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# Lightweight primary structures for High-speed railway carbodies

## De la Guerra, Eduardo

Talgo[1]

**Abstract**

The railway industry are looking to increase the capacity of the railway system, bringing flexibility in order to align capacity and demand, to increase availability, reliability and energy efficiency reducing life cycle costs (LCC) and an improvement of the passenger comfort and the attractiveness of the rail transport.

One of the lines of action to solve the above challenges is the introduction of new carbody structures. The weight saving potential of the use of new materials and technologies in the carbody structures would result in reduced power consumption, lower inertia, less track wear and the ability to carry greater payloads.

One example of the employ of light structures is Talgo AVRIL train, with an innovative layout of seats that allows to introduce one extra seat per row (3+2 configuration), increasing dramatically the capacity of the train. It has been possible, respecting the current regulatory framework, with an optimized design of the extruded aluminium structure.

It will be presented different challenges of introducing lighter structures in the carbodies of coaches of high speed train and different studies and projects to describe the future possibilities of new material and methodologies to improve the lightness of the vehicles.

*Keywords: lightweight, Rolling stock, carbody.*

[1] *De la Guerra, Eduardo. Technical Leader of the R&D Projects. Structures Department. Talgo. Email: edelaguerra@talgo.com*

## 1. Introduction

The railway industry are looking to increase the capacity of the complete railway system, bringing flexibility in order to align capacity and demand, to increase availability, reliability and energy efficiency reducing life cycle costs (LCC) and an improvement of the passenger comfort and the attractiveness of the rail transport.

Different programs inside H2020 framework are working on the development of key technologies to remove already identified blocking points for radical innovation in the field of railway vehicles, as part of a longer term strategy to revolutionise the rolling stock for the future.

These main aims are in line with other transportation sector, like the road transportation (e.g. Superlight Car or ENLIGHT Project) or aerospace (e.g. SESAR, CleanSky…), inside the Roadmap to a single European Transport Area developed by the European Commission to achieve a sustainable transport, also called, White Paper (https://ec.europa.eu/transport/themes/strategies/2011_white_paper_en).

In 2050, it is expected:

- No more conventionally-fuelled cars in cities.
- 40% use of sustainable low carbon fuels in aviation; at least 40% cut in shipping emissions.
- A 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport.
- All of which will contribute to a 60% cut in transport emissions by the middle of the century.

The third bullet point is a key point for the future of the railway sector, different innovation and new concepts should be developed and implemented to comply with the objective of improved capacity in railway sector of the roadmap.

The amount of passengers that can be transported by the railway system is expected to increase dramatically so all new generation subsystems should be made smaller which will allow a rearrangement of the architecture delivering a better use of space, lighter subsystems (traction, vehicle structure, train control and monitoring system) which will reduce axle load restrictions and will bring more flexibility for the future design of high-capacity and adaptability of vehicle capacity to service conditions.

In addition, new technology development actions targeting energy efficiency and vehicle weight, (Joost, 2012) in a combined manner should result in reductions of energy consumption in operation. The main results expected should be:

- Traction efficiency will increase significantly with new developments in power electronics;
- At the same time, the reduction in vehicle weight derived from lighter structures, lighter traction equipment and elimination of physical equipment will equally support energy consumption reduction;

So it is clear that the new generation of carbodies will be a lightweight carbodies, manufactured in new lighter materials, specially made by hybrid structures (composite and metallic materials) compared with the actual ones made fully metallic (steel or aluminium). This approach allows more passengers per vehicle or more equipment without reaching the maximum allowed axle load reducing power consumption, lower inertia, less track wear and the ability to carry greater payloads.

But as the motto of the White Paper said “The future of our mobility…Today”, all the different bidding process and projects in progress are now claiming for trains with the lowest LCC as possible, maintaining the performance, comfort and bringing high capacity. So now it is designing and manufacturing very optimized carbodies in terms of weight with the current technologies, like the carbody of the AVRIL.

## 2. State of the art

The function of a carbody is to be the transport passenger container and also the physical link of all the elements of the vehicle.

Historically, passenger coaches were formed by a frame normally made of wood or steel, which received the loads coming from the track and the other coaches, and a cover which had incorporated the doors, windows and gangways (if any).

Progressive improvements were made and self-supporting steel and aluminium carbodies were created in order to reduce mass and improve crashworthiness. In addition, standardised solutions and subassemblies, see Figure 1, have been introduced to become more cost effective.

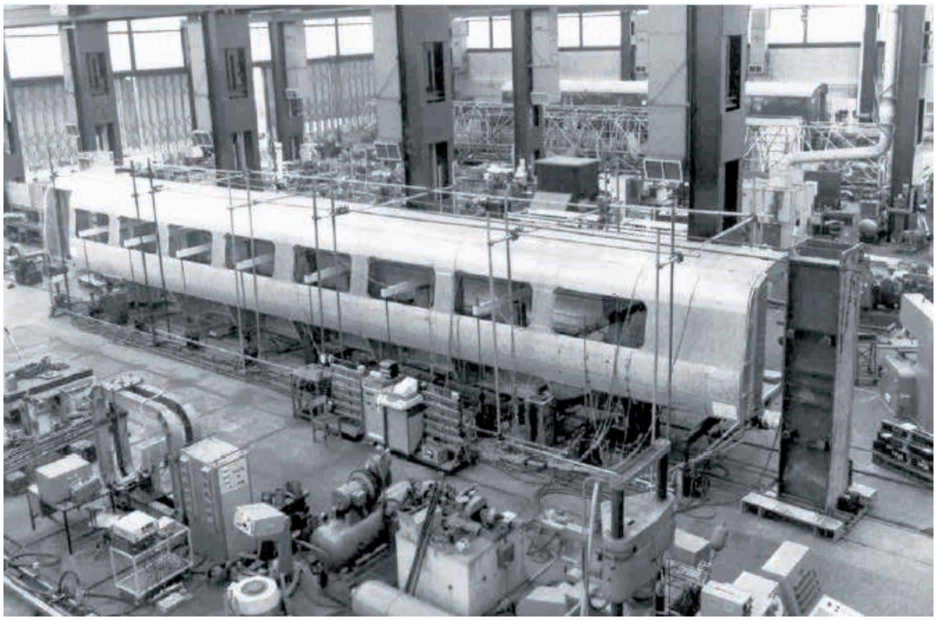

*Figure 1. Assembling of the main frame, the side walls and the roof takes place in a positioning and welding station.*

Nowadays, the railway carbodies are self-supporting structures made of steel and/or aluminium alloys and usually consist of a set of sheets and profiles joined together by different classical bonding technologies such as welding, riveting or bolting forming a set of great stiffness and currently highly optimized regarding weight per axle, Molinari (2016).

Focusing on aluminium carbodies, which were later developed, but due to the manufacturing process firstly open and then closed extrusions profiles, can improve stiffness and also avoid extra reinforcements (see Figure 2) reducing weight compared to steel carbodies. Over time, aluminium has reached a balanced use compared with steel and is in use in metros, regional and high speed trains in more or less the same ratio than steel.

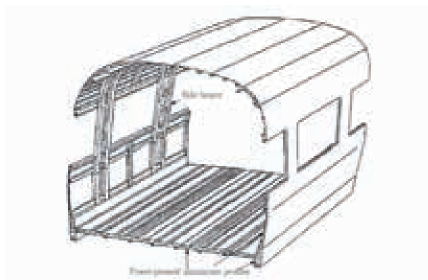

*Figure 2. Typical aluminium carbody.*

Progress has also been made in steel carbodies, with continuous reductions in steel sheet thicknesses and smarter designs.

## 2.1 Characteristic of the AVRIL train

Talgo AVRIL (Figure 3) is the most advanced train and the best solution for railway operators with high capacity demands in the Talgo's portfolio. AVRIL (Light Independent Wheel High Speed or "Alta Velocidad Rueda Independiente Ligero" in Spanish) combines maximum speed, low energy consumption and a high capacity with more than 600 passengers in an extremely lightweight single-deck train, trying to answer the needs for the railway industry explained above, Rodríguez (2016).

*Figure 3. Talgo AVRIL.*

Talgo's design for its trains, which are based on short articulated vehicles together with the Talgo's running gear (rodals or Talgo trucks), allows for the use of lighter carbodies. Talgo trucks use a system with an independent axle per wheel separating the rotation on each wheel.

In addition, in the case of AVRIL offers a greater width for the operator but without exceeding the loading gauge as sketched in the Figure 4. This optimises the train's features since it can seat more people without having to resort to a double-deck layout, which makes boarding and disembarking the train more complicated and brings about an unwelcome feeling for passengers of being boxed-in, mainly in the upper level. Talgo AVRIL guarantees passenger comfort by allowing enough space for each individual passenger without changing the width of the seat.

The ability to carry more passengers improves rolling stock utilisation, allowing operators to offer more competitive prices while decreasing overcrowding on the most popular routes. As a result, operators stand to increase profits and provide a greater return to investors.

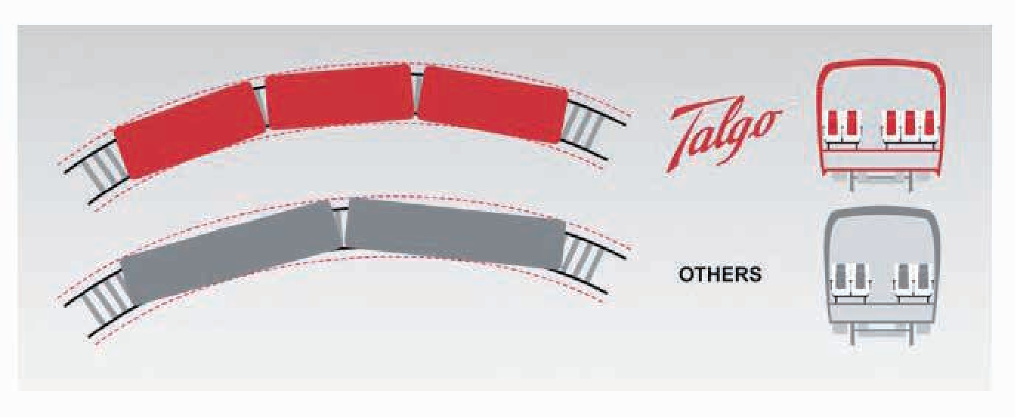


*Figure 4. Widebody Talgo AVRIL.*

Due to the more space available, it can offer various seating arrangements:

- Customised layout offering several possibilities: 3+2 (see Figure 5), 2+2 or 2+1.
- Seats adapted to all uses: a different configuration is available for all types of passengers: individuals, couples, or groups of three to six people.

*Figure 5 Seat layout with 3+2 configuration.*

Thanks to the single floor and the low height floor, at platform level as can be seen in Figure 6, AVRIL is the most accessible transport solution. Passengers carrying luggage can get on and off the train without having to use the stairs. Inside they can move along the train without restriction and without steps due to continuous low floor. But the benefits aren't just limited to increased passenger satisfaction, the design of the train means that the time spent at stops is reduced, which helps to optimise the use of rolling stock and infrastructure, as said previously.

*Figure 6. Improved accessibility without stairs.*

Talgo AVRIL train is designed to be adaptable to the individual needs of every operator. Withmaximum reliability, high interior comfort and low operating costs as baselines, the client is able to decide which solution suits them.

- AVRIL can operate on non-electrified lines by using diesel engines, allowing operators to reach more destinations by simplifying last mile operations.
- The train can be equipped with Talgo's automatic variable gauge system to allow operation on tracks with different gauges.
- AVRIL is compatible with the most common electric voltages used on railway tracks anywhere in the world, including direct and alternating current.
- It can be equipped with any train control or monitoring system, including, ERTMS, TVM, LZB, Indusi, ALSN, ATC, BACC, CONVEL.
- By utilising Talgo's natural tilting system, the train can offer increased speeds on conventional lines which can help to avoid costly infrastructure upgrades.

It is the lightest high-speed train, which means it can offer drastic reductions in operating costs:

- Thanks to its high capacity design and its running gear, it is possible to optimize the AVRIL's energy consumption compared to other high-speed train and previous series.
- On top of that, the design of its components and the ability to use generic systems reduces maintenance costs and the amount of time the train has to spend in the workshop.

In Table 1 is collected the main features of AVRIL (https://www.talgo.com/en/rolling-stock/very-high-speed/avril/).

| Table 1. Main technical features | |
|---|---|
| Maximum speed | 365 km/h |
| Operating speed | 330 km/h |
| Passenger capacity | ca. 500 - 600 |
| Trainset configuration | Typically two powerhead and 12 coaches but adaptable to client specifications |
| Track gauge (mm) | 1435-1668 |
| Floor height (mm) | 760 above TOR |
| Length (m) | 201.9 |
| Width (mm) | 3200 |
| Tare weight (tonnes) | 317 |
| Number of axles | 21 |
| Passengers/WC | 40-55 |
| Power supply | 25kV AC (tri-voltage optional) |
| Power | 2 x 4400 kW (tri-voltage optional) |
| Brakes | Powerhead: regenerative, rheostatic and air brakes Coaches: air brakes |
| Standard | UIC/ETI |

## 3. Challenges of new lighter structures

All the above requirements imposed to the new trains usually imply the reduction of the weight of the primary structure in order to accommodate new payloads, be more efficient, etc.

The design of the lighter structures that can withstand more than the previous one, usually supposes challenges when the structure is analysed in term of stiffness (natural frequencies, damping ratios and mode shapes) and noise isolation. Lighter primary structures under more restrictive loads (without changing concept design) are prone to have low natural frequencies that imply poorer ride comfort values for passengers, (Dumitriu, 2017; Chatti, 2006).

In general, the running gear interacts with the track producing vibrations with different amplitudes and frequencies depending on the line, tracks, defects or maintenance program. The more speed, the more amplitudes and higher frequencies levels (see Figure 7). To avoid passenger discomfort, the carbody should be designed with sufficient stiffness in the vertical, lateral and torsional directions to avoid coupling of frequencies between the running gear and carbody, both should not display similar Eigen frequencies. In addition the interfaces between bogie and carbody should be carefully analysed in order to avoid undesired bypasses of forces through them.

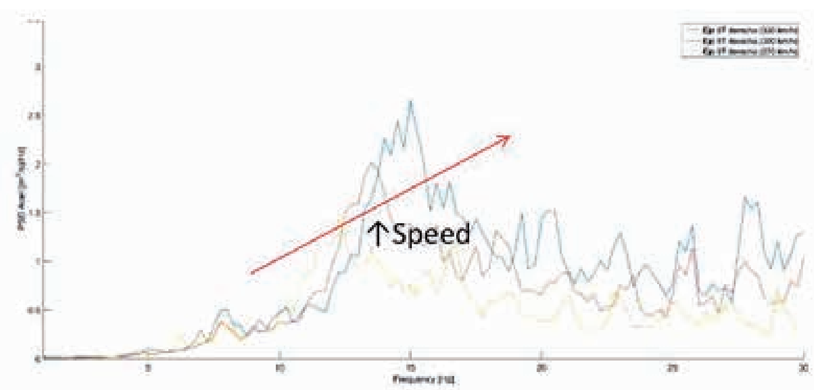


*Figure 7. PSD of acceleration at unsprung mass level depending on speed for HS track Madrid-Barcelona.*

Anderson et. al (2005, 2007) suggested values with some typical carbody Eigen frequencies fora high speed train, Table 2, and as can be seen are very closed to the maximum excitation produced by the track.

**Table 2. Typical Eigen frequencies**

| Mode direction | Frequency (first mode) |
|---|---|
| Vertical | 9-10 Hz |
| Lateral | 10-11 Hz |
| Torsional | 11-12 Hz |

In term of strength, rail vehicle design criteria in Europe are based mainly in EN 12663-1 if no other specific reference is given, usually applied category P-II for High-Speed passenger vehicles, Wennberg (2010).

The stresses to which carbodies are subjected are of various types and defined in EN 12663-1:

- The stresses due to longitudinal, vertical and extraordinary forces caused by the normal movement of trains.
- Also, there are the stresses of vibration of the carbody itself, which occur by the effect of its mass and dynamic loads from the track and its effect on fatigue.
- Finally, stresses due to accidental collisions related with passive safety.

Furthermore, for high speed trains, it is also necessary to consider overpressure/underpressure load cases due to the crossings with other trains particularly in tunnels, and stresses caused by lateral winds.

Regarding carbody vibration behaviour, in the standard EN 12663-1 is only stated that the natural modes of vibration of the carbody should be separated sufficiently, or otherwise decoupled, from the bogie suspension frequencies, so as to avoid the occurrence of undesirable responses and to achieve an acceptable ride quality according EN 12299. The fundamental Eigen frequencies of the carbody in lateral and vertical directions should be above NHz. Commonly the value of N is given by the fundamental resonance frequencies of the bogie frame and other influencing factors like the track or the passenger load.

As a general rule, the natural frequencies of the vertical mode for a typical bogie with the carbody installed are in the range $f0,bf=6\text{-}8$Hz. Therefore, the frequency separation requires that the fundamental carbody Eigen frequency complies $f0,cb>\sqrt{2}\cdot f0,bf$Hz. With this values, it is important to note that in some cases the ride quality according to EN 12299 could not be achieved, due to possible peaks of frequencies that could appear on the track in the range of 10-15Hz (depending on the track default, as can be seen in Figure 7). Then, the stiffness of the carbody must be optimised to increase as possible the corresponding carbody Eigen frequencies o achieve the comfort requirements, i.e. as higher as possible, de la Guerra (2016).

Regarding the interface between bogie and carbody, as rule of thumb the input mobility of mounting points for bogie elements (dampers, rods) shall be below -80dB re 1m/Ns. Alternatively, the input impedance of mounting points for bogie elements (dampers, rods) shall be above: 80dB re 1Ns/m, Shabalin (2013).

## 4. Numerical and Experimental Analysis for design

The use of new methodologies for design (FEM+Multibody Simulation) together with of operational/experimental modal analysis allows the understanding of the behaviour of the new structures regarding vibration and comfort. In addition, it is also checked the effectiveness of the general rules explained above applied in a very specific product like Talgo's trains (non-standard running gear, short, wide and light vehicle).

The structures of the AVRIL's coaches are made by an optimum combination of open and closed profiles with variable inertia to achieve the strength of the carbody. In order to improve the stiffness of the carbody stiffeners and reinforcements inside and outside are welded to the main structure to achieve an assembly very stiff and light. With the new profile architecture is possible to have a bigger structure (mainly wider) saving around 10% in weight compared to the structure of the previous high speed Talgo's coaches (S102/112).

First step is performed a complete modal analysis with a finite element program to estimate the natural frequencies and mode shapes. Mainly we are focused on the first mode shape, frequency and if it is a local mode or a mode for the complete structure (modal mass). The analysis is done in different mass condition (full and empty).

For example in the Figure 8 is shown the 2nd flexural mode of the main frame of the prototypcarbody, in this case at 20Hz.

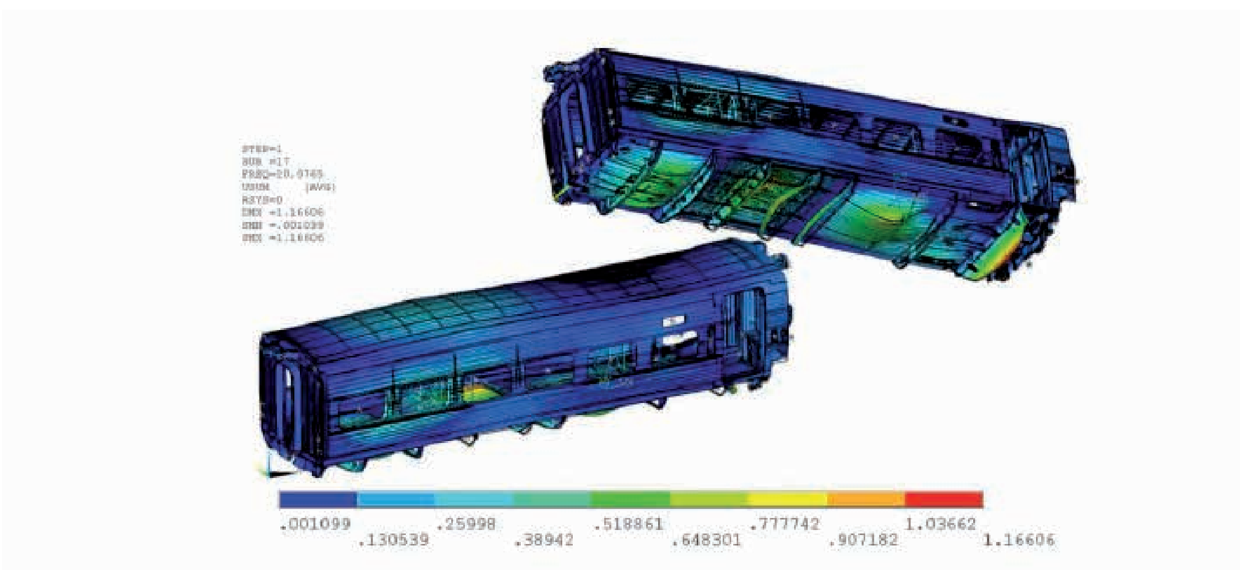


*Figure 8. Modal FEA. 2nd flexural mode at 20Hz of the main frame of the prototype carbody*

This approach is very accurate when the Eigen frequencies are far from the running gear excitation. For this reason, together with modal FEA, a combined analysis with multibody and finite element is done to assess the separation between the Eigen frequencies of the running gear at train level and the flexible carbody. It is very important when you have a lot of interfaces with the carbody like in the Talgo case: guidance system, secondary suspension, dampers.

In addition to computer design different analysis was made in the prototype carbody. Operation modal analysis (OMA) and Experimental modal analysis (EMA) would be a useful tool to obtain the real mode shape and frequencies. OMA is a modal analysis using operating conditions as excitation in contrast to EMA that uses defined and controlled excitation.

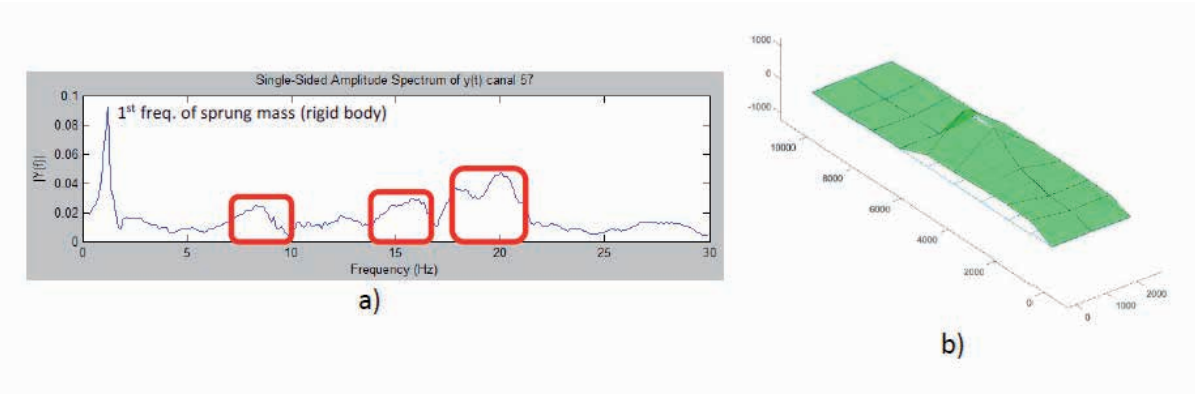


*Figure 9. Eigen frequencies measured over the main frame of the carbody*

In the Figure 9 a different accelerometer signal of the carbody can be seen, three Eigen frequencies groups can be distinguished, 8-10Hz around 15Hz and a third group in the 20Hz environment. With a more detail analysis is possible to extract shape modes (Figure 9b) and detect each frequency in the groups.

The occurrence of frequencies in the vicinity of 8-10Hz is not obtained during the FE calculations but appear due to the guidance system excitation as checked with the testing and Multibody simulation.

## 5. R&D Projects

In addition to the customer project, different R&D projects are in progress regarding lightening of the structures, Figure 10.

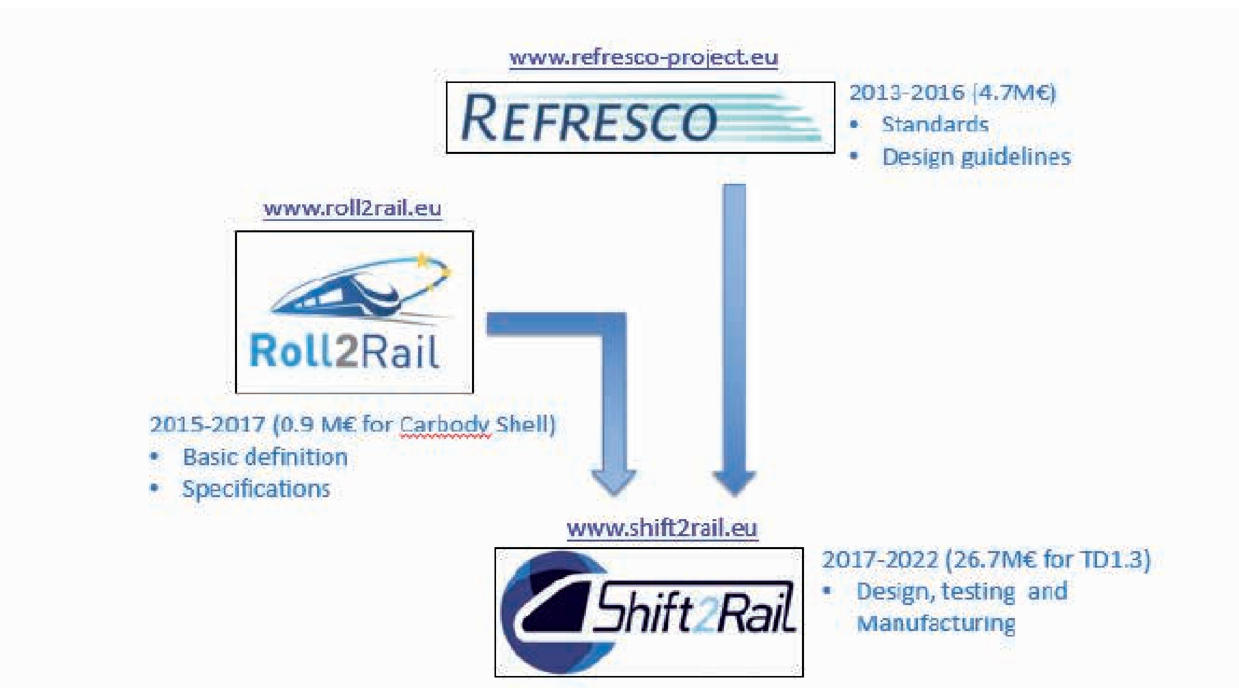


*Figure 10. R&D Project map*

In these case an approach completely different introducing a complete new concept and new materials for the primary structures in railway sector, Peris (2017).

The goal of the work carried out as part of Shift2Rail is to develop lighter carbody shells which make full use of the possibilities of composite materials including integration of functions. This is linked to identifying the specific design principles, materials and manufacturing processes that fulfil the requirements set in previous projects such as REFRESCO and Roll2Rail, in terms of material properties, manufacturing cost and certification. To this end this plan envisages to develop a carbody made of hybrid materials (mainly composites) in the primary structure that will achieve:

- Between 15 and 30% weight reduction.
- Energy savings in operation, resulting from the weight reduction.
- Improvements in maintainability, coming from new concepts.
- The introduction of a specific health monitoring process.

With today's materials and manufacturing technologies, manufacturers of rolling stock are very close to the border in terms of weight optimization (Molinari, 2016), so a change of concept in the structure of the car is imposed in order to reduce the weight of the structure primary. This objective is aligned with the objectives set in the H2020 to reduce the life cycle cost (LCC or Life Cycle Cost) globally of rail transport and to increase the capacity of the rail sector.

The use of material different from metal has been proved in the aeronautic industry, where composites are increasingly being used in structural parts after having passed all tests regarding safety.

In conclusion lighter carbodies could be made with industrial processes, provided that adequate joint methods are used and there is compliance with rail safety standards.

Different conceptual studies have been developed based on topology optimisation and structural/ acoustical calculation of materials and joints in order to lay the foundation for the designing phase of Shift2Rail.

An example of the topology optimisation is shown in figure 2. The influence of the geometry and location of the cut-outs in the weight of the structure was studied. For an urban model, different configurations were analysed achieving a weight improvement of up to 20% in the case of decreasing the width of the door 300mm (-15% in width). For a High Speed model, up to a 14% weight reduction was achieved when the service door is placed at the centre of the coach.

At the end of Shif2Rail project a full carbody demonstrator with a hybrid carbody will be presented fulfilling the requirement of weight reduction mentioned before maintaining or improving the current performance of the metallic primary structures in terms of safety, durability and maintainability.

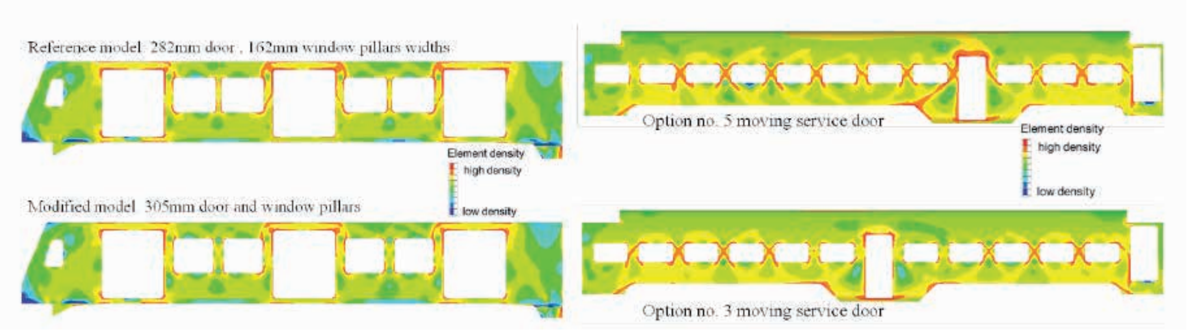


*Figure 11. Topology optimisation for urban trains (left) and high speed trains (right)*

## 6. Conclusions

The weight reduction and optimization of railway vehicles have several positive effects including energy savings, increase payload capacity and reduction of rail damage.

However in order to maintain the performance of the current carbodies regarding comfort some extra cautions should be taken.

A study in detail like done in AVRIL train is necessary to avoid discomfort for the passenger at high speed. FEM calculation together with Multibody simulation are powerful tool for design phases. Prototypes to assess the hypothesis employed are very useful to measure and obtain real mode shapes and Eigen frequencies to compare with the track excitation.

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