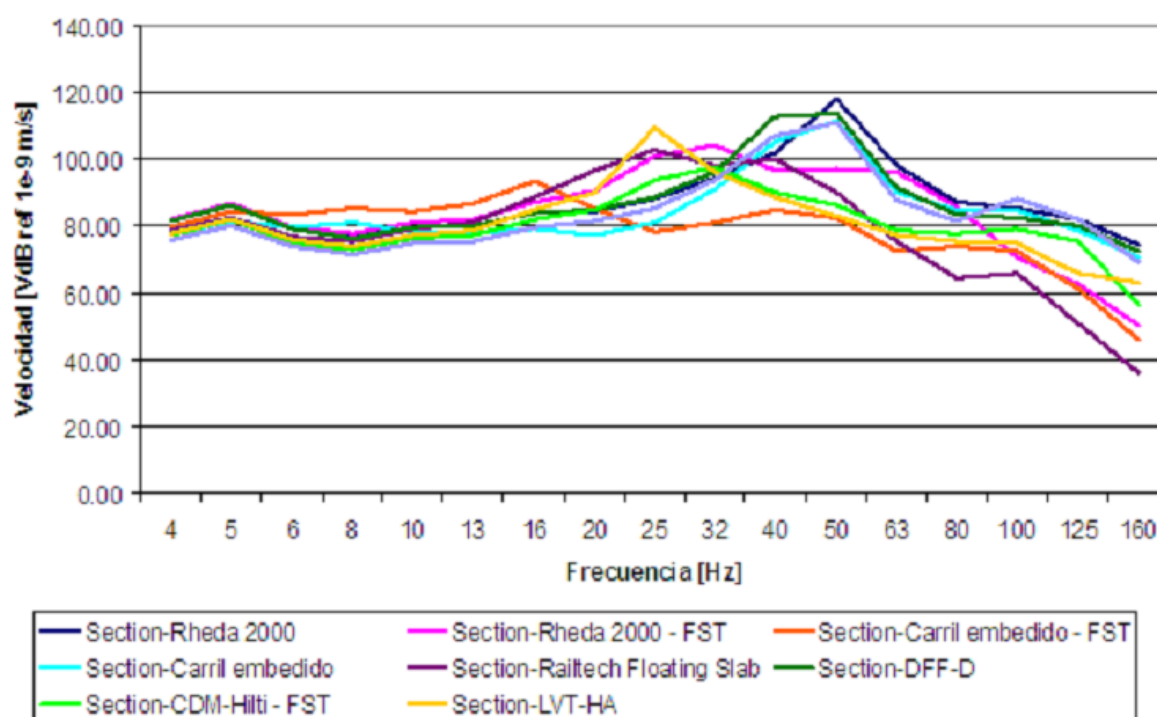
Figure 56. Vibration (Hz)-Speed(dB) in a tunnel section for different ballastless tracks (D2S International, n.d.)

The noise limit is fixed in 75 dB in 86% of the length due to the fact that *Shinkansen* lines run mostly in commercial areas rather than urban areas. Besides the walls along the tracks, the following improvements have been added to ballasted and slab tracks (Okada, 1994):

- Track structure and current-collecting system have been improved.
- Interferences type sound barriers have been developed (walls).
- Car weight has been reduced, and rail and wheel tread cutting methods have been developed.

Furthermore, another environmental issue is related to the emissions as a primary problem against the global warming. As the Figure 57 suggests, the **CO_2 emissions** by car and by plane are seven and five times respectively higher than by *Shinkansen* train regardless expected improvements in The 700 Series *Shinkansen*. The author compares that reduction with the assumption of replacing with trains the flights from/to Haneda (Tokyo) to/from Osaka, Okayama and Hiroshima (*Shinkansen* destinations), which are about 110 out of 720 per day. Indeed, CO_2 emissions would be reduced by 200,000 T/year which is equivalent to the emissions from all the domestic flights in Japan in a month (Kasai, 2003).

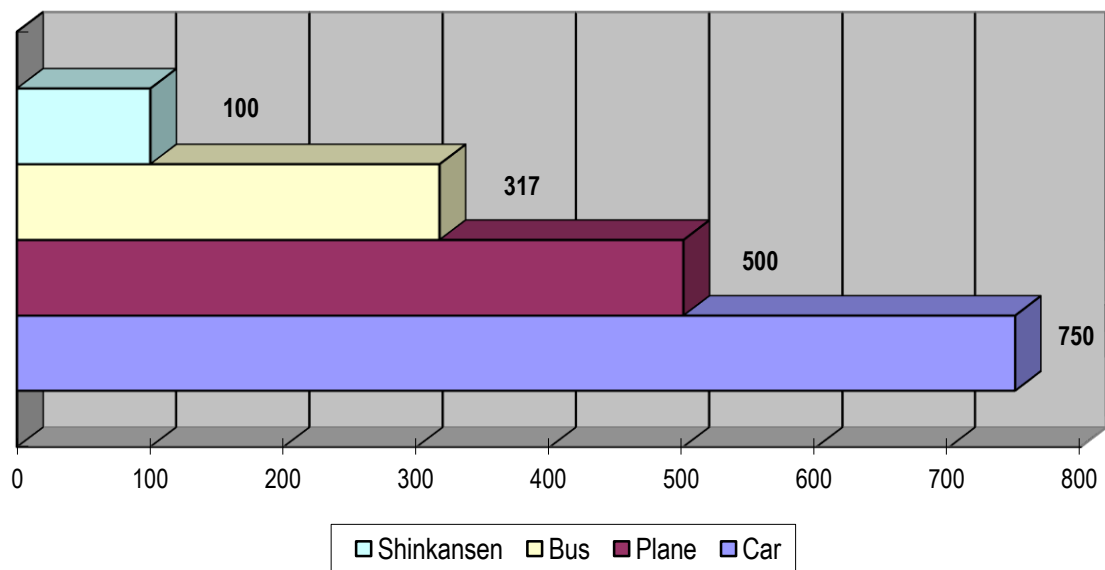**Figure 57. Comparison of CO2 emission in different transports taking Shinkansen as the basis (100) (Kasai, 2003)**

LVT (Low Vibration Track)

As it has been explained before, LVT system is used in areas where more noise and vibrations are generated such as tunnels or viaducts. Due to its function, it works for the environment benefit. Two systems which are accomplished in the track are used as

mitigation measures: LVT HA with single block sleepers and HAS (High Attenuation Sleeper). The first one was measured in a test section by EIFFAGE-RAIL providing it with a reduction of 40 Hz and above compared with ballasted track (Terno, 2011).

EDILON SYSTEM (NETHERLANDS)

A test carried out in a section of The HSR Barcelona-French Border, has compared EDILON system with Rheda 2000 regarding noise and vibrations. The test has used two trains, one running up to 250 km/h (AVE S-100, passenger train) and other one running up to 100 km/h (MERCANCIAS MIII, freight train). The test concluded proving that although EDILON transmitted fewer vibrations on average for both trains (Figure 58 and), vibrations from Rheda 2000 are within the limits too (Cortina, 2013).

A loss from 63 Hz to 250 Hz (benefit class B/C) and a loss from 8 Hz to 16 Hz (benefit class A/B) compared with ballasted track were obtained in another track test in the Mainline (Germany) (Terno, 2011).
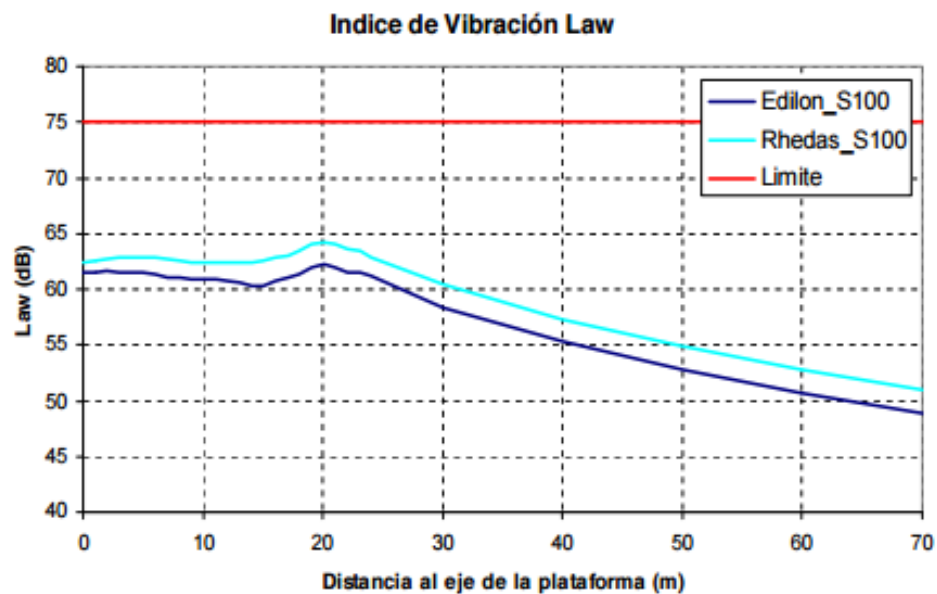
Figure 58. AVE S-100 250 km/h vibrations. Law (dB)-distance from platform axis (m) (Cortina, 2013)
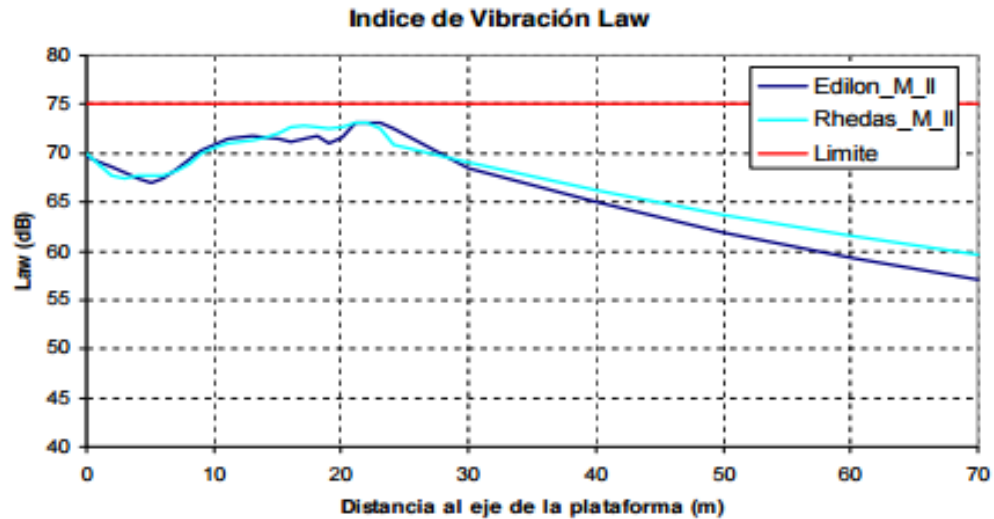
Figure 59. Freight train 100 km/h vibrations. Law (dB)-distance from platform axis (m)
(Cortina, 2013)

RHEDA 2000 (GERMANY)

Regarding noise impact from Rheda 2000 system, the test carried out in the section of The HSR Barcelona-Frech Border proved that it produces light higher noise than EDILON (Cortina, 2013).

A method which is extended in order to damp vibrations in Rheda 2000 is the spring-mass system for instance in the Cologne-Bonn Airport Link and in the Berlin North-South Link. Depending on the level of vibrations to damp different systems are used such as elastomer mats, elastomer blocks or steel springs (RAIL.ONE, 2005).

4.5   WEIGHTING CRITERIA

Once the performance matrices have been formed through the scoring step, weighting factors are chosen and explained during the present section. As it has been introduced, weighting factors depend both on where the costs are located in the life cycle of 60 years and on the discount rate in this case 3% or 6%. In this report, maintenance costs have been equally divided during the 60 years. Nevertheless, it is interesting to know that normally those costs are located at the end of the life period. This fact does not influence in this study due to comparing ballastless systems among them. It does influence the effect of the discount rate.

SHINKANSEN SYSTEM (JAPAN)

Shinkansen present value features have been analysed.

Tables 17 and 18 show kj factor with 6% and 3% as discount rate respectively assuming that each year includes same prices:

- Inspection period is periodically.
- Upgrading and repairing are possible:
  - Nivelling maintenance was carried out each 40 years in the *Sanyo Shinkansen* between 1975 and 1984.
  - Alignment maintenance was carried out each 24 years in the same period.
  - Asphalt concrete layer needs some kind of maintenance 3 times a year.

OWNER COSTS (Co)		SHINKANSEN SYSTEM 6% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is disocunted in year 0
Maintenance (Co2)	Inspection	16.1614	Periodically, mostly fasteners
	Upgrading		Possible to correct elements
	Repairing		Possible to change elements

Table 17. Weighting criteria in Shinkansen system 6% d.r. Source of data (Pañero, n.d.)

OWNER COSTS (Co)		SHINKANSEN SYSTEM 3% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is discounted in year 0
Maintenance (Co2)	Inspection	27.6756	Periodically, mostly fasteners
	Upgrading		Possible to correct elements
	Repairing		Possible to change elements

Table 18. Weighting criteria in Shinkansen system 3% d.r. Source of data (Pañero, n.d.)

LVT (Low Vibration Track)

LVT present value features have been analysed.

Tables 19 and 20 show kj factor with 6% and 3% as discount rate respectively assuming that each year includes same prices:

- Inspection period is periodically.
- Upgrading is possible but not always likely.
- Repairing is mostly related with water filtration problems in the blocks.

OWNER COSTS (Co)		LVT SYSTEM 6% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is discounted in year 0
Maintenance (Co2)	Inspection	16.1614	Periodically, mostly fasteners
	Upgrading		Possible to correct elements
	Repairing		Possible to change elements

Table 19. Weighting criteria in LVT system 6% d.r. Source of data (Pañero Huerga, n.d.)

OWNER COSTS (Co)		LVT SYSTEM 3% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is discounted in year 0
Maintenance (Co2)	Inspection	27.6756	Periodically, mostly fasteners
	Upgrading		Possible to correct elements
	Repairing		Possible to change elements

Table 20. Weighting criteria in LVT system 3% d.r. Source of data (Pañero Huerga, n.d.)

EDILON SYSTEM (NETHERLANDS)

EDILON present value features have been analysed.

Tables 21 and 22 show kj factor with 6% and 3% as discount rate respectively assuming that each year includes same prices:

- Inspection and upgrading frequencies have a large expansion in time.
- Repairing is difficult to happen.

OWNER COSTS (Co)		EDILON SYSTEM 6% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is disocunted in year 0
Maintenance (Co2)	Inspection	16.1614	Almost none
	Upgrading		Almost none
	Repairing		Very difficult

Table 21. Weighting criteria in Edilon system 6% d.r. Source of data (Pañero, n.d.)

OWNER COSTS (Co)		EDILON SYSTEM 3% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is disocunted in year 0
Maintenance (Co2)	Inspection	27.6756	Almost none
	Upgrading		Almost none
	Repairing		Very difficult

Table 22. Weighting criteria in Edilon system 3% d.r. Source of data (Pañero Huerga, n.d.)

RHEDA 2000 (GERMANY)

Rheda 2000 present value features have been analysed.

Tables 23 and 24 show kj factor with 6% and 3% as discount rate respectively assuming that each year includes same prices:

- Inspection period is periodically.
- Upgrading and repairing are possible not always likely.

OWNER COSTS (Co)		RHEDA 2000 6% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is discounted in year 0
Maintenance (Co2)	Inspection	16.1614	Periodically, mostly fasteners
	Upgrading		Possible to correct elements
	Repairing		Possible to change elements

Table 23. Weighting criteria in Rheda 2000 6% d.r. Source of data (Pañero Huerga, n.d.)

OWNER COSTS (Co)		RHEDA 2000 3% discount rate	
		K AVERAGE	NOTES
Construction/Investment (Co1)		1	It is discounted in year 0
Maintenance (Co2)	Inspection	27.6756	Periodically, mostly fasteners
	Upgrading		Possible to correct elements
	Repairing		Possible to change elements

Table 24. Weighting criteria in Rheda 2000 3% d.r. Source of data (Pañero Huerga, n.d.)

5. RESULTS

Scoring and weighting steps have been presented in the previous chapters. Therefore, input data are ready to combine in the different cases that have been presented in this report. Once again, the no generalization of the results must be highlighted being aware that these conclusions are from some subjective data and also are adapted to Spanish railway industry. Inflation has no influence in these results due to the fact that they are relations between two variables under the same impact.

➢ **Construction costs**

As it was properly explained in chapter 4 and Table 25 resumes, scoring index and weighting factors are combined in construction costs from where specific conclusions can be obtained. Results are graphically shown in Figure 60:

- Construction costs present value is 1 due to these payments happen in year 0.
- EDILON and LVT seem to be the system with lowest construction costs in Spain. This statement agrees with Esveld studies.
- Shinkansen and Rheda 2000 are technically equal concerning construction costs.
- LVT and EDILON's ratio fulfil that their construction costs are not more than 30% more expensive than ballasted costs which is the limit suggested by others feasibility studies for slab track to be profitable excluding Rheda 2000 because of its larger experience. However, Shinkansen does not fulfil this requirement (Lichtberger, 2011).

	Approximated c.c. ratios	Scoring construction costs	Weighting 3/6%	**Result**
SHINKANSEN	1.5	4.5	1	4.5
LVT	1.3	3.9	1	3.9
EDILON	1.3	3.9	1	3.9
RHEDA 2000	1.5	4.5	1	4.5

Table 25. Results of construction costs calculations

	Result PV construction costs
EDILON	3.9
LVT	3.9
SHINKANSEN	4.5
RHEDA 2000	4.5

Table 26. Lowest to highest system concerning construction costs
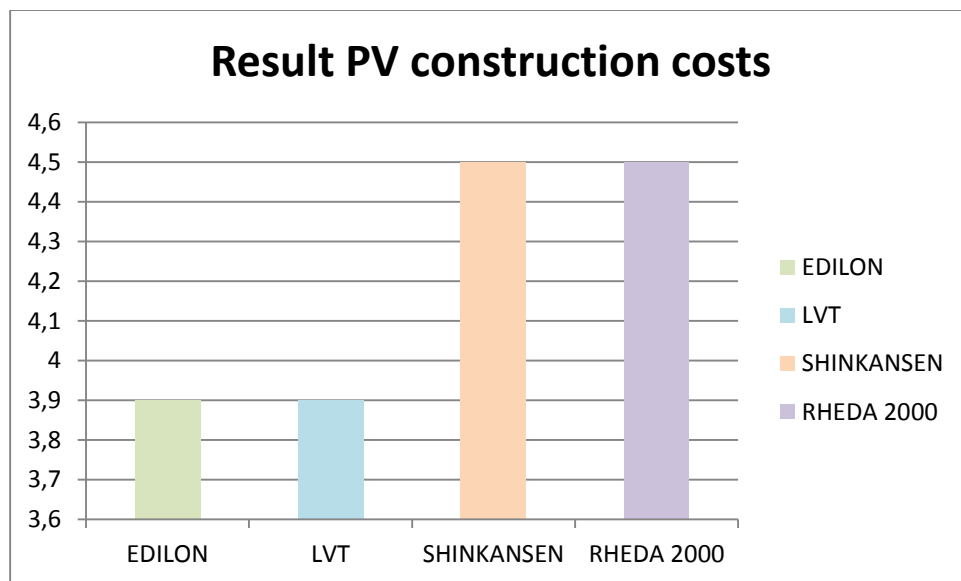
Figure 60. Result PV construction costs

➢ **Maintenance costs**

Same method than used with construction costs, has been used to analyse maintenance costs taking into account the two cases presented in the report, the lowest discount rate (3%) and the highest discount rate (6%). Obtained conclusions are as follow which are also graphically shown in Figure 61 and Figure 62:

- SHINKANSEN seems to be the system which gives lowest present value of maintenance costs with both discount rates.
- LVT appears to be the system which gives the highest present value of maintenance costs with both discount rates.
- The difference between the use of 3% and 6% as discount rate is less than two times higher the results of PV for 6% case.

- It can be seen the favourable results for ballastless systems using high discount rates.

	Approximated m.c. ratios	Scoring maintenance costs	Weighting 3%	Result
SHINKANSEN	0.27	0.81	27.6756	22.417
LVT	0.7	2.1	27.6756	58.119
EDILON	0.5	1.5	27.6756	41.5134
RHEDA 2000	0.5	1.5	27.6756	41.5134

Table 27. Results of maintenance costs calculation-3%

	Approximated m.c. ratios	Scoring maintenance costs	Weighting 6%	Result
SHINKANSEN	0.27	0.81	16.1614	13.09
LVT	0.7	2.1	16.1614	33.939
EDILON	0.5	1.5	16.1614	24.242
RHEDA 2000	0.5	1.5	16.1614	24.242

Table 28. Results of maintenance costs calculation-6%

	Result PV maintenance costs (3%)
SHINKANSEN	22.417
EDILON	41.5134
RHEDA 2000	41.5134
LVT	58.119

Table 29. Lowest to highest system concerning maintenance costs-3%

	Result PV maintenance costs (6%)
SHINKANSEN	13.09
EDILON	24.242
RHEDA 2000	24.242
LVT	33.939

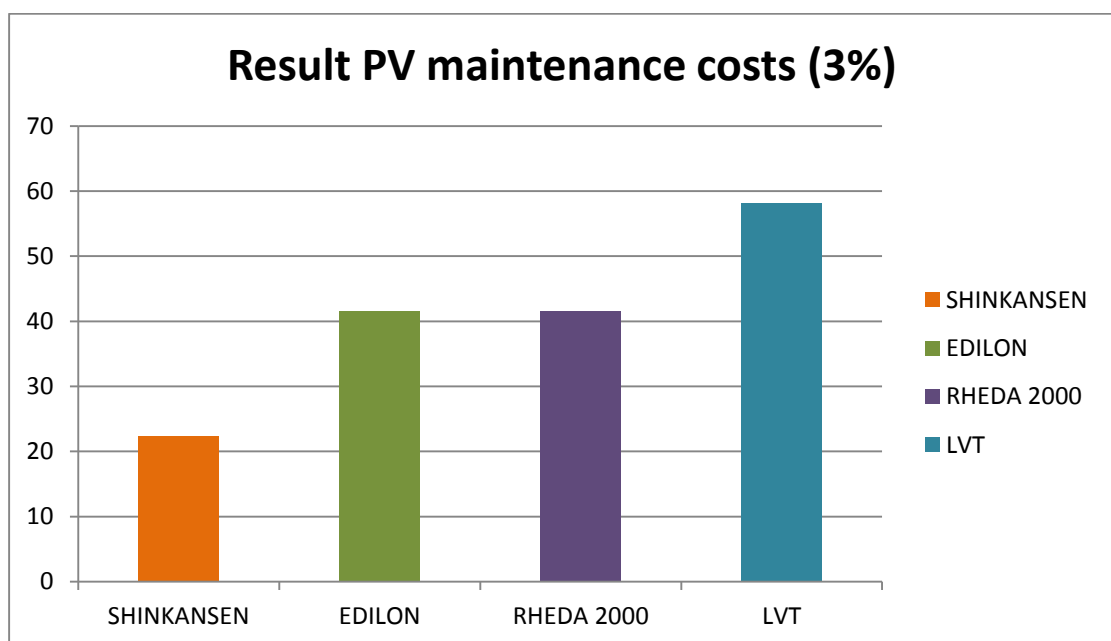**Table 30. Lowest to highest system concerning maintenance costs-6%**

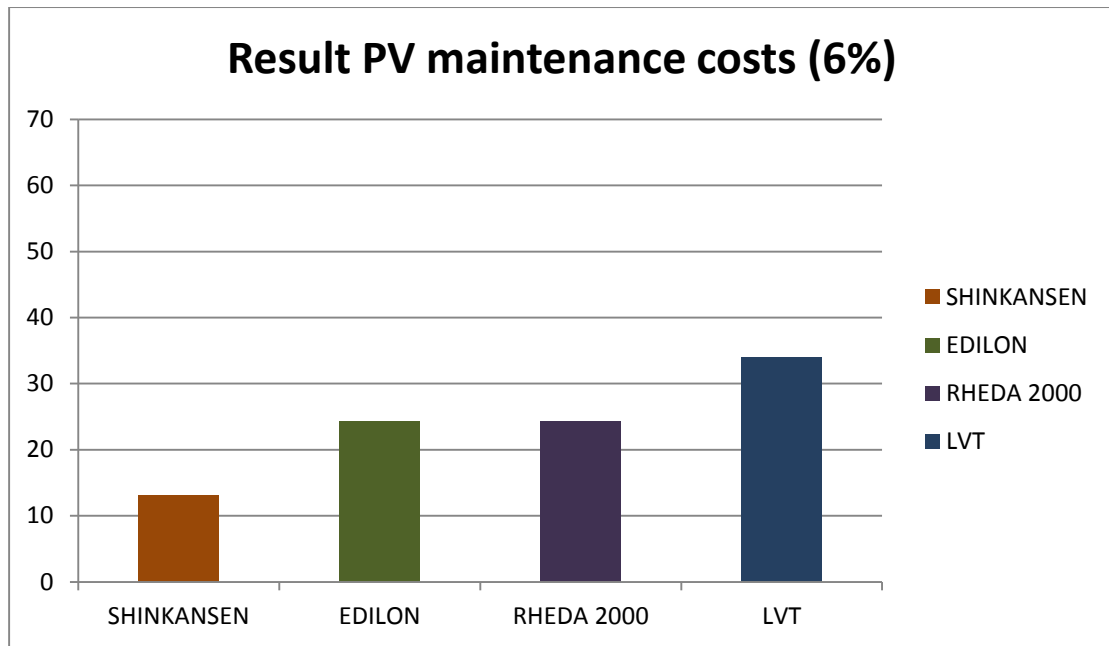**Figure 61. Result PV maintenance costs (3%)**

Figure 62. Result PV maintenance costs (6%)

➢ **Total costs**

Finally, construction and maintenance costs results have been added to analyse their behaviour. In this case, to be able to compare both types of costs is necessary to include a reference system (ballasted). Thus, construction costs results are multiply by a ratio construction/maintenance costs from a ballasted system. Graphically, results are shown in Figure 63 and 64 . Conclusions that can be found are as follow:

- EDILON system once again seems to have the lowest result in PV calculations in Spain
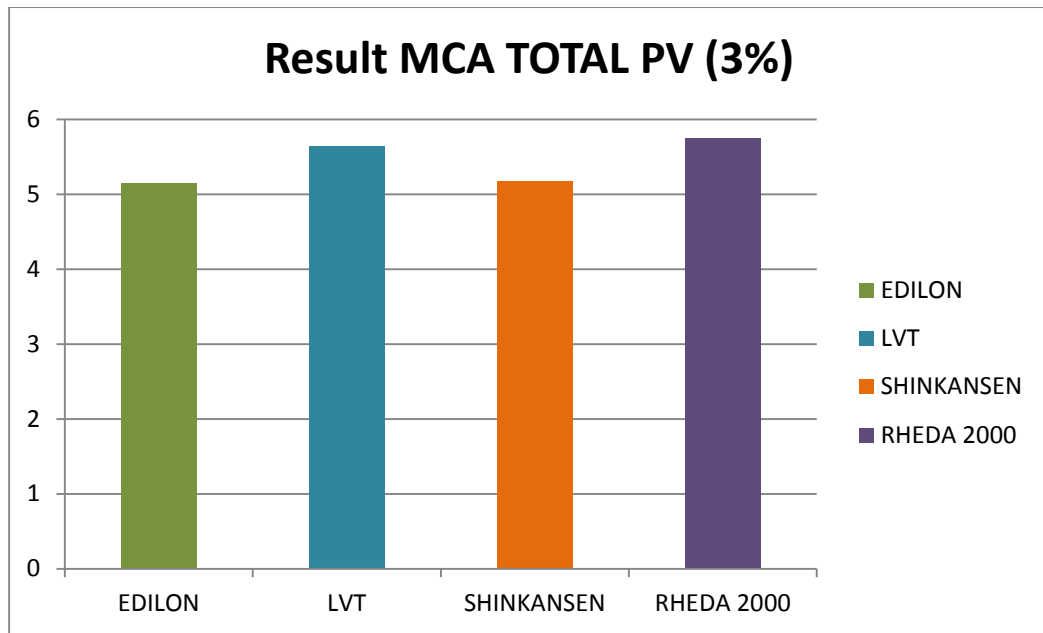- Rheda 2000 system seems to have the highest result in PV calculations in Spain
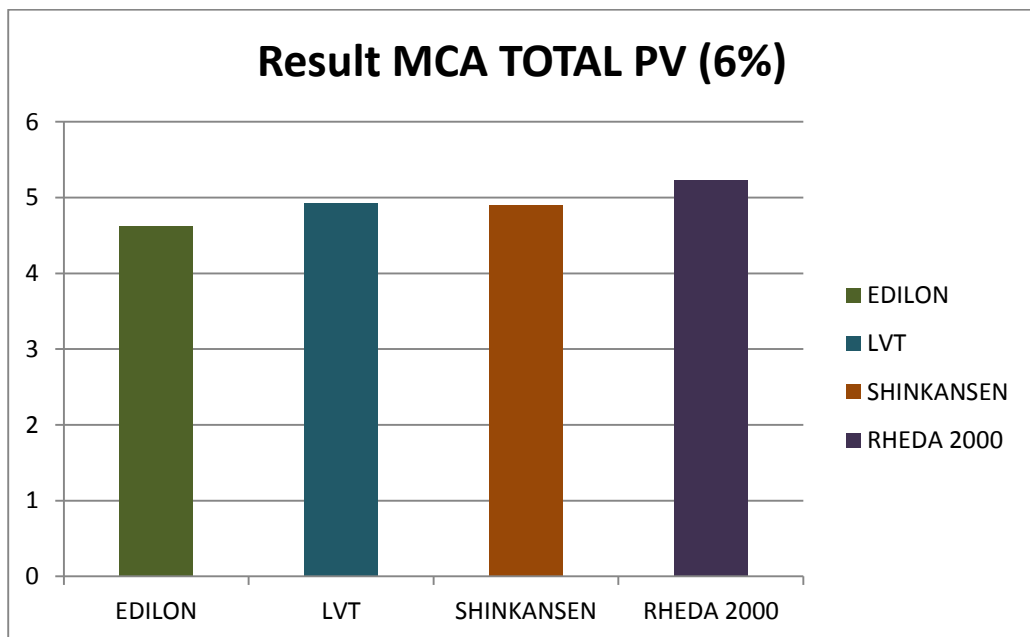
Figure 63. Result MCA total PV (3%)

Figure 64. Result MCA total PV (6%)

6. LCC COMPARISON IN MADRID-SEVILLE HIGH-SPEED LINE (SPAIN)

A practical application has been carried out using data from the first ballasted high-speed Spanish line, between Madrid and Seville (Figure 65), which was installed in 1992 to transport only passengers. The present value calculations are based on the following requirements:

- Construction and maintenance costs from the ballasted track have been taken from reliable data and are shown in Table 35 (CEDEX, 2008a) and (CEDEX, 2008b).
- The indices estimated in this report have been used to approximate construction and maintenance annual costs for the ballastless tracks.
- Present Value calculations have been obtained and after compared both through approximated values (chapter 5 results) and through proper calculations with the help of Excel.
- The period for the study has been 60 years which includes one ballastless track cycle and two ballasted track cycles. Indeed the ballasted track cycle includes construction, maintenance and renovation costs (=construction costs) in year 30. On the other hand, ballastless cycle includes only construction and maintenance costs along 60 years.

Figure 65. AVE Madrid-Seville (www.youtube.com)

Conclusions after comparing the graphs and approximated values from the method used in this research are summarized as follow:

- All approximated calculations (chapter 5) have given close results almost exact than proper calculations using Excel (Table 32, Table 33, Table 34 and Table 35) in which the colours meet the pattern of the graphs. Initial data Madrid-Seville costs are shown in **¡Error! No se encuentra el origen de la referencia.**.

Madrid-Seville (ballasted track)	
Construction costs	-356.900.000,00 €
Annual maintenance costs	-10.752.000,00 €
Load	8.05 MGT/year
Traffic	Passengers
PV (3%)	-795.275.802,42 €
PV (6%)	-590.620.051,13 €

Table 31. Results from costs and present value of ballasted track

- Edilon system seems to be profitable in the 3% case in which the PV in cheaper than the traditional system. Apparently, 30 years would be needed to compensate the initial investment of Edilon in the most favourable scenario (3%). Figure 67 shows these results for this Spanish line which in the author's opinion are not enough to decide to install ballastless track.

- If the Japanese system would be installed in this line, Using 3% as discount rate, this system would be worthy in long-term clearly. However, using 6% as discount rate, ballasted system seems to be worthy taking into account the experience and also that no special benefits are given by Shinkansen as LVT gives in Spain. Figure 68 illustrates its long-term behaviour considering the two study-cases presented.

Edilon (ballastless track)	
Approximated PV (3%)	-612.754.025,60 €
Calculated PV (3%)	-611.841.345,18 €
Approximated PV (6%)	-550.853.686,40 €
Calculated PV (6%)	-550.690.865,46 €

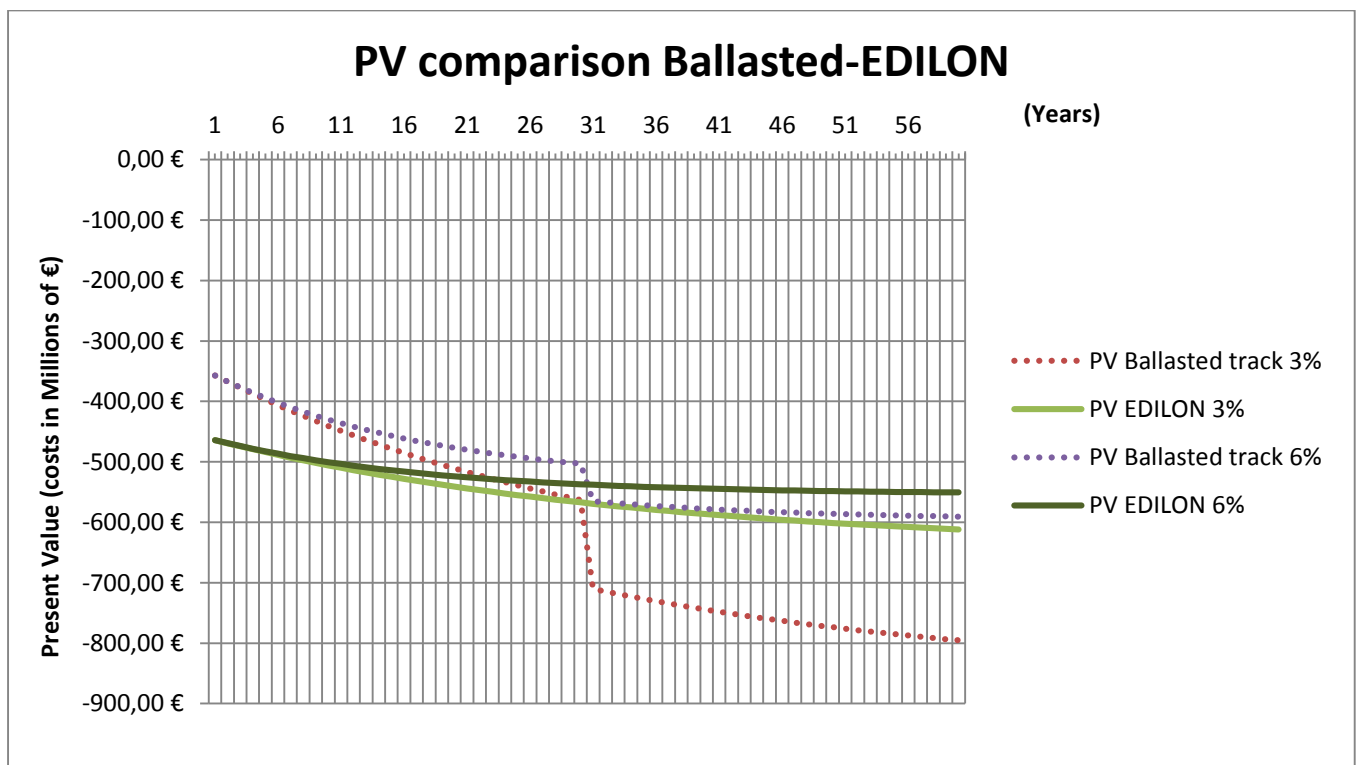**Table 32. Results of approximated and calculated PV of EDILON in Madrid-Seville**

Figure 66. PV comparison ballasted-EDILON in Madrid-Seville

Shinkansen (ballastless track)	
Approximated PV (3%)	-615.693.373,82 €
Calculated PV (3%)	-615.200.526,40 €
Approximated PV (6%)	-582.267.190,66 €
Calculated PV (6%)	-582.179.267,35 €

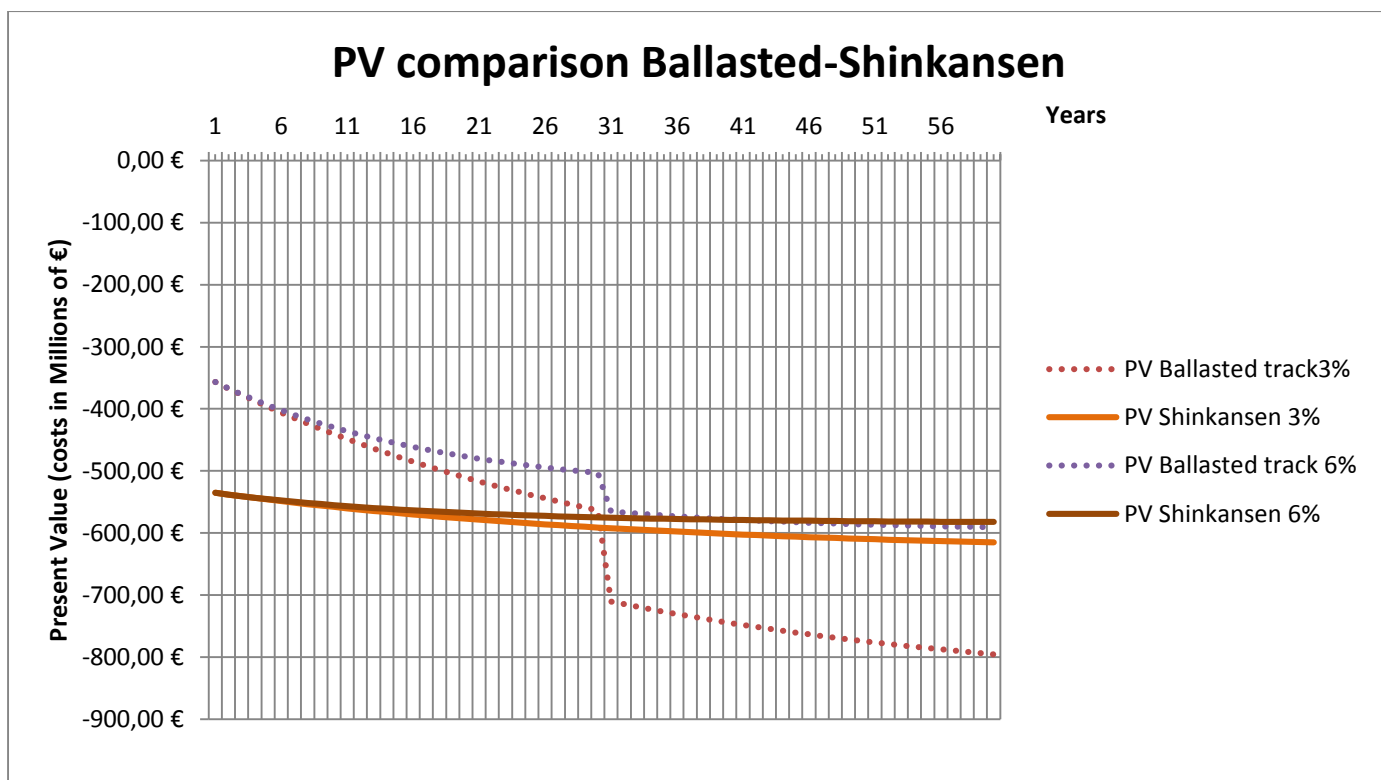**Table 33. Results of approximated and calculated PV of Shikansen in Madrid-Seville**

Figure 68. PV comparison ballasted-Shinkansen in Madrid-Seville

LVT (ballastless track)	
Approximated PV (3%)	-672.267.635,84 €
Calculated PV (3%)	-670.989.883,25 €
Approximated PV (6%)	-585.607.160,96 €
Calculated PV (6%)	-585.379.211,65 €

Table 34. Results of approximated and calculated PV of LVT in Madrid-Seville

- If LVT system would be installed between these two Spanish cities, approximated and exact results with both discount rates give long-term benefits for the ballastless option with 3% but with 6%. The best scenario for LVT system (3%) balances initial costs within 30 years of use as Figure 69 graphically shows. Moreover although the best scenario for ballasted track (6%) would be slightly worse than LVT use, special reasons such as vibration or noise attenuation would be needed to install this system.
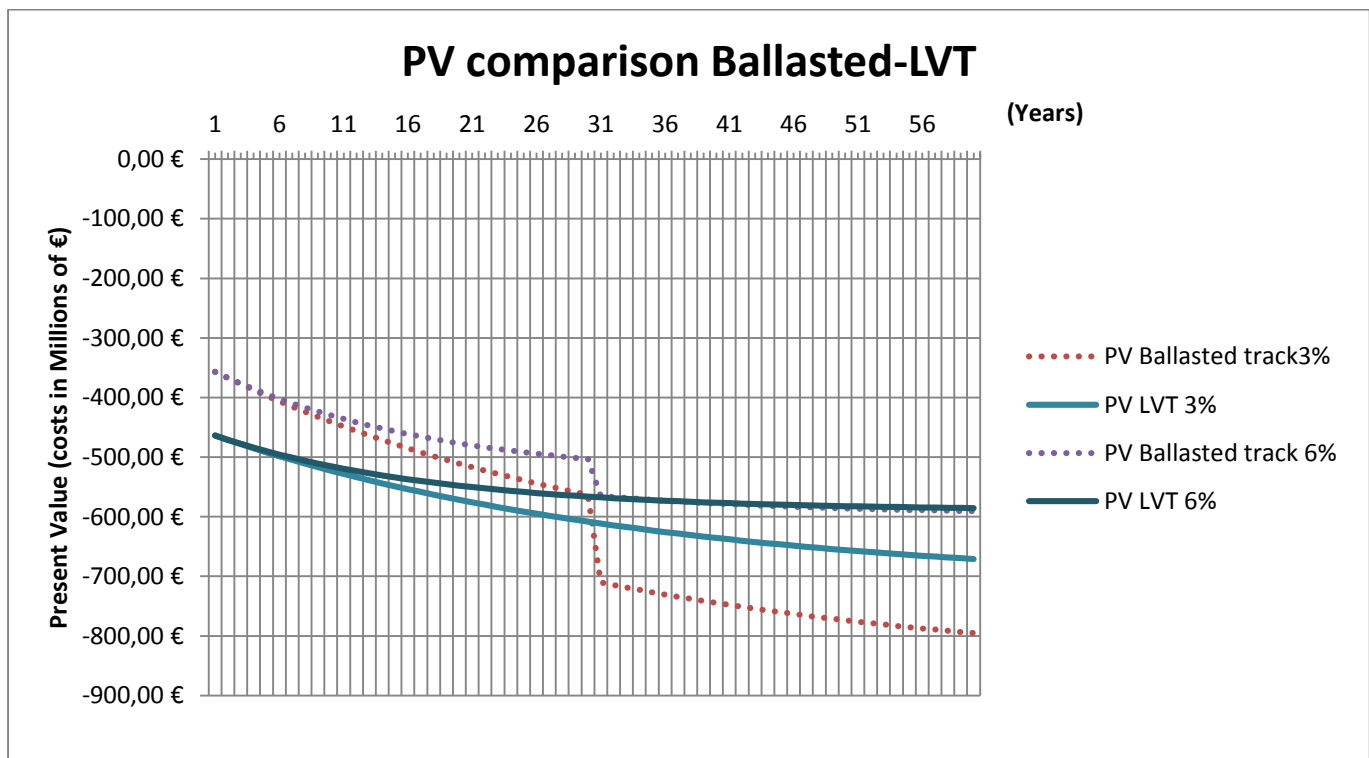

Figure 69. PV comparison ballasted-LVT in Madrid-Seville

- Assuming Rheda 2000 installation and analysing its results, the best scenario for ballasted track shows in Figure 70 the benefits of the traditional track in long-term. Even considering the best scenario for ballastless track in the same figure, the present value is closer to the ballasted track comparing with other systems. Nevertheless, Rheda system has large experience all over the world which is a guarantee of being sure about its long-term behaviour.

Rheda 2000 (ballastless track)	
Approximated PV (3%)	-684.134.025,60 €
Calculated PV (3%)	-683.221.345,18 €
Approximated PV (6%)	-622.233.686,40 €
Calculated PV (6%)	-622.070.865,46 €

Table 35. Results of approximated and calculated PV of Rheda 2000 in Madrid-Seville
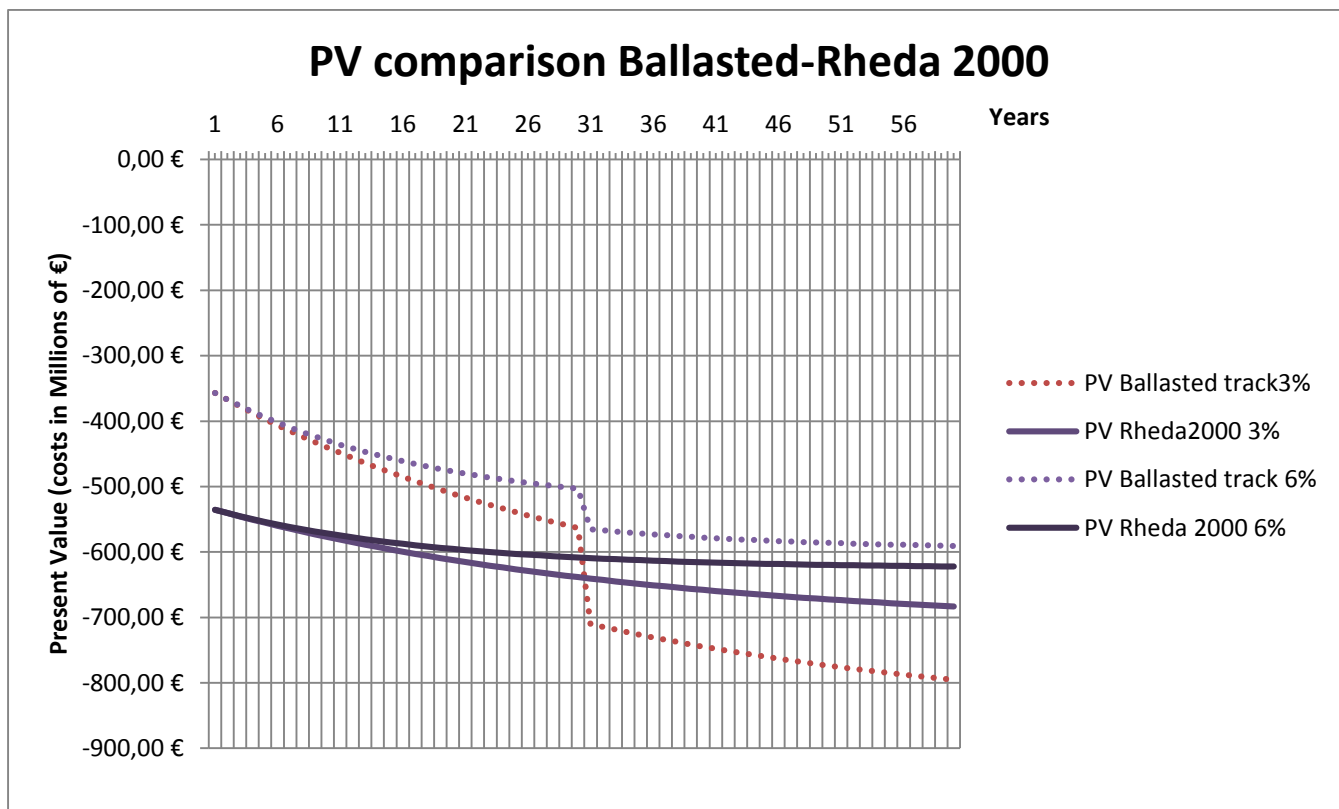
Figure 70. PV comparison ballasted-Rheda 2000 in Madrid-Seville

- Even though EDILON and LVT system seems to be economically worthy in long-term, the loading on this track is not high enough to consider the installation of ballastless systems. Therefore, the current ballasted option seems to be suitable so far.

7. CONCLUSIONS AND FURTHER RECOMMENDATIONS

Life cycle cost analysis in railway field comprises numerous and non-stable variables as it has been perceived in this report. Thanks to European railway organisms' collaboration, there are few projects developing a global method to be closer to these variables such as INNOTRACK project. The method that has been used in this research is simple and provides us with basic understanding on how complex computer programs work when LCC needs to be approached.

Hence this method, which has approximated present value behaviour, gives exact results taking into account the practical comparison from Madrid-Seville line and also the mathematic base of it. However, the use of costs ratios carefully estimated from experience might be a useful tool when comparing economically different systems (ballastless) with one fixed (ballasted). Indeed, a wider perspective of the influencing costs variables can be achieved through the analysis of key parameters such as tonnage, superstructures or soil conditions instead of trying to summarize costs from intermediaries, materials or companies that are involved in. However, general knowledge about which steps involve more costs is important as well as an analysis of why those steps involve those costs in order to adapt the data to a specific country.

It is important to highlight the limitation in the present report when considering tracks loading, which differ if they are exclusive passenger lines or combined with freight, due to lack of data. Specific conclusions obtained from this study for tracks in Spain are summarized as follow:

❖ According to Esveld, who stated that 15-20 years would be needed to balance investments of ballastless tracks, any of these systems seem to fulfil it.

❖ EDILON system has been obtained to be globally the most suitable from an economic perspective being also its construction costs no more expensive than 30% that of ballasted track as Litchberger limits to be profitable. Furthermore, EDILON performs better concerning vibration and noise attenuation than Rheda 2000. However, it is not appropriate for heavy loads that often occur in the best scenario for ballastless tracks.

❖ As expected, Rheda 2000 is obtained to be the most expensive system regarding available data but new improvements might lower its construction costs without using reinforcement in the slabs as it is introduced in this report. Due to its experience, it has fewer uncertainties in its long-term behaviour being also suitable for supporting heavy tonnages.

❖ LVT and Shinkansen have little and no experience in Spain respectively. This fact makes their results uncertain and more subjective than the other systems. Shinkansen system holds higher construction costs due to no development of a proper production process in Spain but an under development project (SULABU) working on it. The first LVT application in this country (2013) will give useful results in terms of construction and maintenance costs in the future. Shinkansen results have shown to need more years to balance the investment in Spain compared with the 12 years suggested by Ando in Japan (Figure 52).

❖ Even though Fastrack is a development, its first results seem to be in the range of costs between Rheda and LVT system. Moreover, its noise and vibration attenuation systems might have improvements comparing with other ballastless tracks (Fastrack, f, 2013).

After having completed the study, the variables which have been thought to influence the most in present value calculations are:

- Discount rate chosen
- Loading of the track. Passenger or mixed line (passenger + freight)
- Maintenance during the first years since they are in charged to balance the investment in case of ballastless tracks. That is the reason because the influence of chosen discount rate cannot be seen in the example. Maintenance costs are equally each year.
- Environmental impacts, which have been analysed and considered their influence.

For further studies, it could be interesting to evaluate recent ballasted track maintenance improvements, and also which are the economic effects of churning in the traditional system. Moreover, it could be stimulating to look into how to decrease soil stabilization works which involve costs increment in slab track constructions. Concerning new ballastless systems, there are developments going on such as Fastrack or The Two Layers Steel track which need of being aware of their progress so they could be new solutions for future tracks.

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