

# **Design For Six Sigma (DFSS) applied to an innovative High-Speed Train Bogie**

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## **Abstract**

High-Speed Trains are defined as the “transport of the future” thanks to three main characteristics: safety, capability and sustainability. It is an environment friendly solution because it relies on electric energy, which can be fully produced from renewable sources, and it pollutes less compared to other transport systems. In fact, in comparison with automobiles and airplanes, High-Speed Trains generate 9 and 6 times less carbon dioxide respectively; and in terms of consumption per kilometer, it consumes respectively 6 and 4 times less. The first ever High-Speed Train was born in Japan and it began service in 1964 under the name of “Shinkansen”. The Japanese railway system has proved throughout history the efficiency and safety of this solution, becoming a model for the development of high-speed networks in other countries. Train designs vary depending on existing railways, geography and market requests. Bogies were born as simple supports for the coaches, provided with wheels and brakes, but with technological innovations, modern models contain electric engines, sensors and security devices. In this work, a new bogie was proposed following the rules of Design for Six Sigma (DFSS), which holds the main advantages of the models provided on the current market by the competitors.

## **Keywords**

Design for Six Sigma (DFSS), Train Design, High-Speed Train, Design Engineering

## **1. Introduction**

The High Speed (AV) train is defined as the transportation of the future because of its three main characteristics: safety, capacity and sustainability; and together with dedicated tracks and a digital signage system, it constitutes the AV network.

It is a fully electric means of transport and can exploit the energy from renewable sources, reducing the production of carbon dioxide, with emissions equal to 1/9 compared to cars and 1/6 compared to airplanes; in addition, the average consumption per person per kilometer is 1/6 compared to cars and 1/4 compared to airplanes.

High-speed rail transport therefore represents an innovative, fast, safe and low environmental impact service.

In this thesis an introduction to the main components of an electric train will be made, to then move on to the study and design of an innovative High Speed train trolley through Design for Six Sigma (DFSS), divided into six phases: Define, Measure, Benchmarking, Analyze, Design and Verify.

Thanks to this method, it was possible to collect and process not only technical characteristics but also information regarding customer needs and market requests..

## **2. Materials**

The main materials used to develop the present work are mostly Aided Engineering Softwares, in particular the ones employed for the research work are:..

- Autocad for 2D technical drawing (CAD 2D)
- Creo Parametric for 3D solid modeling (CAD 3D)

- Ansys for FEM analysis (CAE)

All the softwares assist the engineer during the design phases and have different scopes. Through their employments, the following components of the train cart were developed:

- Pantograph
- Engine
- Safety system
- Brakes
- Cart
- 

### 3. Methods

#### 3.1 Design For Six Sigma - DFSS

Design For Six Sigma (DFSS) is a design method used for the creation of innovative products and at the same time capable of satisfying customer and therefore market demands.

It is divided into six phases: Define, Measure, Benchmarking, Analyze, Design and Verify. (Fig. 1)

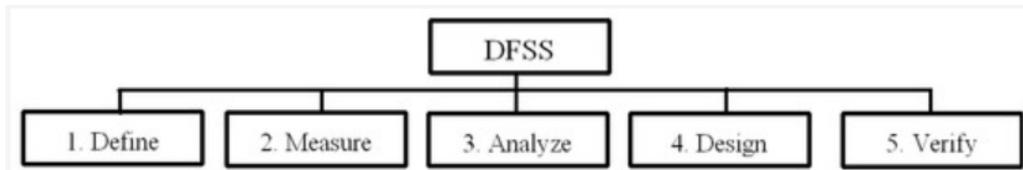


Fig. 1 – DFSS Structure

##### 3.1.1 Define: Market Analysis

The first phase consists of a collection of data and information, which are then reworked through the QFD (Quality Function Deployment) method. The aim is to make clear the goal of innovative design and the demands to be met. Customer needs can be derived by answering the six questions: Who, What, Where, When, Why and How.

- Who uses the AV train?

Commuters, tourists and all those who need to move from one place to another quickly and on time.

- (What) What are the uses of the high speed train?

It is used as a means of transport to travel long distances relatively quickly.

- Where is the AV train used?

On the tracks of the national railway network. Where possible, it transits on dedicated AV lines.

- When is the AV train used?

Usually at any time of day, more rarely during the night. In Italy there is no circulation of high-speed trains between 9pm and 5am, while in China and Japan there are also night trains.

- Why is the AV train chosen?

Because it is a valid alternative to the means of transport for long distances of excellence: the plane. Although the cruising speed is lower, there is no check-in or long waiting times for access to the vehicle. Without forgetting that ticket prices are lower.

- How is the AV train used?

The passenger is a customer and therefore needs services such as, for example, air conditioning and a toilet.

From the six questions, the customer's needs are obtained:

##### **Speed**

Speed is the main feature of high-speed trains, and it is one of the most important since travel times and quality of service depend on it.

##### **Punctuality**

Those who use an HS train often have timetables to respect: conferences, meetings, coincidences, appointments etc.

Delays always create inconvenience and discourage the customer from using the service again in the future.

Punctuality is also undoubtedly one of the fundamental parameters.

##### **Economy**

The cost-effectiveness of the service can lead to an increase in customers. Lowering costs can be achieved by designing a light, low-polluting train that requires non-expensive maintenance.

### Comfort

The noises and vibrations perceived at high speeds (above 200 km / h) are greatly amplified. Therefore, adequate design is necessary in order to reduce them to a minimum, ensuring a high level of comfort.

The spaces inside the carriages should be optimized to increase the train capacity, but at the same time the spaces must be sufficient distances between the seats and the width of the corridor, without forgetting the area dedicated to luggage.

### Security

At any time, at any speed, the passenger must be safe. At high speeds, the signs placed on the sides of the tracks are no longer reliable. A digital system called SCMT (Train Running Control System) is therefore used, which monitors both the maximum speed allowed on the route and the driver's behavior. In case of danger, the system is able to intervene autonomously reducing the speed of the train, if not actually stopping it.

Accurate train design can drastically reduce damage in the event of an unfortunate accident.

### Services

Those who choose to travel on a cutting-edge train also expect the presence of services to feel comfortable: air conditioning, bathrooms, tables, adjustable seats, electrical outlets and Wi-Fi connection.

### Cleaning and hygiene

The environment inside the train must be kept clean, from the seats to the bathrooms. Dirt is a sign of carelessness and disrespect for the customer.

### 3.1.2 Measure: Data Processing

Following the extrapolation of the parameters from the customer's requests, their processing follows by creating two matrices: a matrix of relative importance and an independence matrix.

#### 3.1.2.1 Relative Importance Matrix

It is used to determine which are the most important parameters. The question that arises is whether the element on the row is more important or not than the one on the column. The values attributed are: 0 if it is less important; 1 if the same are important; 2 if it is more important (Tab. 1).

	Speed	Punctuality	Economicità	Comfort	Safety	Services	Cleaning and Hygiene	Total
Speed	1	1	1	1	0	2	1	7
Punctuality	1	1	2	2	0	2	1	9
Economy	1	0	1	0	0	0	0	2
Comfort	1	0	2	1	0	1	1	6
Safety	2	2	2	2	1	2	2	13
Services	0	0	2	1	0	1	1	5
Cleaning and Hygiene	1	1	2	1	0	1	1	7
Total								49

Tab. 1 - Relative Importance Matrix

The sum of the values in the rows indicates the absolute importance of the parameter. The most important ones have been highlighted in green: Safety, Punctuality, Speed, Cleanliness and hygiene and Comfort.

### 3.1.2.2 Independence Matrix

It is used to establish dependency and independence relationships between parameters. One wonders how the dependence is between the element on the row and that on the column.

The values attributed are: 0 if there is no dependence; 1 if it is weak; 3 if it is medium; 9 if it is strong (Tab. 2).

	Speed	Punctuality	Economicità	Comfort	Safety	Services	Cleaning and Hygiene	Total Dependence
Speed	0	0	0	0	9	0	0	9
Punctuality	9	0	0	0	9	0	0	18
Economy	3	3	0	9	0	9	1	25
Comfort	9	1	3	0	1	9	1	24
Safety	9	1	0	0	0	0	0	10
Services	0	0	3	3	3	0	3	12
Cleaning and Hygiene	0	0	3	0	0	3	0	6
Total Independence/ Influence	30	5	9	12	22	21	5	104

Tab. 2 - Independence Matrix

The sum on the lines measures the dependence of the elements on the others. The sum on the columns instead gives us the value of the influence of a certain parameter on the others, and the most influential ones have been highlighted in green: Speed, Safety, Services and Comfort.

### 3.1.3 Analyze (1): Benchmarking – Top-Flop Analysis

At this stage, we inquire about the products currently on the market, in order to compare their different characteristics and to design an asset with better properties. Using the Top-Flop Analysis method, the best and worst values are highlighted for each technical specification of the models compared. The analysis will be carried out between 5 models of trains currently in circulation, produced by 4 different companies.

#### 3.1.3.1 FrecciaRossa 500

Built by the TREVI Consortium (TREno Veloce Italiano), formed by Breda Costruzioni Ferroviarie, Fiat Ferroviaria, Firema Consortium, Ansaldo Trasporti and ABB Tecnomasio, this train is a product of Italian railway technology. It represents the starting point for the new Italian High Speed railway system (Fig. 2).

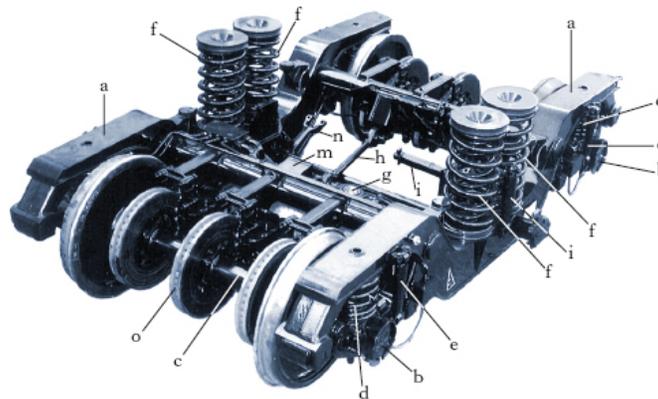


Fig. 2: cart tyoe72464 – FIAT Train – Source: Treccani

The FrecciaRossa 500 was born in the early 90s, with 3kV DC power supply, voltage used at the time, to then be overhauled and returned in 1996 with bi-voltage power supply, capable of operating even at 25kV AC at 50Hz, or the voltage value chosen at the international level to power all the AV lines, allowing interoperability between the different countries.

The ETR500 was one of the first trains to mount the ETCS (European Train Control System) and the SCMT (Train Running Control System), the most advanced and safest digital detection and signaling systems in Europe.

The SCMT was approved in Italy and was born from the union of ATP (Automatic Train Protection) and ATC (Automatic Train Control) technologies, allowing greater network capacity, through more efficient traffic management. This system is widespread on all European AV networks thanks to its versatility.

### 3.1.3.2 FrecciaRossa 1000

Built by Bombardier in collaboration with AnsaldoBreda, it entered circulation on Italian networks in 2015.

It is the fastest train (maximum commercial speed 360 km / h), more environmentally friendly and with the lowest number of noises and vibrations in Europe. Currently it operates only in Italy, but it is also approved in other European countries, for example in Germany, France and Spain (Fig. 3).

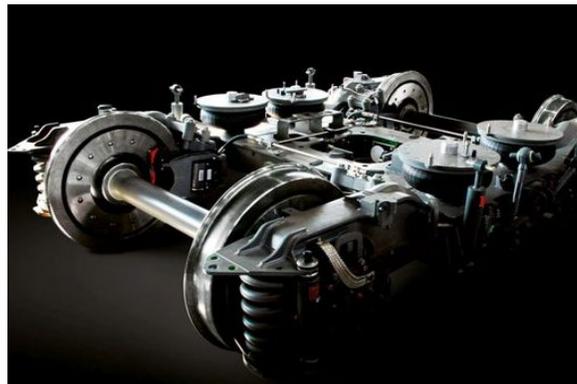


Fig. 3: FLEXX Speed – Bombardier; Source: slideplayer.it

Compared to the previous model, it no longer has the power concentrated in two locomotives, but has the engines distributed on the bogies, ensuring better acceleration and performance.

The ETR 1000 is the first high speed train in Italy to use Telediagnosics, or remote diagnostics technology.

Trenitalia together with SAP, the European leader in information technology, have developed a predictive maintenance system based on the principles of the Internet of Things. The SAP Hana platform processes the Big Data collected by the numerous sensors on the train, reporting in advance anomalies or terms of life cycles of the components, reducing the number of unexpected incidents in favor of safety.

### 3.1.3.3 Italo AGV ETR575

Built by the French company Alstom, the innovative AGV (Automotrice à Grande Vitesse) began operating in Italy in 2012 under the private railway company ntv (New Passenger Transport) (Fig. 4).

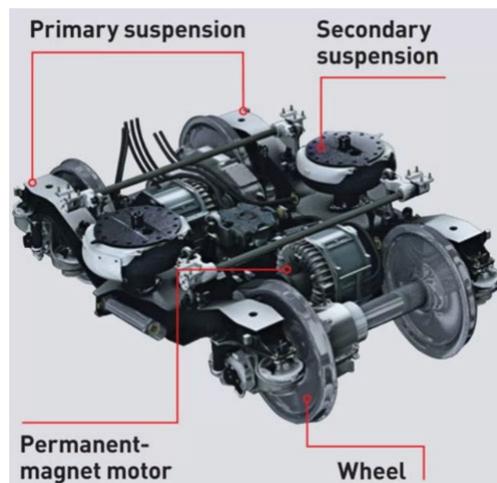


Fig.4 - CL334 - Source: Alstom

It was the first French production train to have distributed traction and no longer concentrated in two locomotives placed at the front and the rear. In addition, it has not plus two trolleys for each carriage (conventional architecture), but an articulated trolley placed between the carriages (articulated architecture). Thanks to this arrangement, noise, vibrations, weights and consumption are reduced; and in the event of derailment, the accordion arrangement is prevented.

The ETR 575 is one of the few AV trains that use Permanent Magnet Motors (PMM). Compared to AC induction motors, they consume less, are smaller, lighter and have higher efficiency.

### 3.1.3.4 Italo Pendolino Avelia EVO ETR675

It is the latest model of the AV train that came into circulation on Italian networks, and is also produced by Alstom. It is an evolution of the model called Pendolino, characterized by the variable attitude to increase speed when cornering without losses in comfort (Fig. 5).



Fig. 5 - Pendolino PKP, cart S220  
Source: Lodz Post, Alstom

Although it has retained the name "Pendolino", it was decided not to implement the pendulum casing technology. Furthermore, the maximum speed is lower than other high-speed trains since its use is foreseen for ordinary railway lines, therefore shared by regional trains.

Unlike most trains, this one does not have access doors for train drivers, a choice made to increase the number of seats.

### **3.1.3.5 Shinkansen N700**

It belongs to the Japanese AV train family and became operational in 2008. Several companies contribute to the realization of this train, the main two being Hitachi Rail and Kawasaki Heavy Industries.



Fig. 6 - cart N700, Source: Kawasaki Heavy Industries

It evolved from its predecessor of the 700 series with 3 objectives:

- Increase the speed when cornering

A new swinging system allows the train to be tilted up to 1 ° in curves, increasing speed without compromising comfort.

- Increase comfort

Each carriage of the N700 is equipped with an advanced suspension system that keeps lateral vibrations controlled.

Thanks to the aforementioned pendulum system, the decelerations-accelerations in curves have been reduced and with the new automatic control system (ATC) it is possible to stop the train with a single braking. The noises were reduced by means of a revised case and acoustic insulation floors.

- Reduce consumption and environmental impact

The aerodynamic drag has been reduced thanks to a new double wing muzzle. Small changes to carriages, trolleys, windows and pantographs have been helpful in reducing noise emissions. Regenerative braking is also exploited, thanks to which it is possible to produce reusable electricity during braking.

In general, compared to the 700 series, the N700 consumes 19% less with a 30% increase in traction. The drive components have been made lighter and more compact, with an increase in the power / mass ratio of about 20%.

### **3.1.4 Method implementation**

We now proceed with the collection of the technical specifications of the models analyzed in order to create the table of the Top-Flop Analysis.

The following were compared:

- Architecture and Composition, that is, the number of carriages and their variability
- Dimensions, therefore width, height and length
- Unladen mass, mass per axle and mass / number of wagons
- Absolute capacity and average capacity for each wagon
- Type of engine, traction system, absolute maximum power and power / mass ratio
- Maximum allowed commercial speed
- Security system

The Top-Flop table is shown on the following page.

3.1.4.1 Benchmarking and Top-Flop Analysis Table (Tab. 3)

Trading name	FrecciaRossa1000 ETR 1000 - V300 Zefiro	FrecciaRossa500 ETR 500-E404	Italo ETR575-AGV	ItaloPendolino Avelia EVO - ETR 675	Shinkansen N700
Producer	AnsaldoBreda, Bombardier	Consorzio TREVI	Alstom	Alstom	Hitachi, Kawasaki
Architecture	Conventional	Conventional	Articulated	Conventional	Conventional
Composition, Variability	8 carriages, a twin can be combined doubling the capacity	2 tractors + 11 carriages, no	11 carriages, no	7 carriages, a twin can be combined doubling the capacity	8 carriages, a twin can be combined doubling the capacity
Width (mm)	2924	3020 engine, 2845 carriage	2985	2830	3360
Height (mm)	4080	4000 tractor, 3800 carriage	n/a	n/a	3600
Lenght (mm)	202000 26300 head-to- tail wagons 24900 intermediate wagon	328032 20466 tractor 26100 carriage	201300 22800 head-to-tail wagons 17300 intermediate wagon	187300 n/a	204700 27350 head-tail wagons 25000 intermediate wagon
Mass per axis (t)	17	17	17	n/a	11,2
Empty mass (t)	454	576	372	400	365
Mass/ number of wagons	57	44	34	57	46
Capacity	up to 600	624	450	479	636
Capacity / number of wagons	75	56	40	68	79
Engine	Asynchronous Three Phase	Asynchronous Three Phase	PMSM	Asynchronous Three Phase	Asynchronous Three Phase
Traction	16 engines distributed	4 engines per tractor	12 engines distributed	16 engines distributed	engines distributed
Power (MW)	9,8	8,8	9,1	5,6	9,8
Power / Mass	22	15	24.5	14	26,8
Max Speed (km/h)	360	300	300	250	330
Safety System	ERTMS/SCMT	ERTMS/SCMT	ERTMS/SCMT	ERTMS/SCMT	ATC
TOP	3	0	3	1	6
FLOP	-2	-3	-3	-5	-2
Δ	1	-3	0	-4	4

Tab. 3 – Benchmarking and top-flop analysis table

In the table for each characteristic the best values (Top) are highlighted in green and the worst values (Flop) in red. Some parameters, for example the maximum speed and architecture, are absolute; while others, listed below, are not, or depend on other characteristics (Tab. 4)

**- Length**

The overall length of the train depends on its composition or on the number of wagons. Since the head-to-tail and intermediate wagons are of different sizes, the one with the longest average length will be chosen as the best value in favour of capacity, space and comfort.

**-Empty mass**

This characteristic also strongly depends on the composition of the train. In order to make a comparison, we will look at the relationship between the mass and the number of wagons. Obviously the lower this number, the lower the consumption and the better the performance.

**- Capacity**

Like the two characteristics listed above, the capacity also depends on the composition. In addition, it also depends on the size of each carriage: the greater the length and width, the greater the capacity. Reference will be made to the capacity ratio for each carriage.

**-Power**

Power depends on the number of engines installed, which can vary from train to train. The comparison is made by comparing the Power / Mass value.

<b>Innovation Table</b>	
Architecture	Articulated
Composition, Variability	> 7 carriages, a twin can be combined doubling the capacity
Width (mm)	> 3360
Height (mm)	>4080
Length (mm)	> 26175
Mass per axis (t)	<11,2
Empty mass (t)	< 34
Mass/ number of wagons	> 79
Capacity	PMSM
Capacity / number of wagons	engines distributed
Engine	> 26,8
Traction	> 360
Power (MW)	ERTMS/SCMT

Tab. 4 – Innovation Table

By making the difference between the number of Top values and the number of Flop values, we obtain the Delta ( $\Delta$ ), innovation index. Among the different models analyzed, the most innovative, that is, with the highest  $\Delta$  of 4, is the Shinkansen N700.

The goal of the design is to exceed the value of this  $\Delta$ , improving characteristics without making others worse. The so-called Innovation Table is therefore created, containing the limit values that indicate the improvements to be made.

Summing up:

- The articulated architecture is advantageous because it reduces vibrations, noise and maintenance costs; increases aerodynamics and safety.
- In modern trains the composition is blocked, i.e. the number of carriages is fixed, it can no longer be changed. It is therefore advantageous to be able to combine a second train, doubling the capacity for the busiest sections.
- The dimensions of the wagons can be increased to guarantee a greater number of seats and more spaces for each carriage. However, it should be remembered that the trains run on double tracks, therefore they cannot exceed the width otherwise they would interfere with the transit in the opposite direction, and have the catenary for the power supply above them, therefore they cannot exceed even in height.
- Axle Load is a value in tons, calculated with the following formula:

$$\text{Mass per axle} = (\text{Train mass} + \text{passenger load}) / (\text{Number of axles})$$

Lower values lead to less wear on the train wheels and tracks, consequently increasing life cycles and decreasing consumption and maintenance costs.

- The most popular motor nowadays is the AC asynchronous one. Thanks to electronic innovation, a Permanent Magnet Synchronous Motor (PMSM or PMM) has been developed, with better efficiency and a decrease in consumption, weight and dimensions. In addition, with distributed engine traction it is possible to use electric brakes and recover energy through regeneration. The mass per axle and maintenance interventions are reduced, with an increase in capacity.
- Travel times decrease as the train speed increases. Today, on the fastest AV lines in the world, the maximum speed allowed is 350 km / h. This parameter is strongly influenced by the security measures adopted in each country and by the infrastructures on which trains run.

Taking into account all the considerations made so far, we proceed to the next phase in which the parameters are chosen and improved, keeping in mind that the  $\Delta$  to be overcome is equal to 4.

### 3.1.4 Analyze (2): What-How Matrix

The customer's needs are compared with the technical characteristics with the What-How matrix. The parameters used are those that emerged most important from the matrices of relative importance and independence, and those from the Top-Flop Analysis table. The question that arises is how is the relationship between the element on the row with that on the column. It will be put 0 if it turns out to be zero, 1 if weak, 3 if medium and 9 if strong (Tab. 5).

	Architecture	Composition	Width (mm)	Height (mm)	Length (mm)	Mass per axis (t)	Mass / N° of wagons	Capienza / N° of wagons	Engine	Traction	Power/ Mass	Max Speed (km/h)	Safety System	Total
Speed	0	0	0	0	0	3	9	9	9	9	9	9	9	66
Punctuality	0	0	0	0	0	0	3	0	3	3	9	9	9	36
Comfort	9	0	3	3	3	0	0	3	0	3	0	0	3	27
Safety	9	1	1	1	1	9	3	1	1	1	0	9	9	46
Services	1	0	1	1	1	0	0	0	0	0	0	0	0	4
Total	19	1	5	5	5	12	15	13	13	16	18	27	30	

Tab. 5 – What-How Matrix

The sum by rows indicates the influence of the customer's needs from the technical characteristics, while the sum by columns indicates which are the most important parameters to improve in order to best meet the requests. The main properties to be improved are highlighted in green: Safety System, Maximum Speed, Architecture, Power / Mass Ratio, Traction System and Mass / N ° of Wagons. For correct design, the influencing factors of these parameters must be analyzed.

**3.1.5 Design (1): analysis of parameters**

**3.1.5.1 Mass**

This parameter influences 3 characteristics: Maximum Speed, Power / Mass Ratio and Mass / N ° of wagons ratio. The main reduction in mass on the train case can take place by replacing steel with aluminum, a much lighter alternative. Carbon fiber composites are also increasingly used, and compared to steel they can be 5 times more resistant to only 1/5 of their weight.

In general, Carbon compared to steel has:

- A reduced weight of 30-40%
- Less manufacturing complexity
- Lower equipment costs (cheaper molds)
- Greater resistance to corrosion
- Greater flexibility in design
- Greater damping of noises and vibrations

Material	Density (g/cm <sup>3</sup> )	Elastic Modulus (GPa)	Traction Resistance (MPa)
Steel	7,5-8	Circa 210	480-1100
Aluminium (series 7000)	2,88	72,5	560
Carbon Fibers	1,6-2,15	250-500	2000-4500

Tab. 6 – Metals parameters: mechanical characteristics

Over the years, the main lightenings on the trolley have resulted from the disappearance of the central crossbar (bolster) and the removal of the crossbars at the two ends following the integration of the brake system in the inside of the trolley.

Furthermore, with the integration of the brake system on the internal tubular crosspieces, it was possible to remove the crosspieces at both ends, reducing bulk and weight. For safety reasons, the main material remains steel.

Nowadays, designers are starting to use resins and glass fabrics as low density reinforcing inserts, while aluminum is increasingly used as a material for the cases. A further weight reduction can be achieved through the decrease of components and the introduction of hollow structures.

Thanks to these modifications, it was possible to drop below the threshold of 10 tons of weight per trolley.

**3.1.5.2 Traction System and Architecture**

The Synchronous Permanent Magnet motor is undoubtedly the most innovative option. In addition to the advantages in terms of weight, efficiency and dimensions, they also have a reduced maintenance cost.

For the reasons discussed above, it is advantageous to take advantage of distributed traction together with an articulated architecture.

**3.1.5.3 Speed and security**

Usually the values of the commercial speeds of the trains are lower than the maximum ones they could reach. The limit is imposed by infrastructure and security systems. On the fastest Italian routes, it is allowed to go up to 300 km

/ h. On average, however, the speed is much lower (around 200km / h) since circulation often takes place on ordinary tracks, shared with regional trains. In Japan there is a large dedicated network, that is, on which only high-speed trains operate, and it is free of intersections with roads, making the whole system more efficient, faster and safer.

Together with an automated vehicle control system (ATC), a single accident has not occurred on Japanese AV tracks since 1964.

In Italy, ETCS level 2 is currently used, a safety system that is based on radio signals and on the transmission of signals to the ground via buoys or balises. The goal is to correctly determine the position of the trains on the tracks and to transmit useful information such as the presence of obstacles or slowdowns. Level 3 ETCS is being developed which aims to establish the absolute distance between trains using only radio signals. Currently, if the presence of a vehicle is detected on the following track, regardless of its distance, the safety system comes into action, slowing down or even stopping the train. Thanks to the new level 3 technology, exact detachment is determined with high precision, allowing an increase in the capacity of the tracks.

### **3.1.6 Design (2): Design and modeling**

The ultimate goal of collecting and analyzing information is to be able to create an innovative railway trolley capable of meeting all market demands.

The main constituent parts of a railway trolley are:

- The assembled halls, or the axles with wheels, including primary suspensions and relative rocker arms.
- The H-frame, usually made up of two side members with a welded cross member.
- The secondary suspensions, which can be springs or air springs.
- Disc brakes.
- Articulation pin.
- Engines and transmissions if it is a motorized trolley.
- Sensors for detecting speed, position and other useful information.

The figure 7 shows the trolley of the Shinkansen Series 0, dating back to 1964.

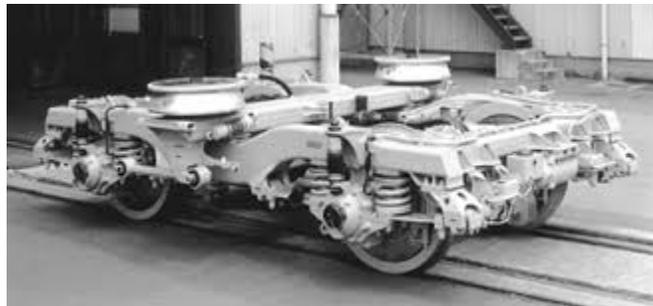


Fig. 7 - Shinkansen Series 0 Cart (1964)

It can be noted that in addition to the main organs for correct operation, there is also the central crosspiece, bolster, and two further crosspieces placed at the front and rear ends of the trolley.

The carriage was installed on the bolster, and had been designed to remedy the snaking effect, ensuring an optimal level of comfort. With technological evolution, it has been replaced by lateral suspensions, significantly reducing the weight of the trolley.

The crossbars at both ends in the past supported the braking organs. Nowadays, brake discs can be installed directly in the internal part of the wheels, allowing to reduce the overall dimensions and the weights.

We went from mounting the brake discs on the axle, to integrating them into the inside of the wheels, making the braking system more compact, with a reduction in size, masses, and therefore inertia.

In the following images (Figg. 8,9,10,11) the two configurations are shown.



Fig. 8 and 9 - brake discs mounted on the shaft and mounted on the wheel  
 Source: Electric Vehicle News; Korail



Fig. 10 and 11 - secondary spring and air suspension  
 Source: Ferrovie.it

Above are the two types of secondary suspension: coil springs and air springs.

The second option is the most widespread and most popular one today because in addition to providing good levels of comfort, it also allows a slight swing of the case, increasing the speed on the curves.

To further lighten the load, in addition to the use of Permanent Magnet Motors, it is possible to take advantage of aluminum transmissions, but it is still a little widespread application. Other considerations concern the dimensions of the wheels and the wheelbase.

The most modern trolleys have reduced wheel diameters and wheelbases, respectively of 860mm and 2500mm, making the trolley smaller.

A freehand sketch (Fig. 12) of a trolley was then made, including the innovative features discussed above, and then reproduced on the Creo Parametric 3D modeling program.

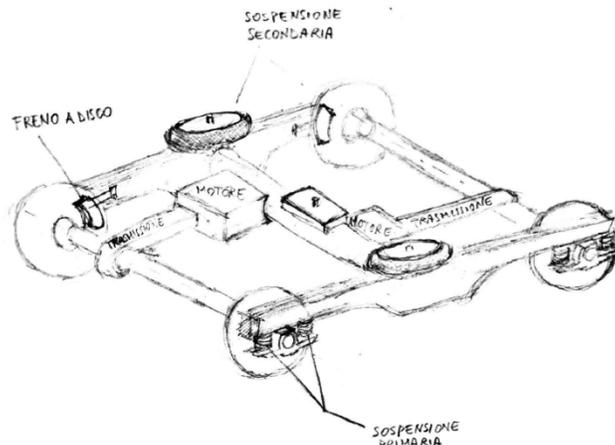


Fig. 12 – free hand sketch of the new cart

The members created and then assembled are:

- Axial
- Wheels
- Coil springs (primary suspension)
- Rocker
- Bearings (SKF catalog)
- H-frame (side members and cross member)

The CAD parts are shown below (Figs 13, 14, 15, 16, 17, 18):.



Fig. 13, 14, 15 Axle with wheels; Outrigger; H-chassis

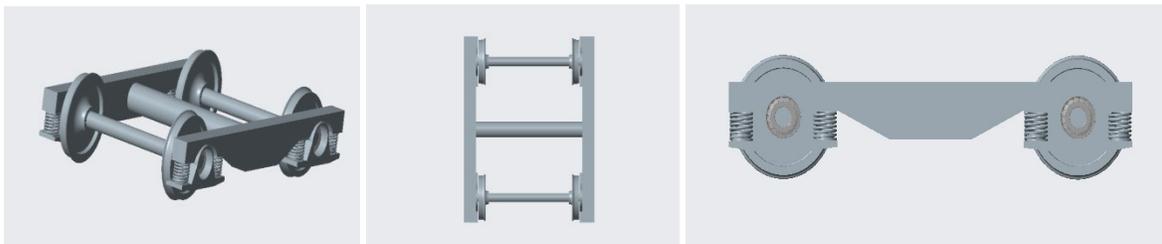


Fig. 16, 17, 18 The new cart

### **3.1.7 Verify: Structural analysis**

The last phase involves checking the model created through a simulation with the finite element method (FEM) using the Ansys program.

Static resistance tests were carried out, taking into account the weight of the crate that the trolley must bear, together with the load due to internal components, such as engines and transmissions.

It was assumed to have a 60 tare wagon empty, with a maximum capacity of 70 seats. The crate is supported by two trolleys, weighing 8.6 tons each.

The average passenger weight is assumed to be 75 kg. On each trolley there will therefore be a weight force equal to:

$$\frac{(60000 + 70 \cdot 75) \text{ kg} \cdot 9,81 \text{ m/s}^2}{2} = 320052 \text{ N}$$

#### **3.1.7.1 H-Frame**

The estimated surface on which the crate rests is given by the sum of the upper surfaces of the two side members and the surface of the cross member.

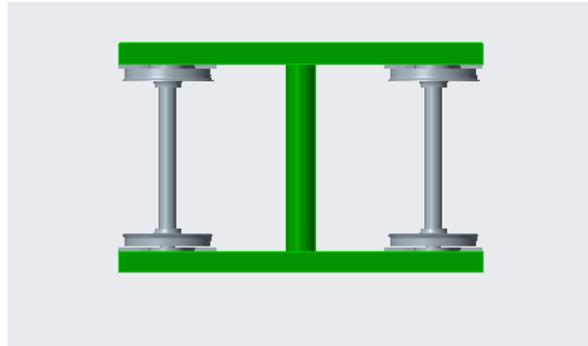


Fig. 19 - Support surface

Areas can be calculated as areas of rectangles:

$$\text{Traversa area } 1758,24 \text{ mm} \cdot 280 \text{ mm} = 492307,2 \text{ mm}^2$$

$$\text{Side member area } 3420 \text{ mm} \cdot 200 \text{ mm} = 684000 \text{ mm}^2$$

$$\text{Total Area } 492307,2 \text{ mm}^2 + 2 \cdot 684000 \text{ mm}^2 = 1,86 \text{ m}^2$$

$$\text{Total Stress } \frac{320052 \text{ N}}{1,86 \text{ m}^2} = 0,172 \text{ MPa}$$

The pressure on the surfaces is distributed proportionally with respect to the percentage in the area (Figs 20,21,22):

$$\text{Traversa } \frac{492307,2 \text{ mm}^2}{1860307,2 \text{ mm}^2} = 26,5\%$$

$$\text{Side member } \frac{684000 \text{ mm}^2}{1860307,2 \text{ mm}^2} = 36,75\%$$

$$\text{Stress on Traversa } 0,172 \text{ MPa} \cdot 0,265 = 0,046 \text{ MPa}$$

$$\text{Stress on Side member } 0,172 \text{ MPa} \cdot 0,3675 = 0,064 \text{ MPa}$$

In addition, the brakes, engines and transmissions are mounted on the crosshead. If you install 500kg engines, 150kg transmissions and a 200kg braking system, estimating an arm equal to half the distance between the cross member and the longitudinal member, or 0.63m, you will have two moments of opposite direction of module equal to:

$$(500 + 150 + 200) \text{ kg} \cdot 9,81 \frac{\text{m}}{\text{s}^2} \cdot 0,63 \text{ m} = 5253 \text{ Nm}$$

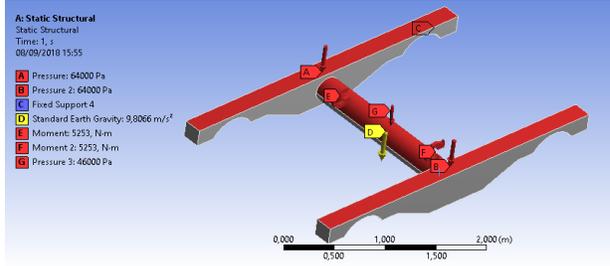


Fig. 20 – Loads applied to the H-frame

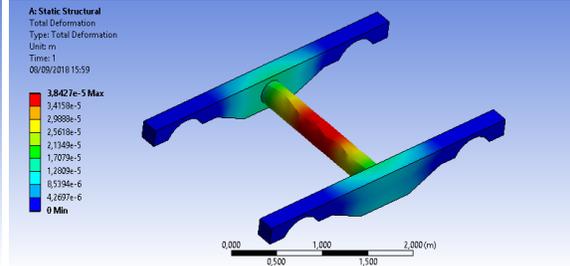


Fig. 21 – Total Deformation

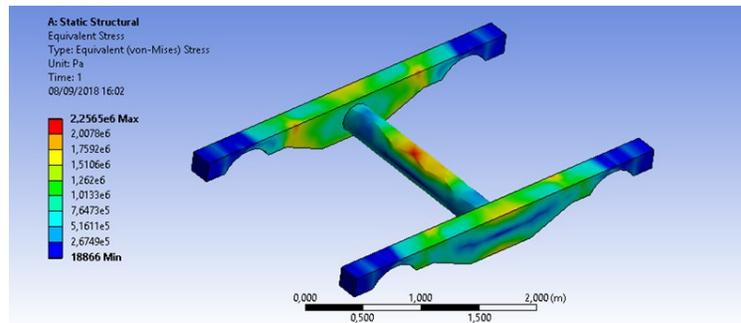


Fig. 22 - Solicitation of Von Mises

From the structural analyzes it can be seen that the most deformed and most stressed points are present on the central crosspiece, with a maximum deformation equal to  $3.84 \cdot 10^{-5}m$  and a maximum stress of 2.26 MPa

### 3.1.7.2 Outrigger

On the outrigger, in addition to the weight of the case, the weight of the trolley must also be taken into account. The H-frame rests on the coil springs, which transmit the pressure on the two lateral surfaces of the outrigger.

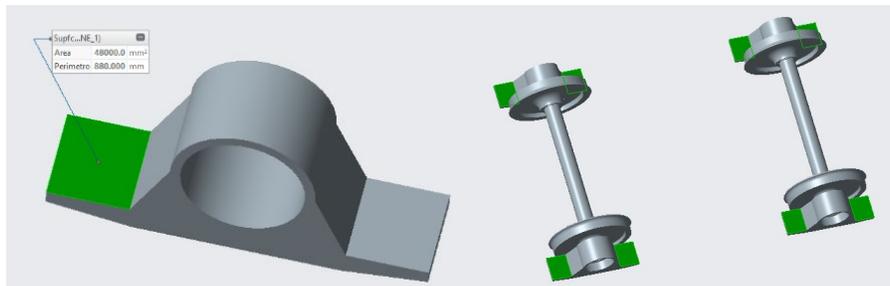


Fig 23 – lateral surfaces of the outrigger

For each trolley there are 8 surfaces on which the load is distributed. Each surface has an area of 48000 mm<sup>2</sup>; the weight of the trolley is equal to

$$8600 \text{ kg} \cdot 9.81 \text{ m} / \text{s}^2 = 84366 \text{ N};$$

on each surface there will therefore be a pressure of:

$$\frac{84366 \text{ N}}{8 \cdot 0,048 \text{ m}^2} = 0,22 \text{ MPa}$$

To this must be added the pressure deriving from the side members, and given that for each side member there are four bearing surfaces, a quarter of the pressure that is on the latter is added.

$$\text{Total stress } 0,22 \text{ MPa} + \frac{0,064 \text{ MPa}}{4} = 0,24 \text{ MPa}$$

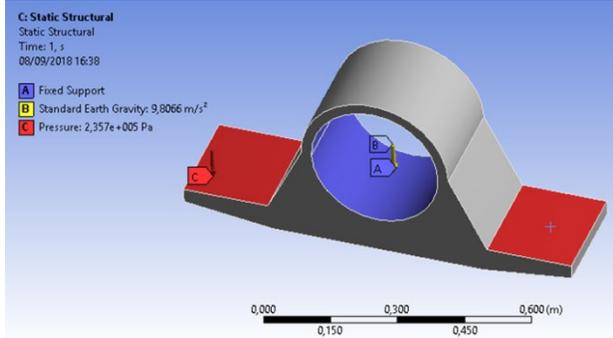


Fig. 24 – Load applied to the outrigger

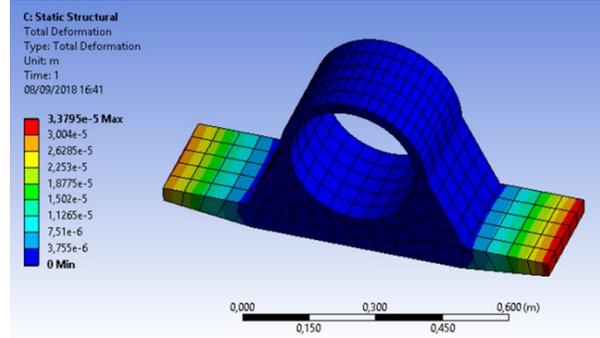


Fig. 25 – Total deformation

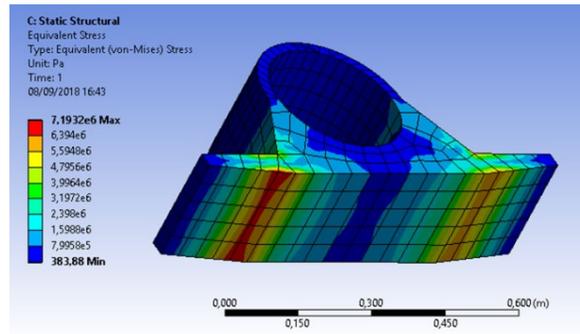


Fig. 26 – Solicitation of Von Mises

At the sides of the balance there are the maximum deformations, up to  $3,38 \cdot 10^{-5}$  m. The maximum stresses are in the lower part, with peaks of 7.19 MPa (Figs. 24, 25, 26).

### 3.1.7.3 Axle

As with the crossbar of the H-frame, also here the surface can be approximated to the area of a rectangle (Fig. 27).

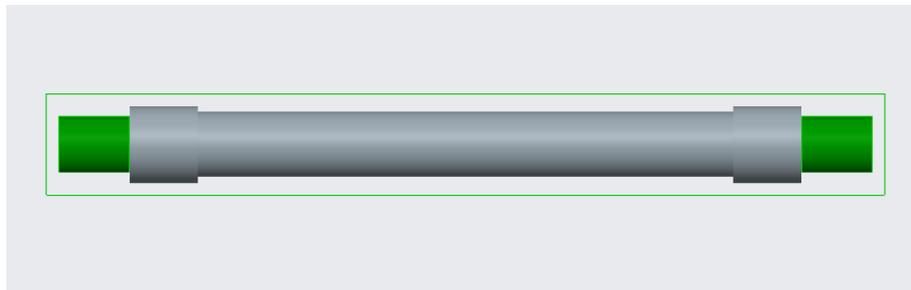


Fig. 27 – Working Surfaces of Axle

$$\text{Working Surface } 140 \text{ mm} \cdot 175 \text{ mm} = 24500 \text{ mm}^2$$

The weight of the case and trolley are unloaded on the axle. For each trolley there are two axles, therefore (Fig. 28, 29, 30):

$$\text{Weight of the case on each axle} = \frac{320052 \text{ N}}{2} = 160026 \text{ N}$$

$$\text{Weight of the cart on each axle} = \frac{8600 \text{ kg} \cdot 9,81 \frac{\text{m}}{\text{s}^2}}{2} = 42183 \text{ N}$$

$$\text{Stress on each surface} = \frac{160026 \text{ N} + 42183 \text{ N}}{2 \cdot 0,0245 \text{ m}^2} = 4,13 \text{ MPa}$$

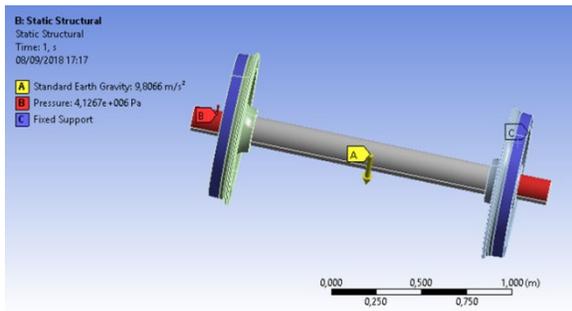


Fig. 28 – Load applied to the axle

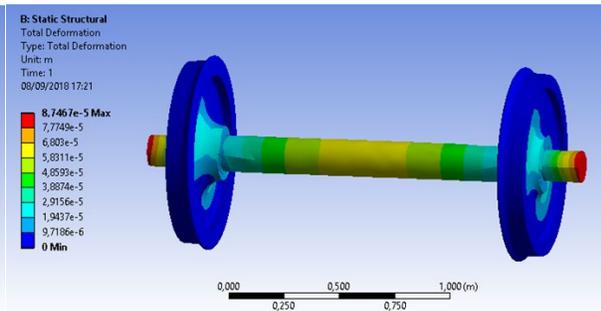


Fig. 29 – Total deformation

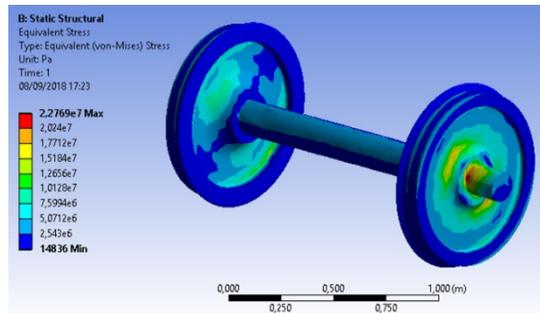


Fig. 30 – Solicitation of Von Mises

The maximum deformations,  $8,75 \cdot 10^{-5}$  m, are at the ends of the shaft, while the maximum stresses are at the connection point between the shaft and the wheel, with a maximum value of 22.8 MPa.

In 1852 the German engineer August Wöhler was entrusted with the task of studying the cause of the fractures of the railway axles by the Prussian Minister of Commerce. He noticed that the wheels broke at a lower load than the breaking load. Wöhler then established that the materials subjected to cyclic loads had a lower resistance than the nominal one, discovering the phenomenon of fatigue failure. Due to the reversal of the bending moment sign, the break occurs after a certain number of cycles  $n$ .

The calculation of the fatigue limit allows to calculate this maximum number of cycles given a generic stress  $S$ . If this stress is below a certain threshold, there are infinite cycles.

Fatigue failure occurs by crash and without any warning, it is therefore necessary to check the moving parts to avoid serious consequences.

Below are the results obtained from the fatigue test. The minimum safety factor in the most stressed points is **6.0941** (Figg. 31 and 32).

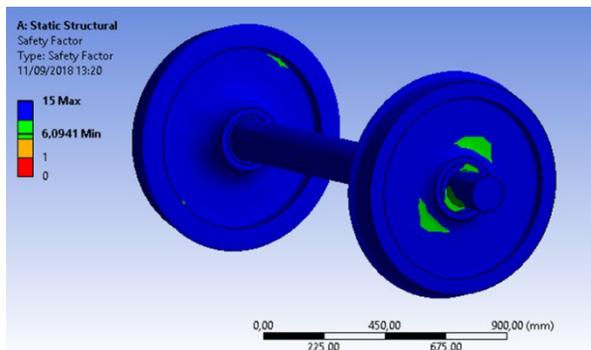


Fig. 31 – Fatigue Verification Safety Coefficient

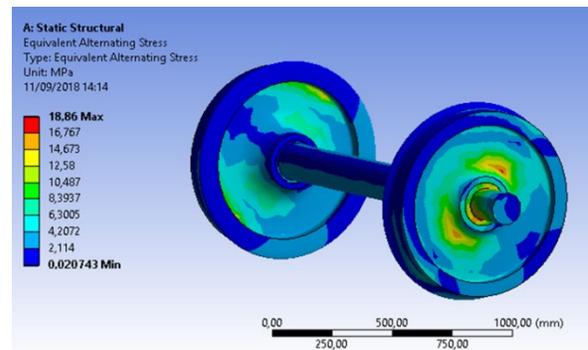


Fig. 32 – Fatigue Verification, Equivalent Alternate Stress

#### 4. Future Developments and Conclusions

The analyzes show that the most stressed points are on the assembled room, as was otherwise foreseeable. Both the axial and the wheels must be made according to European standards (EN 13261), and must have a yield stress of at least 550 Mpa, significantly higher than the 355 MPa of construction steels for general use.

The designed trolley is able to withstand the estimated stresses, both in static conditions and with fatigue. The minimum overall safety coefficient is 6.0941, making the structure verified since the minimum fatigue coefficient must be at least 3.

The trolley was also created at CAD, including the components for the operation (engines and transmissions, brakes and secondary suspensions) and through a PowerPoint presentation all the technical improvements were highlighted, which in addition to making the train innovative, also have the goal of satisfying the customer.

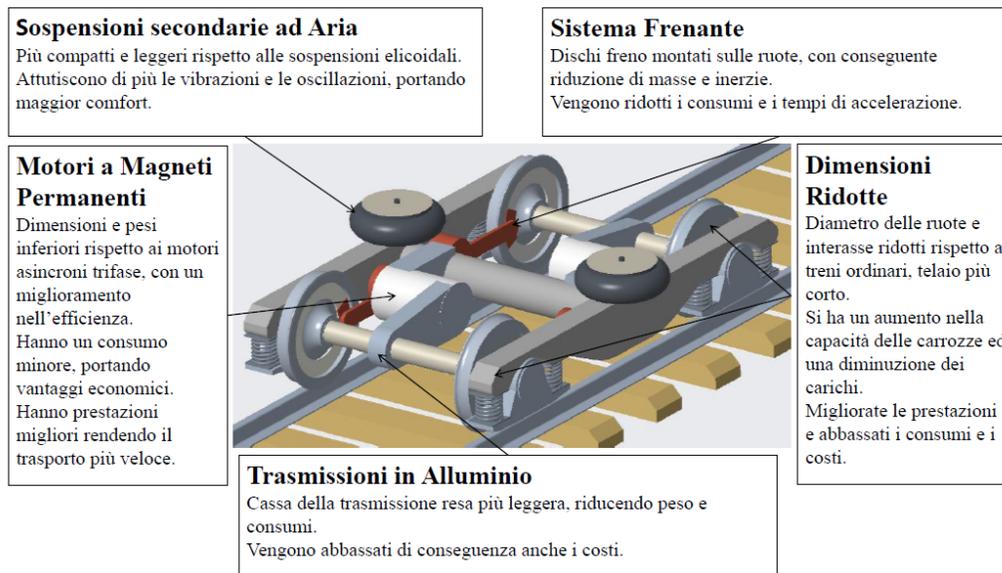


Fig. 33 – Synthesis of the project

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## **Biography / Biographies**

**Leonardo Frizziero** is a Senior Assistant Professor of the Department of Industrial Engineering, at Alma Mater Studiorum University of Bologna. He promotes the scientific issues related to the Mechanical Design and Industrial Design Methods (CAD 2D, 3D, Advanced Design, QFD, TRIZ, DFSS, DFD, DFA, ecc.). In 2005, he was recruited by Ferrari Spa, as project manager of new Ferrari cars projects. In 2009 he came back to University, obtained the Ph.D. degree and started collaborating with the Design and Methods Research Group of Industrial Engineering becoming Junior Assistant Professor in February 2013 at DIN of AMS University of Bologna. He teaches and follows researches in the design fields, participating at various competitive regional, national and international research projects. Since 2018 he has been a Senior Assistant Professor. Since 2017 he is qualified Associate Professor of Design and Methods of Industrial Engineering (ING-IND/15). Prior to the role of university professor, he held relevant positions for some industrial companies.

**Giampiero Donnici** is a Ph.D. Student of the Department of Industrial Engineering, at Alma Mater Studiorum University of Bologna. Giampiero Donnici worked as a mechanical designer in agricultural machinery companies and machine companies. As a consultant he has worked in numerous companies producing automatic machines and PLM and PDM systems. He is now a tutor and adjunct professor at the aforementioned university.

**Alfredo Liverani** is a Full Professor and Chief of Mechanical Engineering Degree Course at the Department of Industrial Engineering of Alma Mater Studiorum University of Bologna. Prof. Alfredo Liverani is a member of CbEM (Computer-based Engineering Methodologies) research group and he is involved in several activities related to Computer Aided Design (CAD), Computer Graphics, Virtual and Augmented Reality. In detail he focuses on real-time visualization and interaction with particular attention to mechanical, aeronautical applications and also Industrial Design. Surface modelling, reverse engineering, mesh generation (FEM) and manipulation, virtual prototyping and live simulations are fields investigated in the several publications available at <http://diem1.ing.unibo.it/personale/liverani>.

**Ye Haoyang** is a student of the course Master Degree in “Mechanical Engineering”, “Mechanical and Automated Design” held by Prof. Leonardo Frizziero at Alma Mater Studiorum University of Bologna.