ANALYSIS OF TECHNOLOGICAL AND COMPETITIVE TRENDS OF WEIGHT REDUCTION IN HIGH SPEED ROLLING STOCK INDUSTRY
GRATITUDES

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ABSTRACT

The incorporation to the transport of passengers sector of the high speed industry is preceded by a global society, which requires the possibility to travel quickly, comfortably and efficiently, imposing the current attitude of the concern with the environment.

The development of the rail sector over recent decades, and especially in recent years, along with the technological development has allowed the formation of a network of high speed lines around the greatest part of the planet. Due to the great acceptance by users, the average occupancy of the most high-speed trains worldwide equals or exceed 80%.

Leading manufacturers like Siemens, Bombardier and Alstom have had to bring their production lines to Asia, specifically China, due to the large difference in production costs. The major consequence of this fact has been the entrance to the high-speed market of Chinese manufacturers JSR and CNR, occupying the positions of former leading manufacturers worldwide.

Both the need to differentiate, by European and American leading manufacturers, the possibility to compete with airline industry on longer journeys and the need to be more efficient, give a great opportunity for the incorporation of the composite materials industry, which offer better properties and lower weights, for high-speed trains.

In this situation, it is proposed the analysis of the application of lightweight materials in the railway rolling stock, called rolling stock any part that is moved.

It begins decomposing all high-speed train systems, explaining their functions, features and structural requirements of each system, in addition to the process construction.

To justify the project, the impacts of weight reduction on high-speed trains are proposed. From a historical point of view, weight reduction has contributed to the possibility of increasing the speed of them, reaching in 1964 the high-speed velocity of 240 km/h with the trains known as “bullet trains”.

Currently weight reduction causes greater competition with the airline industry in journeys which take less than 3 hours by train. This is largely due to the waiting time spent at airports by the passengers, and due to the great distances between airports and city centers. Such competition has brought a decrease of total number of air travelers in 2013 of 4.7 million passengers, increasing the number of passengers on high-speed trains in 3 million in the same year, according to data from the National Statistics Institute.

In addition, there will be a great environmental benefit due to the weight reduction, and consequently the reduction of emissions and energy expenditure by high-speed trains. The occupation is relevant in the factor of emissions per passenger, but with the use of lightweight materials and its consequent weight reduction, there would be no doubt that high speed rail transport is the least polluting of all passengers transports.

In terms of energy expenditure, weight reduction has a major influence on the operating costs of high-speed trains. Therefore, the use of lightweight materials significantly reduce energy expenditure, and although weight reduction would have more influence in trains that operate with slower speeds, due to the higher influence of the total weight in the energy expenditure at these
ANALYSIS OF TECHNOLOGICAL AND COMPETITIVE TRENDS OF WEIGHT REDUCTION IN HIGH SPEED ROLLING STOCK INDUSTRY

speeds. Major manufacturers and operators of high-speed trains include the possibility of increasing the number of seats of the high-speed trains due to their great occupation. The main impediment to do this is the requirement to have 17 tons per axle that all high-speed trains have. The information provided by the president of the Spanish Railway Foundation, Alberto Garcia Alvarez, shows that each ton of weight reduction would represent an increase of 12 seats. With the proposed reduction of 15.9% on the total weight it is concluded that it is possible almost double the current capacity of high speed trains. Thus the project gives a greater interest in good industrial application due to the current needs of the sector.

Composite materials besides being lighter, they have better properties that are manifested in lower maintenance cost of the trains.

Once justified the possible improvements obtained with the use of lightweight materials, both weight distribution and cost distribution are analysed to know the systems that are more sensitive to the weight reduction, by building a database of the world fleet of high-speed trains. With this database and using linear regression models, the most influential parameters in the weight function of high-speed trains are studied.

In addition, the requirements of these systems that form the high speed trains are explained, concluding that the car body, the interior and miscellaneous systems such as air conditioning system, plumbing systems, doors and windows account for 53% of the total weight of the train are the most attractive systems for applying lightweight materials. It is highly possible to achieve a weight reduction with the use of lightweight materials, which will mean a 15.9% reduction in overall weight.

Then the different types of composite materials are introduced and characterized, as well as their production processes and their associated cost.

When performing a market analysis of composites, we can appreciate that the current application of composites is very distributed around different industries such as aviation, marine, construction, aeronautics and rail among others. The high cost of composite materials, is the main cause of a later expansion around other industries, but greater integration between the different actors in the value chain is taken to gain greater knowledge of their properties and become more competitive. It also highlights cases in which companies from other sectors such as BMW have been introduced in the value chain to obtain in this case the batteries of the electric cars i3 and i8. With the economic contribution of other sectors is expected further growth in the composite sector, which will mean greater integration in industries such as automotive or railway industry.

Examples of application of composite materials in different industries are proposed to justify the choice of the appropriate composite and to extrapolate the results to the rail industry.

With this information it is possible to conclude that the situation is excellent to say that the right material is the fibre reinforced polymer composite. The application of such material at high-speed trains will produce the desired weight reduction, making them more efficient.

Finally, an analysis of return on investment is proposed where it is compared two different situations in a travel from Madrid to Barcelona. The first situation involves the acquisition of a high speed train, the AVE S103, without the application of lightweight materials, and the second involves the acquisition of the same high-speed train with the application of lightweight materials in the systems above cited, obtaining a 15.9% reduction of the total weight. In both cases, both maintenance costs and operative costs during the life cycle of the train, 30 years, are taken in
account. Benefits are calculated with an average ticket price of 85 euros, with an occupancy rate of 79% and an operation of 5 trips per day, 365 days a year, during 30 years.
RESUMEN

La incorporación al sector del transporte de pasajeros de la industria de trenes de alta velocidad, viene precedida de una sociedad global, que exige la posibilidad de viajar de manera rápida, cómoda y eficiente, imponiendo la actitud de preocupación actual con el medio ambiente.

La evolución del sector ferroviario durante las últimas décadas, y especialmente durante los últimos años, junto con el desarrollo tecnológico, ha permitido la formación de una red de líneas de alta velocidad alrededor de gran parte del planeta. Debido a la gran aceptación por parte de los usuarios, la ocupación media de la mayor parte de trenes de alta velocidad a nivel mundial iguala o supera el 80%.

Los principales fabricantes como Siemens, Bombardier y Alstom han tenido que llevar sus líneas de producción al continente asiático, más concretamente a China, debido a la gran diferencia costes de producción. La mayor consecuencia de este hecho ha sido la incorporación al mercado de los fabricantes chinos JSR y CNR, desbancando a los antiguos principales fabricantes de los primeros puestos a nivel mundial.

Tanto la necesidad de diferenciarse, por parte de los principales fabricantes europeos y americanos, como la posibilidad de competir con la industria aérea en trayectos de mayor distancia, y la necesidad de ser más eficientes, da lugar a la apertura de una gran oportunidad para la incorporación de la industria de materiales compuestos, que ofrecerán mejores propiedades y menores pesos en los trenes de alta velocidad.

Ante tal situación se propone el análisis de la aplicación de compuestos ligeros en el material rodante ferroviario, denominado material rodante todo aquel que se mueve.

Para ello, se comienza descomponiendo un tren de alta velocidad por sistemas, explicando las funciones, características y requisitos estructurales de cada uno de los mismos, además del proceso de construcción del mismo.

Para justificar el desarrollo del proyecto, se proponen las consecuencias de la reducción de peso en los trenes de alta velocidad. Desde un punto de vista histórico, la reducción de peso en los trenes ha contribuido en la posibilidad de aumentar la velocidad de los mismos, pudiendo llegar a alcanzar en 1964 los 240 km/h con los conocidos como “trenes bala”.

Actualmente la reducción de peso facilitará una mayor competencia con la industria aérea en los trayectos inferiores a las 3 horas en tren. Esto es debido, en gran parte, al tiempo de espera en los aeropuertos, y a las grandes distancias que suele haber entre los aeropuertos y el centro de las ciudades. Dicha competencia ha hecho descender el número total de viajeros en avión durante 2013 en 4,7 millones de pasajeros, aumentando el número de viajeros en trenes de alta velocidad en 3 millones en el mismo año, según datos del Instituto Nacional de Estadística.

Es evidente, que la reducción de peso en los trenes de alta velocidad producirá una reducción de emisiones y de gasto energético, lo que redundará en un gran beneficio medioambiental. La ocupación es un factor relevante en la cantidad de emisiones por pasajero, pero con la utilización de materiales ligeros y su consecuente reducción de peso, se asegura que el transporte en trenes de alta velocidad es el menos contaminante de todos los transportes de pasajeros.
En cuanto al gasto energético, la reducción de peso tiene una gran influencia en los costes de operación de los trenes de alta velocidad, aunque es más significativa para los trenes que operan a menor velocidad, por la mayor contribución al consumo del peso del tren. Los principales fabricantes y operadores de trenes de alta velocidad contemplan la posibilidad de aumentar su capacidad total, debido a su alta ocupación. El principal impedimento es el requerimiento de la limitación a 17 toneladas por eje, que establece la norma para los trenes de alta velocidad. Según la información del presidente de la Fundación de Ferrocarriles Española, Alberto García Álvarez, cada tonelada de reducción de peso supondrá un aumento de 12 asientos sobre los actuales. Con la reducción propuesta del 15.9% sobre el peso total, se concluye que se podría llegar a duplicar la capacidad de los trenes de alta velocidad. Así el proyecto confiere un mayor interés por su buena aplicación industrial, debido a las necesidades actuales del sector.

Los materiales compuestos, aparte de ser más ligeros, poseen mejores propiedades que se traducen en menores costes de mantenimiento.

Una vez justificadas las posibles mejoras obtenidas con la utilización de materiales ligeros, se analiza tanto la distribución de pesos, como la distribución de costes para saber que sistemas son más sensibles a dicha reducción de peso, mediante la construcción de una base de datos de la flota mundial de los trenes de alta velocidad. Con dicha base de datos y con la utilización de modelos de regresión lineal, se estudian los parámetros más influyentes en la función peso del tren de alta velocidad.

Se concluye que tanto el fuselaje o carrocería, como los sistemas interiores y los sistemas misceláneos como el del aire acondicionado, sistemas de tuberías, puertas y ventanas suponen un 53% del peso total del tren. Estos son los sistemas más atractivos para aplicar materiales ligeros, contribuyendo a alcanzar una reducción de peso del 15.9% del total.

A continuación se introducen y caracterizan los distintos tipos de materiales compuestos, también llamados composites, sus procesos de producción y sus costes asociados.

Al realizar un análisis del mercado de composites, se puede observar que su aplicación actual está muy repartida entre diferentes industrias como aviación, marina, construcción, aeronáutica o ferroviaria entre otras. El alto coste de los materiales compuestos es el principal causante de su expansión más tardía en otras industrias, pero en la actualidad se están tomando medidas para una mayor integración vertical entre los diferentes actores de la cadena de valor, con el objetivo de obtener un mayor conocimiento de sus propiedades y ser más competitivos. También se destacan casos en los que empresas de otros sectores como BMW ha participado en la cadena de valor para obtener las baterías de los automóviles eléctricos i3 e i8. Con la aportación económica de estos nuevos sectores se prevé un mayor crecimiento del sector, que supondrá una mayor integración en industrias como la automoción o la ferroviaria.

Se presentan ejemplos de las aplicaciones de los materiales compuestos en las diferentes industrias para justificar la elección del material compuesto más adecuado, y para extrapolar sus resultados a la industria ferroviaria.

Con esta información se puede concluir que la situación actual es inmejorable para la utilización del material compuesto de fibra reforzada con polímeros. La aplicación de dicho material en la alta velocidad producirá la reducción de peso buscada, que los hará más eficientes.

Finalmente se presenta un análisis del retorno de la inversión donde se comparan dos situaciones, en un viaje desde Madrid a Barcelona. La primera de ellas supone la adquisición de
un tren de alta velocidad, en este caso el AVE S103, sin la aplicación de materiales ligeros, y la segunda supone la adquisición del mismo tren de alta velocidad con la aplicación de materiales ligeros en los sistemas citados, obteniendo un 15.9% de reducción del peso total. En ambos casos se tienen en cuenta el coste de adquisición del tren, de mantenimiento durante el ciclo de vida del tren, y los gastos operativos durante el ciclo de vida, estimado en 30 años. Los beneficios se calculan con un precio medio del billete de 85 euros, con una ocupación media, proporcionada por Renfe, del 79% y con una operación de 5 viajes por día, los 365 días del año, durante 30 años.
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INTRODUCTION

The better materials we use, the better machines efficiency. This in addition with an increase of the knowledge about technology could change our world to an efficient planet, letting everyone live in this awesome place that they deserve. The motivation of becoming better making a better world is the one that the railway industry is achieving.

This project shows how new materials and the new technologies could significantly reduce the train weight leading a reduction on emissions and a lower energy consume. For subways or other urban train systems, estimated energy savings from weight reduction range from 6.6% to 8.6% per 10% weight reduction. For high-speed passenger trains, estimates for energy savings are about 3.2% per 10% weight reduction, due to their high and steady operating speeds [1].

Nowadays most of lightweight materials used over different industries are composite materials. Composites can be defined as a combination of a matrix and a reinforcement, which when combined gives properties superior to the properties of the individual components. The reinforcement are the fibres and they are used to fortify the matrix in terms of strength and stiffness. The reinforcement fibres can be cut, aligned, placed in different ways to affect the properties of the resulting composite. The matrix, normally a form of resin, keeps the reinforcement in the desired orientation. It protects the reinforcement from chemical and environmental attack, and it bonds the reinforcement to transfer effectively the applied loads.

A.T Kearney shows on the following project “A.T. Kearney’s view on composite market” [2] that composite materials besides offering a 30-40% weight reduction at equal strength, composites may have lower manufacturing complexity, (as a single composite moulding can take the place of up to 15-20 individual components) and reduced tool cost (composite tooling cost is only 40% of steel stamping tooling cost).

Furthermore, their mechanical properties allow greater design flexibility, smoothness and geometry detail, and have superior chemical and dent resistance than aluminium and steel panels as well as better sound insulation properties.

These benefits push the industry towards a more intense use of plastics and composites at the expense of metals such as steel and aluminium.

Railway industry’s market is rising considerably during the last years, emerging markets, particularly in Asia, Eastern Europe, and South America. New railway projects are created and the train lines are expanded and refreshed covering the four main sectors of this market: infrastructures, rolling stock, signalization and services. Global trends boost the growth of this industry: politics, entrepreneurs and the public take conscience about all the importance of the railway transport as sustainable transport. Using the train is a measure which could solve the environmental problems as the carbon dioxide emissions and climate change are, in addition to the rise of the fuel price.

Rolling stock is referred to any vehicles that move on a railway, including both powered and unpowered vehicles as locomotives, railroad cars and wagons.

The most important rolling stock’s suppliers as Bombardier, Alstom and Siemens and the Chinese CSR and CNR face their production chain goals with similar concerns about the weight reduction
of railway rolling stock, the reduction of energy waste and introducing new sustainable and recyclable materials with the same structural rigidity requirements.

The aim of weight reduction together with the need to reduce the carbon footprint and the use of alternative powertrains, has led to a trend towards plastics and other lightweight materials.

Nevertheless, the adoption of composites in the railway rolling stock industry still faces several challenges. According to a survey carried out by AT Kearney amongst OEMs, the main impediment for the growth of composites against other alternative lightweight materials already mentioned is its cost. Other obstacles faced by composites are the need of high capital investments as current equipment is not compatible, supply chain volatility due to the lack of significant suppliers and the need to comply with safety and recyclability regulations, which are more demanding having a future target of recycling 95% of the total material.

Other industries have been using composite materials since 1970’s, when the air industry began using them in the aircraft structure. Currently the use of composite materials in passenger aircrafts are around the 35-50% of the total structure. The composite materials technology is consolidated in some companies as Airbus, Boeing and other aircraft manufacturers. Composite materials manufacturers are working hard, achieving new properties and lower weight, offering the same security, taking advantage of the increase that is experiencing the demand of composite materials.

On the other hand the automotive industry is experiencing an exciting opportunity to use composite materials in their manufacturing chain, but it is needed more investments to have an important impact in the whole industry. If the chassis would be made by composite materials, its weight would be halved. Also, achieving 10% reduction in vehicle weight can result in a 7% consumption improvement. The restrictive regulation imposed by Europe are quite good to the composite materials industry to be developed.

This project is going to analyse the different trends around the rolling stock industry using the methodology described in the next section, proving why the necessity of weight reduction is...
needed and evaluating which systems are more sensitive to be manufactured with composite materials. There, the evaluation of the improvements achieved in function with the cost investment will be analysed with a case study of the systems chosen to be produced with composite materials.
PROJECT OBJECTIVES

This project attempts to answer to the following objectives:

a. Understand the different trends in railway industry, and more precisely, in reducing rolling stock weight.
b. Understand why the weight reduction is important in the rolling stock industry.
c. Evaluate the impacts of the application of composite materials in rolling stock components.
d. Identify material alternatives and technologies applied in the railway industry towards reducing rolling stock weight.
e. Understand the different applications of composite materials in other industries.
f. Analyse which systems are sensitive to reduce weight.
g. Elaborate a case study to analyse the return of the investment with the weight reduction proposed.
METHODOLOGY

Key questions to answer

The questions that must be answered in order to comply with the objectives are:

<table>
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<tr>
<th>Subject</th>
<th>Question</th>
<th>Methodology</th>
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<td>Characteristics of the railway industry.</td>
<td>Which are actual trends that affect the passenger transport sector?</td>
<td>Research articles and analysis about global transport.</td>
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<td>Which are the actual trends on different players involved in the rail system value chain?</td>
<td>Define the value chain and their presence in the chain.</td>
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<td></td>
<td>Which are the actual trends in the rolling stock component industry?</td>
<td>Research articles and analysis about the OEM's.</td>
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<td>Effects of applying technologies and materials to reduce weight.</td>
<td>What are the economic impacts?</td>
<td>Analyse how would be the energy savings and their impacts.</td>
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<td>What are the technical impacts?</td>
<td>Realize what systems are more sensitive to use lightweight materials, and their requirements.</td>
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<td>What social advantages and disadvantages do they present?</td>
<td>Compare with the reduction of the necessity of other transport industries. Compare the CO2 emissions among the different transports.</td>
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<td>Different technologies.</td>
<td>What have been the materials and technologies used to reduce weight of the rolling stock?</td>
<td>Research information, and classify in function with the strategy followed.</td>
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<td>What are the applications of lightweight materials in other industries</td>
<td>Comparing them with their possible application in the railway industry</td>
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<tr>
<td>Analysis of the investment.</td>
<td>Which are the main costs and drivers to reduce weight?</td>
<td>Analyse the cost of a high speed train and compare it with the composite high speed train</td>
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<td>What is the necessary investment and which will be the consequences?</td>
<td>Analyse future results and compare with the current situation</td>
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Table 1: Key questions to answer.
The methodology that will be followed is:

a) Research and investigate different articles about the trends and regulations in global transport, railway transport and railway OEM's.

b) Measure the economic, social and technological impacts attached to the use of lightweight material compared with the reduction of energy consumed.

c) Study opening markets, as the air industry market share, which the railway industry could compete with and it could become into great benefits.

d) Create a data base to break down the analysis of the weights of the different parts of a train and their costs.

e) Analyse what materials offer the properties required in the railway industry.

f) Research and investigate different news about reducing weight using lightweight materials in railway and other industries, extrapolating it to the railway industry.

g) Analyse if the return on the investment, comparing the case of using lightweight materials and the case of not using them.
DEFINITION OF THE SITUATION

Situation

The railway industry market is becoming bigger since the high speed trains appeared, changing people routines and offering a new transport service which could compete with the air industry in long distances. It is possible because currently trains could exceed speeds over 300 km/h, also there isn’t any long and heavy check in, leaving people on their destinies with an excellent service and comfortable trip. The actual challenge in the railway industry is offering better prices than the air industry in their trips that takes 3 hours or less.

Here it is the importance of the composite materials, because these high speed trains need lightweight materials in their structure and different systems all over the train to achieve these speeds. Firstly, the structure of the trains was made of steel offering a great resilience and security to the passengers but these trains couldn’t reach speeds over 200 km/h. When the Japanese National Railways company designed the bullet train also called “Shinkansen” which could reach speeds over 300 km/h it changed the railway market and the future of the trains. The structure of the trains began building in aluminium instead of steel, and it opened an investigation of light materials which could have an application in the railway industry. Nowadays there are new measures to reduce the average weight of the trains and there is a big net of high speed trains all over the world, giving a great opportunity to the composite materials to be introduced.

On the other hand, the OEM’s are experiencing an important change. The Chinese manufacturers as CSR and CNR are offering their products with a really good rate between price and service leaving behind the “big 3” that are Alstom, Siemens and Bombardier which have to reduce their cost producing in Asia to achieve it or they also could offer great quality products based on composite materials to make difference between them and the Chinese producers.

Complication

The biggest challenge to adopt composite materials in the railway industry is the high cost compared with other alternative materials in the weight reduction. Also is needed great investments to start this business and the supply chain is volatile due to the absence of suppliers.

The norms and regulations over the railway industry impose several difficulties on using composite materials due to the necessity to comply with the security and recyclable norms.

Question

What are the most competitive lightweight technologies of high speed rolling stock engineering and manufacturing in sort, medium and long term?
Figure 3: Issue tree.
1. CHARACTERISTICS OF THE RAILWAY INDUSTRY

1.1 Trends that affect the passenger transport sector

The macro-trends could have an important impact in the market sectors’ future that we concern about, as the railway sector. Their analysis and understanding are vital to elaborate strategy plans because they allow us a better anticipation to the potential changes which are going to happen in our social and economic environment.

Nowadays the global economic integration called globalization, the better mobility and communication among people all over the world, the implementation of economic incentives to support projects that produce benefits to the environment and the restricted access to financing because of the global recession are defining our global world.

Our demography, where young people are growing in developing countries, except in China due to one-child policy, increasing the migratory flows among rising urbanizations.

The acceleration of natural resources demand versus the increase of supply scarcity lead the application of strict regulations on emissions and the promotion of more efficient transport systems by the governments all over the world.

The regulation as higher security requirements and the liberalization of rail market.

Those four macro-trends together and combined with continuous technological innovation as new communication systems and protocols for signalling, new materials for manufacturing rolling stock components, new engines and energy storage systems are changing the shape of passenger transport.

1.1.1 Globalization

The globalization process is driving demand for mobility causing a global transport demand. The increase of the global economy is caused because of the political integration among the most powerful countries in the world, letting an international trade together with the disappearance of economic and labour market borders, as the Europe Union are experiencing.

Mainly, passenger transports have developed as a consequence of the globalization but also, they have been a cause of the globalization letting our world to become in a place where any person could travel, visit and work everywhere he or she desires.

Figure 4: Evolution of distances in kilometers traveled per person by type of transport in EU.
Source: EUROSTAT, European Commission, World Tourism Organization [4].
1.1.2 Demography

Concentration of economic development has encouraged urban development and the creation of megacities. After 2007, most of the world's population were living in cities, with higher growth of metropolitan areas through business-residential areas. Currently, 80% of economic growth will be generated in cities.

The city model and the communication among megacities are another determining factors for shaping urban, national and international passenger transport. In the economic impacts part of this project, which defend the use of lightweight materials in the rolling stock component, is analysed that in routes with a travel time less than three hours high speed infrastructure expansion will allow railways to gain market share at the expense of other transport modes, mostly at the expense of the air transport.

![Image of market share of high speed and air industries in 2008 and 2025. Source: EUROSTAT, European Commission, World Tourism Organization [4].]

1.1.3 Sustainability

Greater environmental awareness is promoting ambitious sustainability objectives. The two objectives that create more value for the environment are to reduce emissions from private vehicles by promoting public transport and to increase strict global CO₂ regulations. Some actions are already delivered by the governments.

For example in Madrid, the government have imposed traffic restrictions in urban areas that recovers urban space for pedestrians as the cyclist mobility plan. Also public transport promotions like the public transport pass cost which was reduced considerably to 20 euros per month, to every zones of Madrid. Other measures as the use of alternative fuel or the reduction of the speed limit are giving great value for the whole society.
1.1.4 Regulation

The market for international rail passenger services has been liberalized in the EU since 2001, but it has put in practice since 2010, because achieving the needed change takes time and requires a partnership approach between governmental authorities, shippers, operators and infrastructure owners. Any licensed, certified rail company established in the EU is in principle able to offer such services, and in doing so has the right to pick up and set down passengers at any station along the international route. The market for purely domestic rail passenger services is not yet being opened up to EU-wide competition.

The liberalization leads the opening up access to the rail transport market for new suppliers so that there will be choice, and so that a quality and price structure can develop in accordance with the market's needs because in practice, railways need to improve their service levels to those available in other transport modes. While the transport industry is becoming more international and deregulated, rail transport in Europe is too often based more on national considerations than on customer needs.

1.2 Trends that affect the main value chain players

The rail system value chain is complex and involves a large number of players. Macro-trends have implications on different players involved in the rail system value chain.
1.2.1 Rail Operator

The increase in demand and state economic incentives that the industry has experienced in the last few years causes a considerably rise in rail transportation services and in the interoperability of rail lines. Then operators are reducing intervals between trains and extending service hours to allow the increased demand, and increasing in authorities that are introducing automated lines to offer a shorter interval between trains and therefore increase the transport system's capacity especially in Asia where there are increasing mobility needs. Those automated lines present some advantages because they reduce maintenance times of infrastructure and rolling stock compared to the non-automated lines. They also promote maintenance-oriented design and manufacturing and development of new billing and control systems, that is need to give a good service to the whole current demand.

Figure 7: Cities with automated metro lines in 2011.

The increase in capacity and adaptation of metropolitan transport systems to rise the passenger’s comfort, making the urban passenger transport service better with a launch of new lines and reduced intervals between consecutives trains and extended hours schedules and integrating it with other transport systems together with the development of more efficient and sustainable transport systems and the acquisition of more energy-efficient vehicles are some actions to strengthen positioning as a means of sustainable transport.

The first automated lines date from 1981. With 30 years of operating experience, automated systems have proven their maturity and accumulated extensive operating experience. In 2011, there were 588 km of automated metro in operation, in 41 lines that together served 585 stations. Some of the longest metro lines in the world are actually automated, as the Dubai metro line is, which length is more than 50 km. Of the 25 cities with automated metros, 13 have more than one
automated line: Barcelona, Busan, Copenhagen, Dubai, Kobe, Lille, Nuremberg, Paris, Singapore, Taipei, Tokyo, Toulouse and Vancouver.

1.2.2 Infrastructure manager

The last measures as the development of high speed transport infrastructure increasing the distance between stations reflecting a deployment of new infrastructure to low-density areas. The promotion of new transport systems such as light rail, which require less investment due to their ease of construction. Upcoming investment in building new infrastructure to provide public transport to low-density areas and the emergence of new infrastructure to interconnect different transport systems are leading the growth of new metropolitan areas.

![Figure 8: Evolution of distance between consecutive metro stations in Madrid. Source: A. T. Kearney, 2009 “Trends in the passenger transport sector and implications for rolling stock manufacturers” [5].](image)

Structuring of economic incentives in specific plans and promotion of TMS (Transportation Management System) are leading the increase in demand because of the state economic incentives.

This metropolitan areas show a development of new urban transport, an adaptation of infrastructure to new mobility patterns, using renewable energy in stations and using ecological material as construction of sustainable infrastructure.
1.2.3 Rolling stock manufacturer

Rolling stock manufacturers have developed high-speed trains and the interoperable rolling stock improving their accessibility during the last years. Demand has grown for urban transport systems and the design and manufacturing has improve to reduce maintenance times optimizing the maintenance operations. There is great extension in the value chain because of the rise of opportunities in providing maintenance services, increasing concessions business and developing capabilities for establishing alliances between the manufacturers and the operators.

Rolling stock manufacturers have invested in increasing trains’ energy efficiency. They have managed a 32% reduction in mass in the design of train bogies. For example in United Kingdom they have reduced system access fees due to the reduction in axle load and they have achieved a 5.1% reduction in power consumption in the Barcelona metro despite the increase in the transport service as a result of installing energy recovery devices in rolling stock.

Figure 9: Reduction in axle load eco versus conventional bogie.
Figure 10: Barcelona metro energy savings.

1.3 Trends in the rolling stock component industry

The rolling stock component industry currently faces a new challenge, maintain historic profit levels. This could look easy but many trends are making of it a really hard work. The main component suppliers need to quickly achieve scale and develop the after-sales business. To comply it suppliers and OEM’s engineering have stronger collaboration to improve the reliability and to reduce the weight, the energy consume and the final cost of their components. The components has developed into electrics and electronics from the common mechanics and hydraulics components. Also, the industry has focused on higher-growth markets as China, Russia, India and North America instead on Europe, and the companies are growing that much that they are becoming global OEM’s. On the other hand, low cost countries show their opportunities as low-cost sourcing and manufacturing countries, this aligned with the increasing
cost reduction pressure and restrictive location regulations make them a profitable place to produce. China is the best example, they have an emerging market, with low cost sourcing and manufacturing so the biggest rolling stock companies are from there, as CSR or CNR are, and they are getting ready to export, making harder to produce for Europe and America companies as Bombardier or Siemens.

1.3.1 New technologies

OEM’s are making strong efforts in increasing train’s energy efficiency designing the new engines with higher reliability, less weight and reducing their emissions using less energy to run them. There is greater integration between suppliers’ and OEM’s engineering because of key components continuous evolution from mechanics and hydraulics to electrics and electronics as the electric brake and the direct transmission from electric motors to wheel-sets.

One example, is Knorr-Bremse, the global leader in braking system technologies for rail and commercial vehicles. Their products portfolio is focused on offering solutions that minimize energy consumption and enhance fuel efficiency, reduce air emissions, minimize noise emissions and protect the environment by using more environmentally friendly materials and production processes. They seeks close alliances with collaborative partners in the areas of Research and Development as Technical University Berlin and Technical University Munich.

1.3.2 Norms and regulations

To access new markets for the component industry is needed to comply with local content regulations in key markets and knowledge of engineering footprint. Localization and technology protection strategies will play a greater role following regulation in profitable markets. The adaptation to the local content regulation combined with cost competitiveness strategies on each market is forcing the redefinition of the main players’ industrial footprint.

![Figure 11: Carbon emissions per passenger travel.](source: RITA (BTS), EIA, DEFRA. “Transportation statistics annual report 2012” [7].)
Supply chain emissions need to be considered, these are emissions made by immediate suppliers and their extended supply chains in the delivery of products and services. The chief advantage of this approach is that some of the most cost-effective reduction opportunities are to be found in the supply chain.

Until now, supply chain emissions have been difficult to measure, because of the sheer number of organizations and emission sources involved.

Figure 12: US travel footprint in 2005.
Source: RITA (BTS), EIA, DEFRA [7].

In China there is a difficult trade-off when investing there because is needed to transfer technology to local partners, being them future competitors, and technology protection strategies are becoming more important to comply while securing the core technical competitive strength. Rail organizations are now able to incorporate a fuller range of opportunities (notably those where the greatest reductions can be made for the least cost) into their environmental improvement and emissions reduction programs, although is the most environmental friendly transport compared with other transports as the picture below shows.

### 1.3.3 Markets

The demand for rolling stock is migrating to high-growth markets as China, Russia, India and North America. In China the rolling stock market will keep strong growth in the next years, giving cost advantage in production to the global players which have established their global production base in China. Chinese OEM’s as CNR and CSR already have strong presence at many segments, with special focus on urban transport developing the Chinese metro and the high speed trains.

China rolling stock market is recovering with a strong growth in 2016, remaining as an important market for local component suppliers.

2012-2016 CAGR

- **12.4%**
- **9.9%**
- **10.4%**
- **5.2%**
- **11.5%**

Figure 13: China domestic rolling stock market by product type in billions of euro.
1.3.4 Customers

“Big 3” domination is vanishing, while CSR and CNR leadership is emerging becoming low-cost global suppliers and giving strong cost pressure across all OEM’s.

Customers, are choosing the cheapest suppliers, that’s why the OEM’s are demanding to reduce supply chain complexity and that will incentivize a stronger Tier structure in the industry. Also main Chinese components and sub-components suppliers are ready to export due to the globalization and because they have grown rapidly supplying other OEM’s.

Figure 14: Temporal evolution of the main OEM’s in 2005, 2010 and 2016. Source: Manager Magazin; company websites and annual reports; 2012 [9].

Figure 15: Railway operators’ structure. Source: A.T. Kearney, 2012 “Trends in the rolling stock component industry” [8].
1.3.5 Business models

The after-sales business is becoming key for component suppliers to achieve sustainable and profitable growth due to the liberalization of rail market leading to new business models and the new financing schemes between operators and OEM’s.

To capture the after-sales market, main component players are developing different formulas.

Knorr-Bremse has a dedicated Rail Services division, offering maintenance, overhaul and repair of its supplied components and systems together and is increasingly protecting technical details through proprietary information to reduce operators’ possibilities to perform the maintenance themselves. Also this company is managing proactively safety critical consideration by homologation/ certification bodies to keep a monopolistic position in spares, which represent the largest portion of the after-sales accessible market accounting for 70% of the total.

But it is necessary to consider that even when operators keep the full-train maintenance in-house, main component players are looking to provide specific services at sub-system level.

1.4 Conclusion

Overall, the railway industry is facing great challenges and changes that token in the correct form could help the industry to develop accurately.

People are demanding increasingly better methods of transport. Railway and air industries are facing a competition where the development of new technologies and materials could be decisive. Lightweight materials would help to the railway industry to settle in the long distance trips market, and it will open new possibilities to compete with the air industry in travels between longer distances journeys.

Because of this increasing demand, manufacturers are working on better trains that could run more hours of service and with less intervals among them. High speed trains are being more demanded as the same time that the rolling stock manufacturers are demanding a weight reduction to achieve lower quantities of energy consumption and CO2 emissions, what is giving a great opportunity to the main producers of lightweight materials to promote and expand their clients among all the rolling stock and infrastructure manufacturers.
Over the railway market, it is dominated by the Chinese companies which are taking advantage of the low cost labour in their country. Other OEM’s are being forced to produce in China and adopting their business models. That is other opportunity for the lightweight material industry that could give the difference for the OEM’s always that they improve their supply chain. Also this manufacturers would have the after sales market because the new lightweight materials need particular treatments and operations and customers’ technic knowledge and experience wouldn’t be enough to perform.

There are many reasons to study the possibility of the adoption of lightweight materials around the railway industry, reason that support the main objective of this project.
2. ECONOMIC, SOCIAL AND TECHNOLOGICAL IMPACTS OF WEIGHT REDUCTION IN HIGH SPEED INDUSTRY

2.1 Characterization of rail products

A train is a series of railway carriage or wagons coupled together and pulled by an engine known as locomotive. The locomotive can pull or push the cars. It was originally powered by steam, but today, diesel or electric locomotives give power to the majority of the trains. Trains with a large number of cars typically require more than one locomotive.

Within the rail transport it is called rolling stock to all kinds of vehicles equipped with wheels able to run on a railway, considering them as isolated vehicle. They are divided into two groups: the traction material, locomotives and trailing material or equipment which are all pull or push by the locomotive attached to it, on the tracks. The locomotive was originally powered by steam, but today, diesel or electric locomotives give power to the majority of the trains and trains with a large number of cars typically require more than one locomotive. The set of rolling equipment interconnected dragging or pushing the locomotive, is called composition. The set of the locomotive with the composition is known as train. Depending on the type of service they provide, trains are called: cargo, passenger services.

- **Cargo trains** are used to transport goods by rail. The wagon box is the most common type of freight cars and is completely closed. Open hopper cars are opened to the air which have openings below for unloading goods such as coal. There are closed hoppers that carry goods, such as grain, they must be protected from different elements, and flat cars are designed to carry containerized cargo that is transferred from trucks. Other types of freight cars include refrigerated wagons, tanks, barns and racks for cars.

![Cargo train](image-url)
• **Passenger trains** are designed to transport people over long or short distances. The train ride was once the main method of travel around the country, but it decreased in the United States when the air transport arrived and with the building of new interstates roads. Long distance passenger trains consist in some passengers’ cars, restaurant’s wagons and sometimes wagons with beds. Sometimes, freight cars are added to passenger trains to transport goods to areas where it is difficult to get by truck.

![Passenger high speed train.](source: Railway gazette)

Since the train appeared for the first time in the history they have evolved in the way the energy to move the train is generated. The firsts trains were moved by the action of the steam, but currently their engines could be differentiated as diesel engines or electric engines.

The current train engines, use diesel, which is connected to a generator, providing power, fuelling the engines, which does not generate steam. Most short distances trains, used DC motors, but use high-speed alternating current.

### 2.2 High speed train description

Among the different types of trains, the one which is using the best technologies are high speed trains. These trains that regularly travel long distances at high speeds require braking systems that can keep these forces under control – both safely and economically. As well as lightweight, compact systems that can be used worldwide, there is a need for intelligent control systems. The highest quality components operate in harmony to guarantee optimum functionality, high reliability and maximum safety.
High speed trains are formed by several component, that together they form the different systems of the train. The main manufacturers are producing the components with the best technologies and Knorr-Bremse and some of the following components are manufactured by them.

- **Air supply**

Compressed air is the carrier of energy for the basic functions of a train. In addition to the actuation of the brakes, it is also used to open doors, turn on the air suspension, as well as to raise the pantograph or to operate the wipers. Combined compressor and air treatment system are adapted in line with the trend towards increasingly compact, lightweight systems.
• **Brake control**

Ensuring the intelligent interaction of all brake functions involved in the braking process facilitating reliable stopping of the train in all operating conditions. A brake management system for the entire train calculates brake force distribution based on different data: available brake effort of the individual brake systems, vehicle weights and adhesion limits and thermal limits of the friction brake are all taken into account to blend the different systems and achieve a balanced braking effort.

![Figure 21: High speed train, brake management. Source: Knorr-Bremse.](image)

![Figure 22: High speed train, brake control components. Source: Knorr-Bremse.](image)

The braking system in high speed trains is more powerful than common and it uses various systems. The engine itself traction acting as a current generator using the energy developed by the train so that slows down as it goes producing electrical energy, which in turn may be returned to the feed line through air catenaries to feed other trains on the same line or to the regulation of the environment or other uses of the train itself temperature. Conventional disc brakes, high power and, in some cases, brake pads are also used.

• **Suspension system**

The suspension of a railway vehicle is that set of elements whose function is to cushion the possible defects of the road. There are two types of suspension that need to be distinguished in railway vehicles: primary suspension and secondary suspension. The first is that which is between the axle and the bogie frame; the second between the frame and the housing. Both
high-speed trains as passenger cars have these two types of suspension together. Trends in high speed trains, compared to conventional trains, are:

- Increasing the flexibility of the suspension linked to the increase of the maximum speed of movement of vehicles.

- All high speed trains have dual suspension system: primary and secondary suspension. The primary is normally composed of steel coil springs and secondary pneumatic usually.

- **Bogie equipment**

The bogie provides several essential functions. Firstly it bears the load, it transmits the traction and braking forces, it steers the car in a safe manner and smooth out track irregularities. A bogie is a metal frame to which the axles and wheels are attached, it is joined to the chassis of the car by way of an articulated joint, the pivot. Thanks to this system, the bogie is mobile with regard to the chassis of each car. During the ride the car round curves in the track progressively and smoothly. A key element, the bogie thus enables cars and power cars to correctly negotiate even the sharpest of bends. Other important functions include guaranteeing passenger comfort and operational safety. To do this, two suspension systems absorb track irregularities and limit their transmission to the car. A primary suspension system which acts like the tyre on an automobile is located between the axles and the bogie. A secondary suspension system links the bogie to the car body shell. This suspension system controls the lateral movement of the body shell and its pneumatic composition insulates the car or power car from vibrations and noise. Bogies can be motorized (dedicated to traction) or simply load-bearing essentially dedicated to braking and on-track steering.

![Figure 23: High speed train, bogie equipment description. Source: Railway technical, “Bogie parts and description” [10].](image-url)
• **On-board systems**

Doors, air conditioning units and more. It is not just braking systems that ensure greater safety and comfort in rail vehicles. It includes products and solutions as entrance systems and platform screen systems and air conditioning units. Also electronic diagnostic systems and windscreen wiper and wash systems.

![Figure 24: High speed train, on-board components. Source: Knorr-Bremse.](image)

• **Body shell**

In the last decade aluminium car bodies have replaced steel car bodies to a large extent. This has been a major step towards light and thus more energy efficient rail vehicles. Aluminium offers some substantial advantages over steel in car body technology due to lightweight properties. Today aluminium car bodies are state-of-the-art technology and will probably continue to be in mid-term since manufacturers are interested in amortization of expensive production facilities. Aluminium technology is very promising for energy efficiency. However, no additional effort is required to facilitate technology diffusion. In long term perspective, aluminium car-bodies will face a growing competition from fibre-reinforced polymers.

![Figure 25: High speed train body shell. Source: KTH, 2010, David Wennberg “A Light Weight Car Body for High-Speed Trains”.](image)
2.2.1 Rolling stock manufacturing

The process to build a high speed train is complex, due to the big quantity of systems that form it. Here, it is an example of building a high speed train from the beginning to the end.

The many parts that make up a car body shell will be made in a machine shops either at the manufacturer’s plant or contracted out to sub-suppliers. These parts may be structural members are bolsters or panels. It is important that the parts can be easily assembled to form the vehicle as it progresses through the manufacturing process. The cost of many vehicles has soared because the design of parts has caused trouble for the assembly process by being too complex, too tight tolerances, or too difficult to handle. Curved shapes are the worst and roofing the most vulnerable to such problems.

Once sufficient parts have been manufactured separately, they are finally brought together for assembly in a jig. The underframe is usually the first part of the body shell to be built and its principle parts will include bars, runners, bolsters, and transoms.

An important feature of the manufacture of the underframe is the provision of a camber. The camber is important because, as all the other structures are added to the underframe, the weight obviously increases. If there was no camber, the resulting car shell would sag in the middle.

The vehicle underframe will be moved through a series of jigs designed to hold the frame in specific locations to accomplish attachment of the various components.

Similarly to the underframe, the various parts of the vehicle side will be brought together in a series of jigs for assembly and welding. If it is a car body that is being manufactured, the windows can either be cut out of the body side panels or the sides will be assembled in sections with the window frames (called pans) already installed. The most difficult aspect of side manufacture is getting an acceptable degree of flatness whilst keeping the weight of the body shell within reasonable bounds. Welding the panels to the frame often causes rippling of the panel due to distortion by the heating of the welding process. Clamping the skin under tension can help but post welding straightening is often necessary.

Once the various parts are completed - underframe, body side and roof - they are brought together in a jig for final welding. This jig will align the assembly and clamp it in place securely in anticipation of welding.

When the welding is finished, the completed shell is moved to an inspection and straightening jig. This is where it can get interesting, watching the craftsmen using their skills to straighten the sides. As it has seen, the sides will usually show ripples on the skin due to the tolerance generated during assembly and the expansive effects of welding. At the same time, grinding of the welds will take place to smooth any rough edges.

Straightening may involve using a large hammer with a blow torch to heat the skin, or it may employ a more sophisticated method such as attaching a magnetic panel to the outside of the skin and a thick panel to the inside, using the magnet as shown below. This ‘thick’ panel will have a series of equally spaced holes through which heat is applied using a multi-nozzle blow torch.
heat applied has the effect of stretching the skin of the body, due to the spot heating, causing the panels to straighten. Vacuum clamping is also sometimes used.

For a mechanically fastened body, the roof goes through much the same process as the underframe or sides. Although there will probably be less items involved than say the underframe, the curved shape of the roof will require a jig to form the contour. This will be complicated if it is a ribbed section and will probably need holes cut out to accommodate vents, HVAC and ducting. The first roof is always difficult to assemble, since the jig has to be just right as well as all the parts making up the roof itself. Once assembled, a roof for a passenger car may be inverted for the fitting of ducting and wiring.

The modern train will often be designed to have an aerodynamically smooth front end. However, certain crashworthiness standards are necessary, so some protective structure will be needed as well. The usual solution is to construct a steel framework and then mount the smooth, shaped end over it. To achieve the three dimensional curved shape in steel or aluminium is difficult, many manufacturers often use a glass reinforced plastic (GRP) moulding. There are normally made by specialist producers, since the process requires skill, special materials, proper environmental protection systems and careful quality control. After that, the car shell could be painted.

Bogies run from the very simple cast steel design to very complicated fabricated designs with steel spring primary suspension, air bag secondary suspensions and both tread brakes and discs (such as French TGV bogies). The various parts that make up the side frames are assembled in a rotating jig and welded together and then moved to a new jig where the bolster or transom, depending on the type of bogie, will be welded in place.

It is very important to have the "tram" of the bogie correct - this is the diagonal measurements taken from corner to corner - and special measuring equipment will be used to ensure the bogie frame is within tolerance before final welding takes place. Once the frame is manufactured, it is painted and then the externally mounted parts will be added.

Normally, wheels and axles are bought as completed items and only need a minimal amount of machining work for assembly. The wheels will need to have the centres bored to suit the axle end diameter. This will be carried out on a wheel boring machine, which is a very big vertical borer with the wheel held in a large chuck. Once this task is complete, the wheel is taken to a wheel and axle press. This is a large horizontal press where the various items that make up the wheel and axle assembly will be pressed onto the axle.

Besides the wheels, there may be brake disc centres, inside or outside bearings and gear wheels. Each of these items will be pressed on in turn. The fit is an "interference fit" and often there is an oil plug in the wheel to allow the injection of oil to assist in the pressing process. The oil is injected between the wheel and the axle to lubricate the mating surfaces during the pressing process.

During assembly, records will be kept of the pressing process just in case there is a problem with the wheelset in the future. It is important during this stage to maintain the correct dimensions for the 'back-to-back' gauge. This is the measurement between the back face of the wheel flanges and it is necessary to ensure the correct fit is achieved otherwise there would be serious and embarrassing consequences when the completed vehicle is placed on the track.

After pressing, the wheelset is transferred to a portal lathe where the wheel treads will be machined to ensure consistency of diameter between the two wheels. It does not apply to all
assembly processes and will be dependent on the type of vehicle being manufactured. It is, however, very important on vehicles that use a mono-motor bogie design where high torque can occur on curves due to mismatched wheel diameters. If the suspension has chevrons, these will be the first items to be connected, if the suspension is using coil springs then that will be one of the last steps as the wheelsets are added. Next comes the air pipes, followed by the brake rigging, then the wiring and finally the wheelsets, culminating with the completed bogie undergoing a load test, which will ensure that the suspension is installed correctly and the bogie is functioning as designed.

The steps described above could be in a different order depending on which item makes logical sense in the sequence, or to the particular bogie manufacturer's preference.

There can be a considerable amount of wire in a rail vehicle and it is important to ensure that the wires are all running from point to point along the most economical route. At the same time, to make life easier for the maintenance department, all wires should run as close together as possible. The only exception to this is that high voltage wiring will be kept away from communications wiring or safety sensitive cables. Wiring is assembled in looms off of the vehicle; in fact, very often, wiring looms are a contracted out item. On modern rolling stock where more consideration has gone into the maintainability of the vehicle, a cable tray arrangement will be used to run the length of the vehicle with arms extended out at convenient locations along the main tray. The wires will be colour coded and/or numbered at regular spacing along the loom, or tray, to ensure the wire is identifiable for connection during assembly or replacement during the life of the vehicle.

Similarly to the wiring there can be a considerable amount of piping on a vehicle and it can be advantageous to assemble some of the runs of the piping away from the vehicle. This will be performed in the pipe shop where the lengths of pipe will be cut, threaded on the ends and connectors applied to suit, maybe with a few off-shoots, as required. These will then be delivered to vehicles for installation, either during underframe invert or in the fitting out shop.

Once the body shell is complete, our vehicle is sent to another shop for fitting out. Some of the bodyshell parts may have been painted before assembly, depending on the method. The common assembly method is firstly to attach the cable looms and then the piping to the underside of car. After air reservoirs ready for fitting under car and it is possible to do the interior ducting and insulation. Then the use of jigs for interior fitting out could be retired.

Of course, not all manufacturers follow the same format for assembly but the following description is a typical method for final assembly of a vehicle, but equipment may not necessarily be installed in this order.

Secondary structure is used to attach interior equipment panels or the body linings. At this stage, any interior insulation to go into the walls, roof or floor will be installed along with any hidden wiring or piping. It is also a good time to hang the doors and door gear as there is minimal other equipment around to interfere with the installation. Whilst this is going on inside, underfloor equipment can be welded or bolted on below the body shell, unless the "invert" method of assembly has been adopted. This stage will include battery boxes, low voltage power supplies, chemical toilet retention tanks, brake resistors, HVAC and brake equipment.

Then wiring will commence in earnest with the installation of control cubicles and electrical boxes and possibly the driver’s compartment equipment and lighting. At this point, handrails and maybe
the seats will be installed. If the HVAC unit is roof mounted, this may now be craned in and installed. If there have everything complete, it is possible now to install the roof lining. Outside, the coupler will be installed and our piece of rolling stock is almost complete.

Nearing the end and the car will be lifted onto its bogies and electrical and mechanical connections made. At this point, there will be a final check through the vehicle and clean out remaining debris. Once this is done, the vehicle is handed over to the testing department to complete all the integration tests described below.

Final cleaning and removal of protective covers will not take place until all the testing, and probably the commissioning, has been completed. Too early removal of protective covers leads to possible claims from the customer for scuffing or ingrained dirt and subsequent costly rectification by the manufacturer.

2.3 The importance of weight reduction in High Speed

2.3.1 Evolution of the high speed during the last 50 years

It’s been more than 50 years since it is known that some trains could reach 300 km/h applying greater pulling power, but it was impossible to apply because the wagons severely damaged train rails and preservation required much effort, being overly expensive.

Japanese engineers built train rails with little bit tight curves and little pronounced slopes achieving 200 km/h in some journeys. Afterwards, in 1964 it was inaugurated the “bullet train” which connects Tokyo and Osaka being the most speed train reaching 240 km/h.

Currently the high speed is much more developed, having the TGV train in France, the ICE lines in Germany or the AVE in Spain. The TGV has the world record speed with 515.3 km/h.

To achieve those speeds new measures are needed as constructing wagons with lower weight materials’, pulling engines are lighter but they have the same power and the materials of the current transformer weigh less than before. Mainly the development of the high speed is about reducing weight to achieve higher speeds, but also it may need several technical advances to be useful, as the following ones.

The next step after the “bullet train” was done by JR Central, in 1992 with the weight reduction in the 300 series having a new traction system and a new engine of alternating current power (AC power). The new traction distribution allows better adhesion and higher payload.

To achieve speeds around 270 km/h, the Japanese engineers redesigned the boogies, lightening them and improving their capabilities. In 1992 the cars were constructed directly over the top surface of the boogies offering better stability at high speed and better behaviour at curves. Also, the brakes had to change because of the higher speed from the solid friction brake to the electric brake that guarantee a better reliability at 300 km/h.
The use of materials as the aluminum for the body of the cars and plastic inside them have allowed reduce the average weight of the trains. The best example is between the Series 0 and the current N700, that with the same length (400m) their respectively weight are 970 tones and 320 tones.

![Figure 26: Bogie DT 200 and bogie TDT 203. Source: JNR.](image)

In the nearly future, the railway industry wants to compete with the air industry, offering better services of travel with a duration less than 3 hours. Long range trips are still obviously much faster by plane, while on relative short trips the train is the transport of choice. It is the mid-range trips where things get interesting, and more exactly those trips which are less than three hours.

To achieve a better position than the air market, it’s necessary to reach 360 km/h or more, maintaining the minimum impact with the environment and with an efficient power consumption. This improvement could be reached by the new lightweight materials.

Nowadays, the main manufacturers reduce the weight of their trains using lightweight materials to manufacture cars of two floors which do not weight more than the conventional car of one floor. Traction engines have lightened without sacrificing the power thanks to new designs and the use of lighter materials. Also, transformers, which have the mission to supply different voltages and powers for engines, parts are heavier train; the construction of transformers with sheets of aluminium and steel alloyed with cobalt instead of copper wires has allowed to reduce his weight of 11 to 7.5 tons.

During the last decade, manufacturers have developed Maglev train (derived from magnetic levitation) which uses magnetic levitation to be moved without touching the ground. This new technology with a vehicle traveling along a guideway using magnets to create both lift and propulsion, reduces friction by a great extent and allows very high speeds.

The Shanghai Maglev Train, is the fastest commercial train currently in operation and has a top speed of 430 km/h. It covers a distance of 30.5 kilometres in 8 minutes. Maglev trains move more smoothly and more quietly than wheeled mass transit systems. They are relatively unaffected by weather. The power needed for levitation is typically not a large percentage of its overall energy consumption.

Compared to conventional trains, differences in construction affect the economics of maglev trains, making them much more efficient. For high-speed trains with wheels, wear and tear from friction along with dynamic augment from wheels on rails accelerates equipment wear and prevents high speeds. Conversely, maglev systems have been much more expensive to construct, offsetting lower maintenance costs.
Despite decades of research and development, only two commercial maglev transport systems are in operation, with two others under construction. In April 2004, Shanghai’s Transrapid system began commercial operations.

2.3.2 Impacts attached to the weight reduction in the high speed

There are many impacts caused from the weight reduction in trains in general, but the most interesting are those caused by the high speed trains.

2.3.2.1 Competence with air industry

I’m analysing very common route travelled in Europe, that it is Amsterdam to Paris. A new high speed train has been put into use not too long ago, reducing the total travel time from four hours and nine minutes to three hours and eighteen minutes. When flying the skies it becomes a bit more difficult to estimate total traveling time. Let’s assume a check-in takes about one hour, a flight thirty minutes and checking out no more than thirty minutes. That leaves us with two hours. However, since airports are mostly located outside the city centre, it is fair to add at least another hour for traveling from and to the airport. So flying will take about three hours. With the same duration it’s necessary to consider the emissions. Not surprisingly, the train produces around four times less CO2 per passenger compared to the plane. Also it’s remarkable the different prices of taking a train and a plane. These prices vary depending on when you book, but the train was mostly cheaper at around €55 for a return ticket. A plane ticket would cost you no more than €90 including taxes.

Some data from INE (“Instituto Nacional de Estadistica”) [11] shows how the quantity of passengers using planes during 2013 in Spain have been reduced in 4.7 million passengers, and during the same year the users of high speed trains have risen around 3 million passengers. Estimations says that most of the passengers have changed planes to high speed trains, being around 2.1 million with a 55 euros return tickets makes an amount of 115.5 million of euros. Having a benefit around the 10% to the high speed industry offering their services, data verified by the Spanish Railway Foundation, it makes 11.5 million of euros in benefits.

That’s a reasonable amount of money to justify the investment in lightweight materials to reduce trains’ weight and reducing their journey times between other cities to less than three hours and starting a competition between the air industry and the high speed trains industry for more long distances trips.

2.3.2.2 Environmental improvement

The main question after developing the high speed trains is if it is more efficient and how much it contaminates.
There is not an exactly answer to this question because it depends on each case. The drivers that makes high speed trains less contaminant are the big distances that they go through, mostly with the same speed due to the low stops between stations and the use of the regenerative brake, which returns current to the electric net. Also, the better aerodynamics and technologies make the difference with other transports like car or bus.

Alberto García Alvarez shows on his project “Efecto de la alta velocidad ferroviaria en el consumo de energía y en los costes operativos” in 2008 [12], a comparison among the main kind of transports in efficiency and in CO2 emissions. The following picture highlights how the energy consumption per passenger of high speed trains between Madrid and Barcelona is five or six times less than the car’s consumption, four or five times less than the plane’s consumption and a little bit less than the bus or the conventional train’s consumption, as it happens between Madrid and Seville too. Also, the emissions of high speed trains are four or five times less than the car’s or the plane’s emissions, and almost the same than the bus or the conventional train’s emissions. The picture reflects consumption per passenger with a total occupancy by the different types of transport.

<table>
<thead>
<tr>
<th></th>
<th>Distance (km)</th>
<th>Consume (kWh/pax)</th>
<th>Emissions CO2 (kg/pax)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight</td>
<td>528</td>
<td>217</td>
<td>67,1</td>
</tr>
<tr>
<td>Car</td>
<td>612,5</td>
<td>283,3</td>
<td>63,1</td>
</tr>
<tr>
<td>Bus</td>
<td>614,5</td>
<td>55</td>
<td>12,8</td>
</tr>
<tr>
<td>Conventional</td>
<td>707,7</td>
<td>63</td>
<td>16,4</td>
</tr>
<tr>
<td>High speed</td>
<td>627,2</td>
<td>50</td>
<td>13,1</td>
</tr>
</tbody>
</table>

Table 2: Comparison of consume and emissions of different types of passenger transport.
Source: FFE, Fundación de los Ferrocarriles Españoles.

It is easy to notice that the high speed is the best choice to go through long distances, but the efficiency depends on the occupation. Cars with five people could match the emissions of high speed trains, conventional trains or buses when they have a very low occupancy. However, the plane, although it flies full, does not match the emissions of conventional and high speed trains or buses, even when these are only with 20% of its seats occupied.

Differences among the conventional and high speed train and bus, they are small, but it is possible to cause significant reductions if there are lower cars on the roads or if less aircrafts take off. Mainly, if we want to reduce the passengers using cars and planes, high speed trains have to reduce their long distance travels to less than three hours to be competitive.

That’s why lightweight materials have to be used to reduce the weight of the high speed trains, increasing their speed offering better services to the users.
2.3.2.3 Energy savings using lightweight materials

It is known that using lightweight materials the energy consumption it is considerably reduced, but we have to know how big the impact of this weight reduction is. As IFEU (“Institut für Energie und Umweltforschung”) says the relative energy savings of the railway products are:

<table>
<thead>
<tr>
<th>Train type</th>
<th>Relative energy savings [%/ 10%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subways/ Urban trains</td>
<td>8</td>
</tr>
<tr>
<td>Short distance trains</td>
<td>7</td>
</tr>
<tr>
<td>Long distance passenger trains</td>
<td>4</td>
</tr>
<tr>
<td>High speed passenger train (ICE)</td>
<td>3.2</td>
</tr>
<tr>
<td>Long distance freight trains (electric)</td>
<td>5</td>
</tr>
<tr>
<td>Long distance freight trains (diesel)</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3: Relative energy savings per 10% of weight reduction in different types of trains.

But currently the main OEM’s are developing new light weighting projects as Bombardier achieve a reduction of 28% with Aventra and Siemens has reduced 25% of Desiro City train in the UK. So it is known that achieving 15% of weight reduction is possible, on a conservative way.

The following graphic highlights how different trains reduce their energy consumption in function with the percentage of weight reduction in different trains, long distance trains and regional trains. I’m focusing in the LD-7200 that with a 10% of weight reduction has 3.2% reduction of net energy consumption. It is possible to see that with 20% of weight reduction, the reduction of net energy consumption is 6.4%, so it follows a lineal function.
It is easy to notice that with a 15% of weight reduction, the net energy consumption is reduced in 4.8%.

**Practical case**

The high speed line Madrid-Barcelona has 627 km length and data from Renfe shows that the first train leaves at 5:50h and the last one leaves at 20:30h, so there are 14 hours and 40 minutes of difference. Taking in account that for one train takes from 2:30h to 3:10h, every train could travel 4 times a day, and it runs 365 days per year. Also Renfe says that this high speed line has a 79% of occupancy, and there are 404 seats in the AVE Serie 103, so 319 passengers travel in each train in average.

To calculate what is the economic impact, the data from the Spanish government says that the price of the kWh is 0.12061 €/kWh, and Renfe says that the average consumption is 0.02 litres/passenger*km. The relation between litres and kWh is 1 litre is 10 kWh, we can proceed to calculate:

\[
627 \text{ km/travel} \times 4 \text{ travels/day} \times 365 \text{ days/year} \times 0.02 \text{ litres/km*passenger} \times 319 \text{ passengers} \times 10 \text{ kWh/litre} \times 0.12061 \text{ euros/kWh} = 7.044.081.84 \text{ euros of energy consumption per year.}
\]
With an 4.8% reduction of energy consumption:

\[ 7.044.081,84 \text{ euros/year} \times 0,048 = 338.115,93 \text{ euros/year} \]

in savings with the 15% of weight reduction.

Trains could work during from 25 years to 40 years in exceptionally cases, but their useful life in average is 30 years, so building a train with lightweight materials and achieving 15% of weight reduction generates savings in their whole useful life of:

\[ 338.115,93 \text{ euros/year} \times 30 \text{ years} = 10.143.477,8 \text{ euros} \]

per train during their entire life cycle.

Also, the current concern of the main operators is increasing the number of seats to reduce the energy consumption per passenger and per kilometre, which is the way we compare the efficiency with other kind of transport. It occurs because almost every high speed train use the limit charge per axle that is 17 tonnes per axle. Using lightweight materials, the charge per axle will be reduced and the manufacturer can add more seats until the maximum charge per axle.

With the cooperation of Alberto Garcia, I could realise that with a reduction of the total weight of 1 ton it is possible to add 12 seats more to the train. The data base I made, shows the average total weight per train that is 481 tonnes So, only with a 15.9% of weight reduction the average capacity of 606 passengers could be more than the double, and the consequence is the energy consume per passenger and per kilometre will be more than halved.

The effect is that the high speed trains could be differentiated being the lowest energy consuming per passenger of all kind of transports.

**2.3.2.4 Maintenance cost savings using lightweight materials**

Maintenance costs have now gone commercial, along with the rest of railway financing. Few published prices exist to give an idea as to how much maintenance can cost. Often the details of individual contracts are deliberately obscure to preserve commercial confidentiality. Even railway companies which have tried to compare maintenance costs amongst their peers have not been able to get reliable like for like figures. One of the best examples about maintenance costs savings using lightweight materials is the next.

The new train roof composite repair system developed by TRB engineers, has been approved by Virgin Trains in preference to using conventional welded mild steel patch repairs, which remain susceptible to corrosion and subsequent re-repair. Polymeric composites materials inherently do not corrode. It is the first composite repair work of this type to be used for rail maintenance in

![Figure 28: Virgin high speed train manufactured with polymeric composite materials. Source: AZOM 2015 “Using lightweight advanced composites for rail applications” [14].](image)
the UK. The composite patched roof section provides the same structural integrity as a welded steel patch.

The composite roof repair sheet material from TRB is manufactured from a glass fibre with reinforcement of epoxy prepreg resin. The resin is placed in the clean room and then moulded at high temperature under pressure in the autoclave, according to the aircraft specification quality regulations. Sheets measuring 1 m², with a thickness of 0.765 mm, are produced and then cut to the size requirements of the train roof design profile.

An epoxy glass patch is bonded over the damaged section of the roof. This roof repair format is cost-effective, and requires minimal maintenance due to the long lasting corrosion-free feature. Overall, it prevents the need for a £100,000 entire train roof replacement. Furthermore, the rolling stock is out of service for less time because roof repairs can be done within 24 hours, thanks to easy and rapid application of the TRB composite patch.

2.4 Systems weight and cost breakdown

Basically, high speed trains weight is based on five parameters that are:

- Car body
- Both powered and trailer bogies
- Traction system or propulsion equipment
- Interior
- Other miscellaneous systems

![Figure 29: High speed train weight breakdown.](source)

Source: Networkrail, 2010 “Comparing environmental impact of conventional and high speed rail” [15].

Firstly, the car body is mainly made of aluminium and in some rare cases is made from steel in most of the trains as the TGV family and some of the Shinkansen family, or from carbon composite and silicone in the newest trains as the ETR 575 from the AGV family made by Alstom in 2012. So, applying composite materials to reduce weight of the car body is achievable.

Powered and trailer bogies together with the traction system almost the half of the total weight. Their structure is formed by axles, frame structure, reducer device and obviously by the engine and the wheels. Additionally the traction system needs to have the power converter. Most parts of the bogies and traction system need to hold on with great forces, moments and vibrations, so they are mainly made by steel and some components of aluminium. Because of this, the components have to satisfy many technical requirements, and it needs some investigation to use lightweight materials in them.

On the other hand auxiliary systems as the HVAC, doors, break system, WC’s, seats, walls and other components that improve the passenger satisfaction during the service represent almost a
third part of the total weight. Those components do not need to achieve great requirements, and it is possible to use lightweight materials in them easily.

The costs of one single high speed train is formed by acquisition costs, operating costs and maintenance costs. I’ve found some interesting data in the “Economic Analysis of High Speed Rail in Europe” made by BBVA Foundation [16].

The following pictures shows the different costs of a high speed trains in Europe in cost percentage and in grand total in millions of euros during its total life cycle, 30 years.

<table>
<thead>
<tr>
<th>Country</th>
<th>Train</th>
<th>Acquisition cost (M€)</th>
<th>Operating cost (M€/year)</th>
<th>Maintenance cost (M€/year)</th>
<th>Total operating cost (M€)</th>
<th>Total maintenance cost (M€)</th>
<th>Grand total (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>TGV Réseau</td>
<td>12,441</td>
<td>7,1</td>
<td>1,6</td>
<td>213</td>
<td>48</td>
<td>273,441</td>
</tr>
<tr>
<td>France</td>
<td>TGV Duplex</td>
<td>16,83</td>
<td>7,9</td>
<td>1,6</td>
<td>237</td>
<td>48</td>
<td>301,83</td>
</tr>
<tr>
<td>France</td>
<td>Thalys</td>
<td>12,441</td>
<td>8,4</td>
<td>1,9</td>
<td>252</td>
<td>57</td>
<td>321,441</td>
</tr>
<tr>
<td>Germany</td>
<td>ICE 1</td>
<td>40,775</td>
<td>9,7</td>
<td>3,1</td>
<td>291</td>
<td>93</td>
<td>424,775</td>
</tr>
<tr>
<td>Germany</td>
<td>ICE 2</td>
<td>23,92</td>
<td>8,4</td>
<td>1,4</td>
<td>252</td>
<td>42</td>
<td>317,92</td>
</tr>
<tr>
<td>Germany</td>
<td>ICE 3</td>
<td>26,975</td>
<td>8,7</td>
<td>1,6</td>
<td>261</td>
<td>48</td>
<td>335,975</td>
</tr>
<tr>
<td>Germany</td>
<td>ICE 3 Polyc.</td>
<td>26,26</td>
<td>9,1</td>
<td>1,7</td>
<td>273</td>
<td>51</td>
<td>350,26</td>
</tr>
<tr>
<td>Germany</td>
<td>ICE-T</td>
<td>23,205</td>
<td>7,1</td>
<td>1,8</td>
<td>213</td>
<td>54</td>
<td>290,205</td>
</tr>
<tr>
<td>Italy</td>
<td>ETR 500</td>
<td>21,83</td>
<td>9,5</td>
<td>4</td>
<td>285</td>
<td>120</td>
<td>426,83</td>
</tr>
<tr>
<td>Italy</td>
<td>ETR 480</td>
<td>20,304</td>
<td>7,8</td>
<td>3,2</td>
<td>234</td>
<td>96</td>
<td>350,304</td>
</tr>
<tr>
<td>Spain</td>
<td>AVE S103</td>
<td>21</td>
<td>8,1</td>
<td>2,9</td>
<td>243</td>
<td>87</td>
<td>351</td>
</tr>
</tbody>
</table>

| Average  | 22,36190909 | 8,345454545 | 2,254545455 | 250,3636364 | 67,63636364 | 340,3619091 |
| Percentage| 6,570038683 | 73,5580656  | 19,87189572 | 100         |

Table 4: Different high speed trains life cycle cost.

The operating cost of the table include the energy consumption cost and the human resources for the operation of the high speed train.
As it is possible to notice, mainly the operating costs are the meaningful costs of a high speed train. Basically, the total weight of the train has influence in the operating cost, bigger operating cost are related to heavier trains due to the energy needed to run the high speed train. The acquisition costs are not meaningful due to it hasn't taken in account the infrastructure costs that are the greatest ones. These results has been verified by Alberto Garcia, Spanish Rail Foundation president.

![Average high speed train costs](source.png)

**Figure 30: Average high speed train costs**


On this way, the effect of the lightweight materials on the acquisition cost is expected to increase it due to the cost of new technologies and the effect on the operating cost per seat is expected to decrease because of the lighter weight of the systems that allow more seats in the high speed train.

### 2.5 Main sensitive systems to reduce weight

A data base has been made with the global fleet of high speed trains and there are 64 different high speed trains from different manufacturers and operators. From all of these projects it is only possible to research some interesting information from 51 of all of them. The other 13 high speed train projects are mostly manufactured by Chinese companies and the language didn’t allow to extract the information.
Table 5: High speed trains global fleet.
Source: Different manufacturers and operators’ websites.

The total number of trains taken in the sample are 3905 high speed trains.

From the total number of trains in the sample it is possible to appreciate different manufacturers as Alstom, CAF, Talgo, Bombardier, Siemens and other Asian manufacturers as Kawasaki or Hitachi. The distribution among them is:
The main operators around the world are Renfe, Trenitalia, SNCF, THSR, JR and CR. The number of trains that they are currently operating are:

High speed trains are also classified in some families of trains. The most representative families are Siemens Velaro, Pendolino, TGV, Bombardier Zefiro, Shinkansen and Talgo. The number of trains of each family are:
Some interesting measures are:

- The average train weight is 481 tons and the median weight is 435 tons.
- The average and median of number of cabins are 10 cabins per train.
- The average power per train is 9297 kW and the median is 9200 kW.
- The trains’ commercial speed are from 250 km/h to 320 km/h with an average of 287 km/h.
- The average first year of service was in 2004.
- The average trains’ total length is 244 meters long.

The following pictures show the lineal regression of the dimensions of the train as the total length, the width or the height, in meters, with the unloaded total mass in tons. These pictures shows the dependence of these parameters in the weight function.
The total length of a high speed train is significant in the total mass of the train, because $1-P\text{value}>0.95$. Also the 82.4% of the green points are close to the regression line.
### Regression Statistics

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Lower 95,0%</th>
<th>Upper 95,0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>2,784726</td>
<td>0,08718</td>
<td>31,94208</td>
<td>2,60953</td>
<td>2,959922</td>
<td>2,60953</td>
<td>2,959922</td>
</tr>
<tr>
<td>X Variable</td>
<td>0,000515</td>
<td>0,000169</td>
<td>3,056436</td>
<td>0,000177</td>
<td>0,000854</td>
<td>0,000177</td>
<td>0,000854</td>
</tr>
</tbody>
</table>

**Figure 35**: Lineal regression comparing the car width and the unloaded mass for high speed trains global fleet.

Source: High speed trains global fleet.

The car width of a high speed train is significant in the total mass of the train, because 1-P-value>0,95 but not that much because only the 16% of the green points are close to the regression line.
The car height of a high speed train is not significant in the total mass of the train, because $1-P\text{value}<0.95$ and only the $3.2\%$ of the green points are close to the regression line.

Also I have studied the relation that the number of cabins, the power and the commercial speed have with the total mass of the high speed train. It is highlighted on the following pictures.
The number of cabins in a high speed train is significant in the total mass of the train, 1- \( P\text{-value}>0.95 \) and the 59.3\% of the green points are close to the regression line. Also, the number of cabins are related to the number of boogies, usually there are one motor bogie each two cabins, so the number of boogies have to be significant in the total mass of the trains.
### Coefficients Table

<table>
<thead>
<tr>
<th></th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Lower 95,0%</th>
<th>Upper 95,0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>283.2842</td>
<td>11.29754</td>
<td>25.07487</td>
<td>260.581</td>
<td>305.9874</td>
<td>260.581</td>
<td>305.9874</td>
</tr>
<tr>
<td>X Variable 1</td>
<td>0.007633</td>
<td>0.021851</td>
<td>0.3493</td>
<td>0.03628</td>
<td>0.051545</td>
<td>0.03628</td>
<td>0.051545</td>
</tr>
</tbody>
</table>

### Regression Statistics

- Multiple R: 0.049838
- R Square: 0.002484
- Adjusted R Square: -0.01787
- Standard Error: 29.31152
- Observations: 51

### Figure 38

*Figure 38: Lineal regression comparing the total commercial speed and the unloaded mass for high speed trains global fleet.*

*Source: High speed trains global fleet.*

The car height of a high speed train is not significant in the total mass of the train, because 1-Pvalue<0.95 and only the 0.2% of the green points are close to the regression line.
The power of a high speed train is significant in the total mass of the train, 1-P-value>0,95, and the 48,9% of the green points are close to the regression line.

Finally, the most significant parameter related to the total mass of the train is the length, which is highly associated with the weight of the car body. The second most significant parameter related to the total mass of the train is the number of cambins, which is also highly associated with the weight of the car body.
2.6 Conclusion

After the description of the main components and systems of a high speed train the necessity of weight reduction is studied. The main impacts of this weight reduction justify why it is so necessary.

Environmentally, this reduction of the total weight mass could cause the reduction of the air traffic density, which currently is one of the important tasks in Europe, as it is in London with the construction of the new Terminal 5 in Heathrow which is generating big problems for the England government. Also, this weight reduction will cause a great reduction in the energy necessity and in CO2 emissions that is one of the biggest global problems in the destruction of the ozone layer, because as I proved, traveling with high speed trains produce less emissions that any other type of transport.

On the economic point of view, this weight reduction has sense because of the great reduction in operating costs, mainly based in energy costs, which are the 73% of the total costs in a useful life of a high speed train. Also, the maintenance costs are always reduced with the use of lightweight materials due to their better properties that are going to be described in the following part of this project.

But then, what are the main sensitive systems to reduce weight? With the analysis done, it is possible to appreciate that the dimensions of the body shell, the number of bogies and the interior and other miscellaneous components, which represent the 17%, 37% and 32% of the total weight respectively, are the most interesting systems to reduce weight.

The number of bogies represent big percentage of the total weight, however their great resistance requirements make using lightweight materials nowadays in them almost impossible.

The body shell has aerodynamic requirements, but it is proved by new projects like the new ETR 575 from the AGV family made by Alstom in 2012 that composite materials can be applied in high speed car bodies.

The interior and other miscellaneous components, which represent almost a third part of the total weight of a high speed train, and the easy implantation of other materials in them, make it a quite interesting place to use lightweight materials.

Finally, this project is going to study the application of lightweight materials to these three systems, the car body, the interior and the miscellaneous systems, which together, they represent the 53% of the total train weight.
3. USEFUL MATERIALS AND TECHNOLOGIES TO REDUCE WEIGHT

3.1 Characterization of composite

3.1.1 Composite definition and types of composites

A composite material can be defined as a combination of a matrix and a reinforcement, which when combined gives properties superior to the properties of the individual components.

In the case of a composite, the reinforcement is the fibres and is used to fortify the matrix in terms of strength and stiffness.

The reinforcement fibres can be cut, aligned, placed in different ways to affect the properties of the resulting composite.

The matrix, normally a form of resin, keeps the reinforcement in the desired orientation. It protects the reinforcement from chemical and environmental attack, and it bonds the reinforcement so that applied loads can be effectively transferred.

There are many types of composites, but the fibre composites are the ones which offer the biggest substitution potential for conventional materials, so fibre composites are the one which are going to be focused on. The following picture shows the different composites.

![Figure 40: Different types of composites. Source: AT Kearney, 2011, “AT Kearney’s view on composite market” [2].](image-url)
3.1.2 The better properties of the composites

The primary reason composite materials are chosen for components is because of weight saving for its relative stiffness and strength. For example, carbon-fibre reinforced composite can be five times stronger than 1020 grade steel while having only one fifth of the weight. Aluminium (6061 grade) is much nearer in weight to carbon-fibre composite, though still somewhat heavier, but the composite can have twice the modulus and up to seven times the strength. Mainly, composites offer additional advantages such us:

- **Weight reduction**: they are 30-40% lighter than steel parts of equal strength.
- **Lower manufacturing complexity**: a single composite moulding can take the place of up to 15-20 individual components reducing manufacturing costs and speeding up to design completion.
- **Reduced tooling cost**: composite tooling cost is only 40% of steel stamping tooling cost.
- **Damage and corrosion resistance**: they offer superior dent/ding resistance than aluminium/steel panels. High chemical resistance and stability make them ideal for engine components.
- **Greater design flexibility**: moulding offers shape complexity, geometry details, and a depth-of-draw range unavailable with metal stamping.
- **Better internal damping**: they offer better sound insulation properties than steel, leading to reduced noise, vibration and harshness. Also they offer equal or better surface smoothness than surrounding steel parts.

As with all engineering materials, composites have particular strengths and weaknesses, which should be considered at the specifying stage. Composites are by no means the right material for every job.

However, a major driving force behind the development of composites has been that the combination of the reinforcement and the matrix can be changed to meet the required final properties of a component. For example, if the final component needs to be fire-resistant, a fire-retardant matrix can be used in the development stage so that it has this property.

Stiffness and strength can also be influenced at the development stage. The material structure can be engineered so that the directionality of the reinforcement material is arranged so as to match the loading on a given component.

A wide range of coatings and paints are available to match appropriate environmental conditions, which can be highlighted in the initial development stage or applied later should it be decided that a particular property or standard needs to be met further down the line.

Cost is ever present in the engineering equation and it is the balance of cost, performance and life-cycle analysis that should determine whether or not to use polymer composites over an alternative structural material option.

3.1.3 Manufacturing processes of composites

As it is said before, fibre composites offer the main substitution for conventional materials that is why I am focusing on them.
Fibre-reinforced polymer composites (FRPs) can be processed in different ways, depending upon the components final intended to use that can also affect the properties of the piece. The main manufacturing processes of fibre-reinforced composites are:

- **Wet lay-up**

  It is required a mould in the shape of the final component. The reinforcement it is a woven fabric that is carefully laid into this mould and the matrix, which is a resin, is poured on and spread, usually with the aid of a roller. Then, this is left to cure.

  A gelcoat can be added to the mould before the reinforcement is placed into it depending on what surface finish is required, knowing that the top surface is the side which is face down in the mould. A release agent can also be applied to the mould to assist with removing the part after curing.

- **Filament winding**

  This process is used for producing hollow tubes. The reinforcement are taken through a resin bath, coating them with the matrix. The access resin is squeezed out by rollers and the reinforcement fibre are then wound onto a mandrel to form the round and hollow shape.

  The direction the fibres are wound contributes to the performance properties required of the finished parts.

- **Compression moulding**

  Compression moulding is normally used with prepreg, which consist of reinforcement fibres already impregnated with resin. The prepreg is placed in an open, heated female mould. The male mould is then placed down on to this with the combination of heat and pressure shaping and curing the component. Parts are then allowed to cool before removing from the mould.

- **Resin transfer moulding**

  A male and female mould is required. The reinforcement is placed into the female mould. The male mould is then pressed down on this and clamped. Resin is injected under pressure from one side of the mould with optional vacuum assistance at the opposite side. This then “wets out” the fibres and is then left to cure. On some occasions the mould is heated to assist the process.

- **Vacuum bagging**

  This process can be used as an extension of the wet lay-up technique. The reinforcement (as woven fabric) is placed into a mould, which can be pre-coated with a release agent and/or gel coat. The resin is then rolled on top.

  A plastic film is placed over this and is fully sealed at the edges. A vacuum then extracts the air from process helping to consolidate the part. It ensures that the resin is evenly spread.

- **Pultrusion**

  Pultrusion is a process used for making long, continuous components such as cable trays (for example, those used in the Channel Tunnel). Multiple strands of reinforcement fibres are pulled from reels along a conveyer-belt type process through guides into a heater. During this heating process the strands are coated in resin. The warm, resin-coated strands are then pulled through a moulding die, forming the final components shape. It is then cut to the desired length with a saw.
3.1.4 Costs associated to the composites manufacturing

The costs associated with composite materials can generally be broken down into five areas – fibre (reinforcement), resin (matrix), consumable materials (needed to assist the combination of reinforcement and matrix), labour costs and machine costs.

The major cost is typically the reinforcement element, the fibre for which can be off a spool or pre-woven into a stitched fabric depending on the manufacturing process.

- **Fibre cost trends**

There are a number of variants within each material that affect the overall cost. Generally the mechanical properties and environmental resistance, particularly temperature resistance, increase the cost.

- **Resin costs**

The resin is the key controllable item that can reduce the other costs. Though not the single major cost, the chemistry and processability of the resin is critical. For example, prepregs and wet / dry lay-up materials can be cured at ambient temperature (or little higher), made possible by tailored resin formulations. The resin also affects the costs involved in wet-out of fibre mats, room temperature out-life, frozen storage life and good handling for laminating by hand.

Generally the mechanical properties and environmental resistance, particularly temperature resistance, increase with increasing cost.

- **Consumable costs**

Consumables vary depending on the chosen material processing and lay-up methods. They do not form a major part of the overall costs and cost trends would need to be identified for specific applications.

- **Labour and machine costs**

These are intertwined and are dependent on chosen processing technique(s). Specialist motor racing and aerospace laminators are charged at far higher rates than construction labour gangs, since the construction market cannot tolerate such high labour costs. However, this is overcome by specialist training by material suppliers and the creation of lists of approved installation contractors for tendering purposes.

- **Overall costs**

It is impossible to give a single comparison of composite costs and traditional material costs, as the steel, because suppliers use discretion on a job-by-job basis and the prices of raw materials are frequently updated to reflect advances in material processing technology. The range of composite / steel cost ratios usually spans between 5 and 10, but the final delivered product is often no more expensive than, say, steel alternatives. This is due to easier installation of lighter composite components and far lower whole-life maintenance costs. It is recommended that supply chain managers of projects be consulted directly for the initial capital outlay and whole-life cost implications of using composites.

- **Indirect costs**

Additionally, there may be a number of indirect costs, such as quality control, health and safety considerations, etc. which need to be taken into account. Also, there is an increasing emphasis on environmental factors including maintenance, recycling, and disposal, which, over the lifetime
of a component, can be important. For many components, the benefits from the use of reinforced polymer composites can become very significant when whole-life costs, rather than just fabrication costs, are included.

3.2 Characterization of composite’s market

Composite materials are becoming increasingly important offering significant weight reduction potential compared to conventional materials, for example the steel. Therefore, composite suppliers as well as OEMs are seeking to explore business opportunities in the composite market.

The major opportunities are given to fibre composites, due to their properties and their possible applications among the industries, mostly in high-end applications. In terms of size and future growth, the fibre composites are really attractive because their market size is growing above 7-8% per year and the market size in 2011 was of $20-25 billion.

Figure 41: Penetration of fibre composites among different industries. Source: AT Kearney, 2011, “AT Kearney’s view on composite market” [2].

Furthermore, the cost advantage of other lightweight materials over composites is expected to decrease. The cost of composite materials is expected to significantly decrease in the next 10-15 years. Additional cost savings arise from improving processes to the new material, for example, shorter cycle time which will produce processes cost savings of up to 50%. Alternative fibre technologies can decrease cost even further, being in an optimistic scenario lower than the current steel cost. Also, additional advantages are the better recyclability and the lower environmental impact. The following picture shows a cost comparison between steel and carbon fibre.
The majority of the value add in the composite value chain is generated in the production of composite parts (including the 5% of the value add in distribution of the parts).

Also, EBIT has a broad range between -10% and 15% in fibre composites due to the dependence on operational excellence and on the access to sizable commercial programs.

There have been significant merge and acquisition activity during the last years and a clear trend towards integration along the players of the fibre composite value chain in order to gain knowledge, control and access to materials and innovations.
Also, partnerships with material manufacturers are being explored by OEMs to address challenges and gain own expertise. The following ones could be great examples:

- BMW and SGL Carbon Group have invested around $135 million in facilities to produce BMW’s battery powered i3 and hybrid i8 cars with carbon fibre, that were introduced in 2013.

- Daimler and Toray have developed mass production techniques for carbon reinforced components

- Daimler and BASF have collaborate on the all-electric Smart Forvision concept, an electric vehicle with carbon epoxy passenger cell doors.

- Audi and Voith have developed an automated process chain to make high-volume carbon fibre parts

- GM and Teijin have also developed new technologies to incorporate it into GM vehicles.

Figure 44: Vertical integration among different players of the composite value chain. Source: AT Kearney, 2011, “AT Kearney’s view on composite market” [2].

Figure 45: Partnerships between OEMs and composite material manufacturers. Source: AT Kearney, 2011, “AT Kearney’s view on composite market” [2].
The lifecycle phase of composite market is showed in the picture and it is defined by the next issues:

- Growing sales with increasing penetration in industries
- Few dominant players, but it is attractive for new entrants
- There is low or no profit due to the high investments and the low sales
- Good technical performance and industry acceptance.

![Lifecycle phase of composite market](image)

Figure 46: Lifecycle phase of composite market.

In conclusion, composite market is attractive, but requires the players to add critical success factors. These factors are the necessity of improving technological capabilities as having a deeper and better technology about the know-how. The customer access is also relevant and it is possible to improve with commercial relationships or cooperation with key players. Finally, the necessity of higher production volumes which will lead the competitive cost is pretty clear but it needs an involvement in long term viable programs and projects.

3.3 Composites among the industries

The choice of materials and design for the different elements is one of the most important factors in every technical projects. In order to take decisions, they must be evaluated according to certain criteria, which may be the outcome of performance results, environmental regulation, safety concerns or customer requirements. The most important criteria that should be met are lightweight, cost effectiveness and safety considerations.

- **Lightweight**: It has become the most important criterion for the railway industry given the emphasis placed on the reduction of emissions and fuel efficiency improvement. Experiments have proven that for high-speed passenger trains, estimates for energy savings are about 3.2% per 10% weight reduction, due to their high and steady operating speeds. In order to achieve this weight reduction, all rolling stock manufacturers and suppliers are investing significantly in lightweight materials.

- **Cost effectiveness**: It is one of the most important consumer driven factors in railway industry and determines whether the materials and designs may be selected for a vehicle component. Cost includes three components: actual cost of raw materials, manufacturing value added, and the cost to design and test the product. Alternatives to conventional steel such as high strength steel, aluminium or composite materials are more expensive, hence, decisions to select light metals must be justified on the basis of improved functionality.
• **Safety**: One of the most important safety concepts to consider in the railway industry, and especially, in the body and chassis structure area, is crashworthiness. It is defined as the potential of absorption of energy through controlled failure modes and mechanisms that provides a gradual decay in the load profile. Therefore, chassis and body structures must be stiff, and present excellent energy absorption and a good resistance to fatigue failure.

According to this, it is possible to find composites in many items in our daily use and in many industries as the following picture highlights it:

![Figure 47: Use of composites around the industries. Source: UK Composites, “The 2016 UK composites strategy” [17].](image)

### 3.3.1 Automotive industry

The automotive industry is a large volume sector and a large percentage of the cost is in the capital plant needed for manufacture and so once required equipment has been procured and
commissioned it is very costly to change the design of a component. This naturally makes the industry very conservative, and encourage extensive prototype testing in both real and simulated of any new system before the investment is made.

However, automotive industry is following a trend towards lightweight materials driven by the need to improve the CO2 footprint and the use of new alternative powertrains as we could appreciate in the hybrid cars. This is small volume production and its resistance to change materials is somewhat less.

From 1970, plastic materials had been use and they become the substitution for metal parts in the automotive industry. The following chart shows the evolution of this trend in the automotive industry.

![Figure 48: Evolution of plastic materials substituting for metal parts in the automotive industry. Source: AT Kearney, 2011, “AT Kearney’s view on composite market” [2].](image)

However, as it happens to the railway industry too, the new EU directive says that it is mandatory 95% recyclability of materials used in cars. So, thermosets that are not recyclable can’t be used, and in the other hand, this rule it is in favour of thermoplastics that are easier recyclable. This fact will be translated into a raise of thermoplastics market share and a decrease of thermosets market share in the early coming years. In addition, thermoplastics have potential for reduced fabrication costs, improved reparation and higher damage tolerance.

![Figure 49: Thermoplastics and thermosets market share. Source: AT Kearney, 2011, “AT Kearney’s view on composite market” [2].](image)
3.3.2 Aviation and aerospace industry

In the aviation industry composites had been mainly used in wide-body aircrafts, and the use of lightweight materials provides an important raise of the fuel efficiency.

The first military applications were in radomes, that are a structural, waterproof enclosure that protects an antenna, and then in secondary structures and internal components. The modulus of glass, however, is low compared with that of metals and so it was not until the introduction of carbon reinforcements that primary composite structures were developed. Nowadays, composites are widely used and this has been the result of a gradual direct substitution of metal components followed by the development of integrated composite designs as confidence in FRPs has increased.

The Airbus 320 uses a range of components made from composites, including the fin and tail plane. This has allowed a weight-saving of 800 kg over its equivalent in aluminium alloy. Composite materials comprise more than 20% of the A380’s airframe. Carbon-fibre reinforced polymer and glass-fibre reinforced are used extensively in wings, fuselage sections (such as the undercarriage and rear end of fuselage), tail surfaces, and doors.

The following chart shows the materials the different Boeing aircrafts are made of from 1970 to 2010.

![Composite materials composition of airbus aircrafts](image)

Figure 50: Evolution of materials composition of airbus aircrafts in 1970, 1990 and 2010.
Source: Boeing “Boeing 787 from the Ground Up” [18].

In the aerospace industry the successful application of composites in missiles has led to the development of primary structures for space vehicles. In fact, space applications lend themselves in many ways to the utilisation of new materials. For satellites, for example, the timescales from concept to manufacture can be as little as two years and the short product runs normally involved, the materials element in the final cost is often relatively low. Also in many applications no other material is suitable for technical reasons.

Once in orbit, mechanical loads are comparatively low. Environmental conditions can be extreme and severe thermal cycling can occur, as well as the effects of high-vacuum and erosion through atomic oxygen or micrometeoroid impacts. Glass fibre composite is used in applications where...
thermal insulation is important, for example in local bracketry. The material is also used in some antenna reflectors.

Carbon fibre composite, however, is most often associated with space applications. The potential for very high-stiffness and excellent thermal stability over a wide temperature range make carbon fibre composite ideal. Examples of their application include: fairings, manipulator arms, antennae reflectors, solar array panels and optical platforms and benches. They have also recently been used for primary structure applications. In the past the need for a combination of stiffness and strength, and for thermal and electrical conductivity have favoured metals. However, the constant pressure for weight reduction means that now some satellites have been built with a predominantly composite structure.

### 3.3.3 Renewables industry

- **Wind energy industry**

The actual trend in wind energy industry is increasing blade lengths in order to produce more energy, and to do that it requires the use of lightweight materials. They shift from glass-fiber reinforced resins to lighter carbon-fiber due to the necessity of higher strength to weight ratio. The following picture highlights how the blade length has increase during the last 15 years.

![Blade system](image)

**Figure 51:** Evolution of blade length from 2000 to 2015.

The blades are the main components, predominantly manufactured from glass-fibre, and the performance of the turbine is ultimately dictated by their efficiency. The use of lighter weight FRP materials means that the turbines can produce more power per unit volume, minimising impact on the landscape.

Compared to conventional all-glass-fibre designs, composites that replace some of the glass with carbon-fibre reinforcements can produce the same blade using less fibre and resin, while increasing blade stiffness, improving aerodynamics and decreasing the loads imposed by the blades on the tower and hub. A design that incorporates carbon fibre also can make power input from the blades more predictable.

Fibre reinforced polymer materials have justified their proven performance in corrosive and hostile environments, which will maintain efficiency of the structures under increased locational loads.
• **Marine turbine**

Due to their inherent properties, fibre reinforced polymer composites work well as marine turbine blades as they do not rust. Epoxy resin is less susceptible to water penetration and is generally, but not always, used as the matrix in an underwater composite. Excellent fatigue performance means that the turbine do not need to be constantly maintained.

![Figure 52: Marine turbine. Source: Materials Today, 2014 “Tidal energy, an emerging market for composites”[19].](image)

• **Power transmission**

Composite-reinforced aluminium conductor cables (CRAC) replace traditional steel-strength members in cables with a pultruded continuous-fibre core, which is expected to reduce weight and to increase power-transmission efficiency by an estimated 200%. If successful in upcoming tests and demonstration projects, CRAC technologies may find application in infrastructure modernisation projects. CRAC cable developers claim that power needs will actually increase, by as much as 19 percent, in the next 10 years, making CRAC cabling an attractive alternative for upgrading power lines on the existing grid, without erecting new towers or obtaining additional rights-of-way.

![Figure 53: Composite-reinforced aluminium conductor cables. Source: Composite Technology, 2013 “Aluminium composite core conductors”[20].](image)
3.3.4 Medical

Fibre reinforced polymer composites are finding more applications in the medical sector because of their light-weight, high-stiffness characteristics and bio-compatibility. External components such as artificial limbs use the high specific properties, fatigue resistance and flexibility of manufacture of composites to advantage. The chemical inertness of carbon fibre has led to a number of surgical applications where the material is used in conjunction or instead of metallic or polymeric materials.

Early designs of artificial limbs employed press-moulded carbon-fibre composites as the main load-bearing structure. More recent developments incorporate a wider use of carbon-fibre to include load-carrying links in the joint mechanisms, foot keels with sprung energy return, and hybrid designs incorporating elastomers to dampen shock loads.

The behaviour of artificial joints, which conventionally consist of an ultra-high molecular weight polyethylene, UHMWPE, component articulating against a polished steel part can be improved by enhancing the wear characteristics of the polymer. The UHMWPE can be reinforced by a random distribution of short (~3 mm) carbon fibres to provide the desired tribological properties.

Carbon composites are being implanted into cartilage to promote biological resurfacing of damaged areas. The open weave structure of the material promotes cell growth along and between individual fibres ultimately resulting in a suitable repair.

Carbon fibre tows, either used individually or in plaits, are also being employed in the repair of damaged ligament. Loops of material are passed through holes drilled in the adjacent bone structures and then their length adjusted to achieve the correct tension for the particular patient.

The mechanical properties of bone repair materials, often a self-curing acrylic, can be enhanced by the addition of carbon fibres. Tensile, compressive and shear strengths as well as creep and fatigue performance are all improved and this could lead to wider clinical use of the material.

3.3.5 Rail industry

Fibre reinforced polymer composites are being used in rail application such as track beds, gantries, vehicles/modules, interiors, furniture, and platform systems.

Fibre reinforced polymer composites are widely used in train interiors, including vestibule pods that can be moulded and then 'dropped in' to the vehicle structure to be connected to internal services.

Also, the platform at East Midlands Parkway (United Kingdom) station is made up of pultruded structural composite profiles that were installed in a matter of days.

3.4 Conclusion

After a wide explanation about how composite materials market is evolving among the different industries and the good adaptation received from those industries to get the composite materials introduced, it is possible to consider a great adaptation for composite materials in the railway
industry. Also, the big expectation of composites becoming cheaper due to their better integrated chain value, will help to get better adaptation.

As it is said in the previous chapter of this project, the best improvements could be achieved using fibre reinforced polymer composites in the car body, the interior and the miscellaneous systems of the high speed train. It, will produce a big change in the high speed industry, letting the manufacturers to produce high speed trains almost up to its double passenger capacity.

High speed industry has rocketed during the last years, and the use of composite materials will help to increase the applications of the composite industry together with the improvements in the high speed industry.
4. RETURN ON INVESTMENT ANALYSIS

In order to justify this project, it is going to be analysed how profitable it is going to be the rolling stock weight reduction.

4.1 Definition of ROI

Return on investment analysis is essentially a performance measure used to evaluate the efficiency of an investment, or it is used to compare the efficiency of a number of different investments.

To calculate the benefit or return of an investment, it is divided by the cost of the investment. The result is expressed as a percentage or a ratio.

The return on investment formula is:

\[
ROI = \frac{\text{Gain from Investment} - \text{Cost of Investment}}{\text{Cost of Investment}}
\]

Due to the result is expressed as a percentage or a ratio, it can be easily compared with returns from other investments, allowing one to measure a variety of different investments against one another.

4.2 Return on investment analysis

As it is highlighted in the chapter 2 of this project, due to not taking in account the infrastructure cost, the operating costs are the most meaningful of the high speed railway industry.

Then, the analysis is going to compare the difference from manufacturing and operating a common high speed train made with steel and aluminium and manufacturing and operating a high speed train made with composite materials in the car body, the interior systems and miscellaneous systems, such as doors, windows, HVAC, pipelines, etc.

The train that is taken as an example is the AVE S103, and the route is from Madrid to Barcelona. The main costs are showed in the following chart:

<table>
<thead>
<tr>
<th>Train</th>
<th>Number of seats</th>
<th>Total weight (t)</th>
<th>Acquisition cost (M€)</th>
<th>Total operating cost (M€)</th>
<th>Total maintenance cost (M€)</th>
<th>Grand total (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVE S103</td>
<td>404</td>
<td>447</td>
<td>21</td>
<td>243</td>
<td>87</td>
<td>351</td>
</tr>
</tbody>
</table>

Table 6: AVE S103 capacity, total weight and total cost decomposition.
Due to the higher cost of composite materials than steel and aluminium the acquisition cost is expected to increase. The current price of composite materials is around 150% more expensive than steel. The systems what are going to be manufactured by composite materials are the car body, the interior and miscellaneous and they represent a 53% of the total high speed weight. It is known that a 30-40% of weight reduction is possible using composite materials instead of steel. Achieving a 15.9% of weight reduction is possible.

The main concern from the main manufacturers and operators around the world is to increase the number of seats. The good acceptance of high speed trains as a fast and low emission transport by the society, it cause the opportunity of increasing the capacity of the high speed trains.

But there are requirements which do not allow manufacturers to increase the number of seats. It is because the maximum charge per axle is 17 tons, and every high speed trains have 17 tons per axle. With the 15.9% weight reduction, it is possible to reduce 71,1 tons of the total train weight.

Firstly, its needed to calculate the increase of weight of the two floors car body. The car body weight is: 21% * 447 = 93,9 tons in a AVE S103 without composites.

Then, the one floor car body weight applying fibre reinforced polymer composite is: 21% * 447 * (1 – 0,3) = 65,7 tones. With two floors train the car body weight will be increased around 60%, due to the biggest weights are on the lower parts of the car body, as the information of Alberto Garcia shows of trains with two floors. That would be: 1,6 * 65,7 = 105,1 tones. The weight increase of the car body will be: 105,1 – 93,9 = 11,2 tones.

The weight of the powered transmission and the bogies don't change.

The weight of the interior and miscellaneous in the AVE S103 is 143 tones, and applying composite materials to a train with one floor the weight would be: 143 * 0,7 = 100,1 tons.

The two floor train has to weight the same as AVE S103, it is 447 tons, to comply with the regulation of having 17 tons per axle. The available weight to include more interior and miscellaneous systems will be 447 – (210 + 105,1) = 131,9 tons. Due to the one floor train miscellaneous and interior systems made by composite material weights 100 tones, it is possible to add more seats till adding 31,9 tons.

Alberto Garcia affirmed that with one tonne of weight reduction it is possible to add 12 seats, so with 31.9 tons of weight reduction is possible to add 383 more seats, almost doubling the actual capacity. The total capacity will be 787.

<table>
<thead>
<tr>
<th>System</th>
<th>Weight (%)</th>
<th>Total weight (t)</th>
<th>AVE S103</th>
<th>System</th>
<th>Total weight (t)</th>
<th>One floor train with composite</th>
<th>System</th>
<th>Total weight (t)</th>
<th>Two floor train with composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior and miscellaneous</td>
<td>32%</td>
<td>143</td>
<td></td>
<td>Interior &amp; miscellaneous</td>
<td>100</td>
<td></td>
<td>Interior &amp; miscellaneous</td>
<td>131,9</td>
<td></td>
</tr>
<tr>
<td>Car body</td>
<td>21%</td>
<td>94</td>
<td></td>
<td>Car body</td>
<td>66</td>
<td></td>
<td>Car body</td>
<td>105,1</td>
<td></td>
</tr>
<tr>
<td>Bogies and transmission</td>
<td>47%</td>
<td>210</td>
<td></td>
<td>Bogies and transmission</td>
<td>210</td>
<td></td>
<td>Bogies and transmission</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>447</td>
<td></td>
<td>Total</td>
<td>447</td>
<td></td>
<td>Total</td>
<td>447</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Weight breakdown for the different high speed proposes.
Finally, the maintenance cost will be almost doubled because the train will have the double number of seats and pieces, it could be with two floors.

Operating cost are divided into energy consumption and the human resources cost of the crew. The energy consumption costs are dependant to the air resistance, which with a drag coefficient equal to 0,3 the drag resistance will increase for the two floor train around 60% (0,3 * 2 floors * 100). The energy consumption cost: 7,04 * 1,6 = 11,26 M€ per year, and during 30 years: 11,26 * 30 = 337,9 M€, plus the human resources cost of operating the train that will be: 1,1 * 30 = 33 M€. The total operating cost will be: 337,9 + 33 = 370,9 M€.

The costs of the car body, interior and miscellaneous systems are around the 20% and 30% respectively of the acquisition cost, as the Spanish Railway Foundation says. So, the total acquisition cost of a composite material high speed train will be:

Total cost = 21M€ * (0,5 + (0,2 * 1,6 + 0,3 * 2) * 2,5) = 57,8 M€ of acquisition.

The AVE S103 with composite materials in the car body, interior and miscellaneous systems would be:

<table>
<thead>
<tr>
<th>Train</th>
<th>Number of seats</th>
<th>Total weight (t)</th>
<th>Acquisition cost (M€)</th>
<th>Total operating cost (M€)</th>
<th>Total maintenance cost (M€)</th>
<th>Grand total (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVE S103</td>
<td>808</td>
<td>420,8</td>
<td>57,8</td>
<td>370,9</td>
<td>174</td>
<td>602,7</td>
</tr>
</tbody>
</table>

Table 8: AVE S103 capacity, total weight and total cost decomposition, using composite materials.

Now, it is needed to study the gains of AVE S103. The current average of occupancy is 79% [21], so there are 319 seats occupied by travel. The train goes from Madrid to Barcelona and from Barcelona to Madrid 4 times in a day, during 30 years, 365 days a year. The average ticket cost is 85€ per single tickets and 170 per return tickets.

Gains = 85 * 4 * 365 * 30 * 319 = 1.187.637.000 euros.

It is estimated that reducing the single ticket price a 10% it is possible to keep the same occupation ratio in the near future.

The return on investment analysis is highlighted in the following chart:
The new purpose provide a significant improvement in the environmental impact of transport. Estimating that the rise of number of passengers comes from air transport industry. The two floor high speed train energy consume is 60% higher than the current, but the estimate of the average occupation is 622 passengers per trip, instead of the average occupation of 319 passengers per trip on the current AVE S103, which represents an increase of 95% of users.

The new emissions ratio could be estimated (kg CO$_2$/pax): $13.1 \times 1.6 / 1.95 = 10.75$ kg CO$_2$ per passenger. This value is 20% lower than the current for high speed trains. This emission ratio is lower than any other transport emission ratio, included the bus.

Taking in account that the new passengers come from the air transport industry, the emission reduction during the entire life cycle of the new high speed train would be: $(303 \times 1460 \times 30 \times (67.1 - 10.75) + 319 \times 1460 \times 30 \times (13.1 - 10.75)) / 1000 = 780.678$ tons of CO$_2$

Table 9: Return on investment analysis.
4.3 Conclusion

Investing on composites is an attractive possibility for the rolling stock components industry. As it is possible to notice, composites applied on high speed trains may give to the railway operators an opportunity to increase their high speed trains’ capacity almost the double. Manufacturers will be able to produce high speed trains with two floors, complying with regulations that impose having less than 17 tons per axle. This fact will rocket the amount of money gained by the operators all over the world.

Users prefer using high speed trains and it is reflected on the occupancy ratio, that it is 79% or more in most of the trains. The quantity of users is expected to grow and the opportunity of using composites has to be taken in the near future.

The environmental impact is reduced in 20%, achieving the lowest ratio of all kind of transports, and the total emissions reduction to the atmosphere is more than 780,000 tons of CO₂.

As the analysis shows, it is more interesting the investment on composite materials high speed train due to the higher value of ROI parameter, including the 10% reduction of ticket price.
5. CONCLUSIONS

5.1 Conclusion about the methodology

The methodology followed has been inductive, introducing the key questions to answer and the methodology to answer them. This process has helped to focus on the main factors that give value to this project.

The analysis of the main trends that affect the railway industry describe how this industry is currently being developed by the main value chain players and the main concerns of the rolling stock components manufacturers. This knowledge has allowed to realise that main European and American OEMs need to differentiate from Chinese manufacturers, giving an opportunity to develop the analysis of the applications that could have the composite materials in the railway industry. The earliest conclusions are basic to continue with the project and the rest of the project is conditioned by these hypothesis.

The characterization of the high speed trains and the necessity of weight reduction has been the chapter that has required more time to investigate. It is the reason why is required to contact railway industry professionals, as Alberto Garcia, president of Spanish Railway Foundation, to get easier better quality data. It is important to work inductive to look for only the important information.

The explanation about the composite industry has been more specific because it is possible to find many applications for them, but not all of them could give an important impact.

The analysis of the return of the investment it is important for manufacturers and operators and the study of the great reduction of emissions justify the value of this project.

5.2 Conclusion about the weight reduction impacts

The increasing number of passengers that use the high speed transport has given the opportunity for the manufacturers to produce trains with more seats, but the regulation do not allow to have more than 17 tonnes per axle. The reason of this weight reduction is to increase the seats per train, almost doubling them with a weight reduction of 15.9%. That will produce more benefits to the railway market letting the OEMs produce with more expensive materials as the composite materials are.

The project shows how important is the weight reduction in the high speed trains. It is possible to conclude that high speed trains could have the lowest environmentally impact of all the kinds of transport. With a weight reduction of 15.9% the total weight of the high speed train and almost doubling its capacity, the ratio of emissions of CO₂ per passenger is reduced in a 20%, achieving the lowest ratio of all kind of transports. The total emissions reduction to the atmosphere during the entire life cycle of each high speed train is more than 780,000 tons of CO₂.
The good use of different data and other studies has given the opportunity to deduce the great economic impacts attached to this weight reduction. The first of them, comes because the high competence with the air industry, which is constantly growing, causing more passengers prefer using high speed transport instead of air transport on journeys of less than 3 hours by train. The application of lightweight materials could achieve better competition for high speed industry, because of the bigger capacity the ticket prices could be 10% lower. This fact will allow the passengers to use high speed trains instead of using aircrafts, spending less amount of money.

The data base of the worldwide global fleet of high speed trains has been used to know what parameters have impact on the total weight function using regression charts. Then, the high speed train systems breakdown shows which components are the most sensitive to be reduced weight, with the same safety, reliability and comfort for the users. The weight reduction of 15.9% is achieved using lightweight materials in the manufacture of the car body, interior and miscellaneous systems.

Train costs let to know how economically important is operating the high speed trains, being them the most expensive costs, and it is also possible to conclude the great importance that will have if the train has the possibility of almost doubling the number of seats.

The return of investment of the new high speed train manufactured with composites is higher than the one obtained with the current materials. It makes very attractive for the manufacturers and operators the use of the lightweight materials.

The composite industry is experiencing an important grow and it is necessary to be introduced in the railway sector. Other industries has taken advantage, like the automotive industry, leaving the possibility to take advantage of the previous development in the composite supply chain. Big investments are necessary but other players has showed the profits of investing in composite materials.

The main conclusion of the composite sector is the extrapolation of the possibility to use fibre reinforced polymer composites along the railway industry. It is proved due to it is already placed in many systems of aircrafts, marine turbines and power transmission systems.

This composite material, complies with the regulation of recyclability that the railway industry has, due to it is thermoplastic material that could easily be recycled.

Concluding, this projects shows how using new composite materials for light weighting the high speed trains obtain profit for all the stakeholders: return of the investment for the enterprises, reduction of ticket prices for the users, reduction of the environmental impact of transports for the whole society and developing both industries, high speed and composite materials.
6. BIBLIOGRAPHY


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