POLITECNICO MILANO 1863

Scuola di Ingegneria industriale e dell'informazione

Mobility Engineering - Dynamics, control and diagnostic of ground transportation

Design of a New Railway Line

Monopoli to Matera

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RAILWAY LINE PROJECT

Touristic link between the cities of Monopoli (PUG) and Matera (BAS)

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Introduction: The Scope of the project

Our project is based on the study of a new railway line that connects the cities of Monopoli to Matera, with intermediate stops in the towns of Alberobello and Santeramo in Colle, all places with a strong tourist attractiveness. The goal is to create a sustainable railway line, for sustainable tourism, served, in fact, by a hydrogen train, that crosses Puglia from east to west and back.

This decision is driven by the high potential of the region in the energy production from renewable sources, in fact Puglia produces a total of 10 thousand GWh/year of clean energy, which account for about 60% of its requirement. Also given the fact that these figures are expected to grow in the future, thanks to efforts put into de-carbonization, clean energy could be the right solution to a carbon-free and shared transportation. Indeed, hydrogen, as a fuel, is potentially fully carbon-neutral, if produced using renewable energy.

The line will be mainly intended for tourists and will be characterized by a high frequency. The railway connection will shorten travel times between the different locations and discourage the use of private vehicles.

In almost all the selected stops, the already existing railway connections and stations are exploited in order not to impose themselves architecturally on such a delicate and precious heritage.

The project is mainly focused on the dynamics of the vehicle, as well as the analysis of the required energy to operate the train. Also, since our goal is to design a sustainable and innovative railway line, a set of comparisons with traditional means of transportation is carried out.

1. Route analysis

General overview of the connected cities

Monopoli

Monopoli is a great city on the east coast of Puglia. It offers multiple services and it's a crucial place during summer since it hosts a lot of people coming for tourism; The Monopoli railway station is located on the Ancona-Lecce Adriatic railway line, between the cities of Bari and Brindisi. Three tracks were in operation until 2003, but with the doubling of the section between Bari and Lecce, the third track was converted into a terminal track for the local line connecting with Bari.

Alberobello

Alberobello is placed in the center of Puglia region and it is known due to its particular aesthetic: it presents very strange houses called "Trulli" that joined together, create a magnific landscape. Alberobello is served by a station located on the Bari-Martina Franca-Taranto line. Managed by the Ferrovie del Sud Est, inaugurated on the 14th of December 1903 and entered into service on the 6th of September 1905, together with the Putignano-Locorotondo section of the Bari-Martina Franca-Taranto line.

Matera

Matera is probably the most famous city among all of these. Like Alberobello, it's known due to its landscape and due to the district "Sassi di Matera" where buildings are made of the rock of Matera, caved near the city center.
Following its proclamation as a city of culture 2019, Matera has seen its notoriety and tourist flows grow significantly.
The Matera Centrale railway station is located on the Bari-Matera railway line and it is managed by the Appulo Lucane Railways (FAL).
Originally born as a surface station, it was then transformed into an underground station and finally into a simple stop that anticipates the head station located in the southern part of the city.
The station has an optimal position. Here, regional trains leave for Bari and Gravina di Puglia.

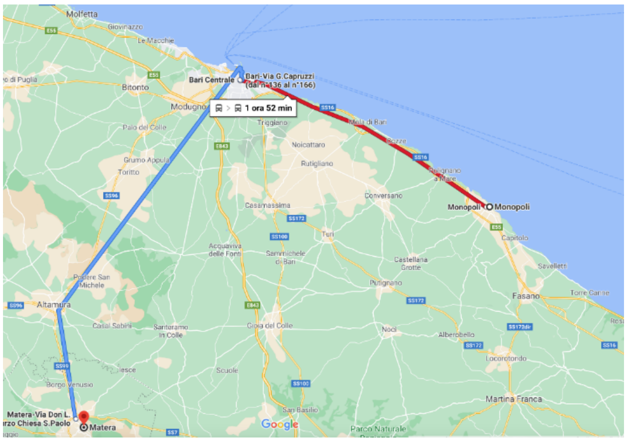
Santeramo in colle

The route also crosses a small town, Santeramo in Colle. Its railway station is located on the Rocchetta Sant'Antonio-Gioia del Colle railway line, managed by RFI. Through an official statement from Trenitalia in 2016, the entire route was cancelled.

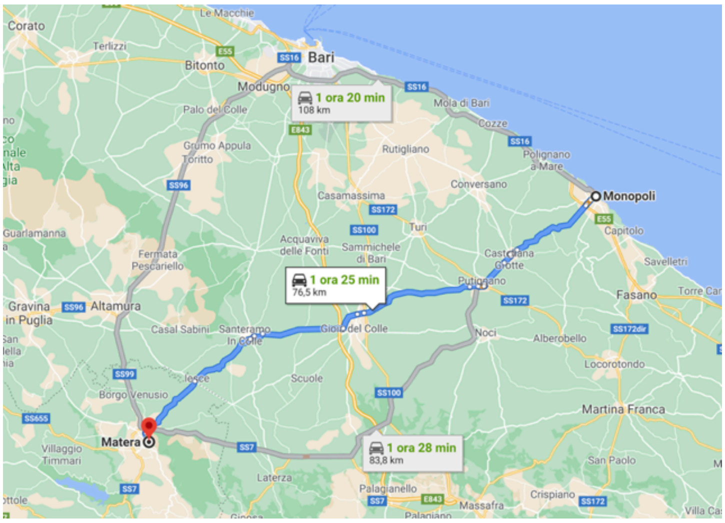
Analysis of the current situation and Path Design

The need for a Monopoli to Matera connection comes by the fact that there are not direct lines, operated by public transport providers in Puglia, that connect the two cities. This induces people to use private transportation, and since a lot of tourists reach Puglia via airplane, landing in Bari, they have to rent a car. This could lead to even abandon the idea of travelling.

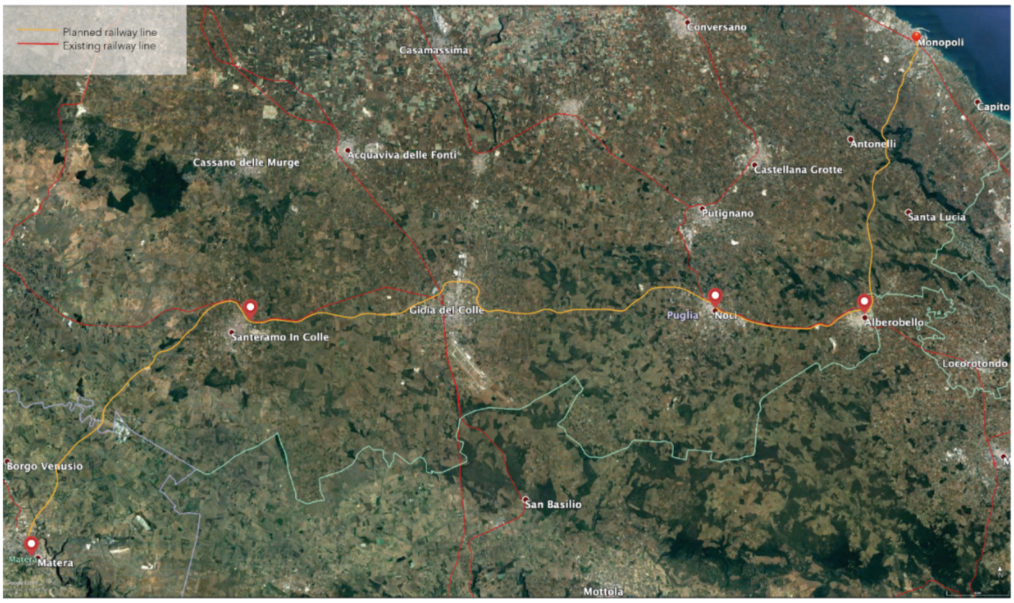
The only way to travel from Monopoli to Matera using public transport, nowadays, is to use the train; however this involves 2 changes and the use of 3 different trains: one from Monopoli to Bari, one from Bari station to Bari airport station, one from Bari to Matera. This journey also took about 2 hours to be made and 109 km travelled.

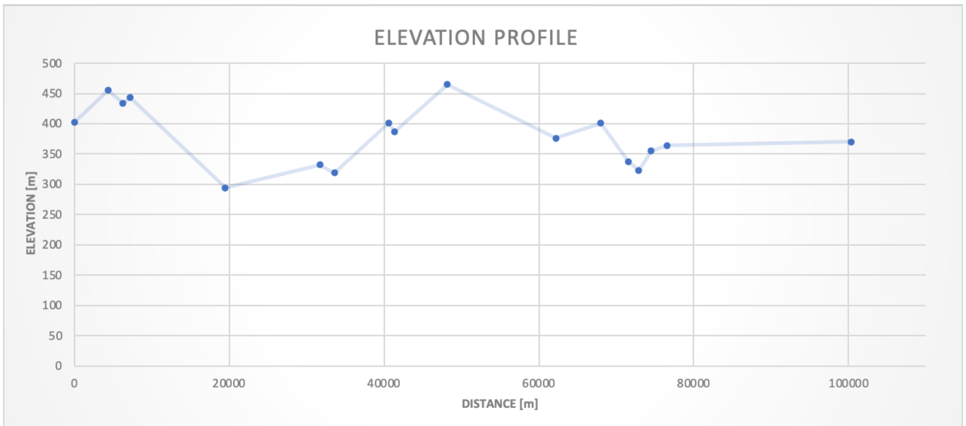


The same trip by car takes only 1 hour and 25 minutes and 76 km travelled.



In planning the route, it was decided to follow the existing railway sections as far as possible and then to create new connections by crossing rural areas.There is no need to build any new station: the stations already in operation in Monopoli, Alberobello, Noci and Matera will be used, while that of Sant'Eramo in Colle will be reopened to the public.The layout constructed and which will also be used for the analyzes through the Excel software is shown below.



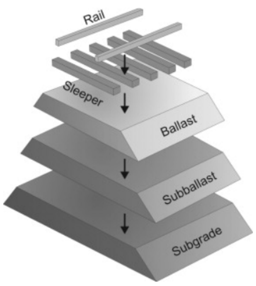


Infrastructure

The chosen train, although it is hydrogen powered, does not need a specific railway infrastructure: the track will be the typical one of regional railway lines.

The only difference lies in the elimination of the overhead contact line and therefore of the pantograph on the vehicle. As a matter of fact, the traction comes by the reaction of hydrogen with oxygen in a fuel cell to run electric motors, so the overhead contact line is not needed. This factor simplifies the construction of the infrastructure, in particular of the railway superstructure.

The diagram illustrating the composition of the armament is shown below:



2. Vehicle features

The reasons for hydrogen

The proposal for a hydrogen train finds its reason in the objectives of decarbonisation of the production system, that have been drawn up both at an international, European and national level.

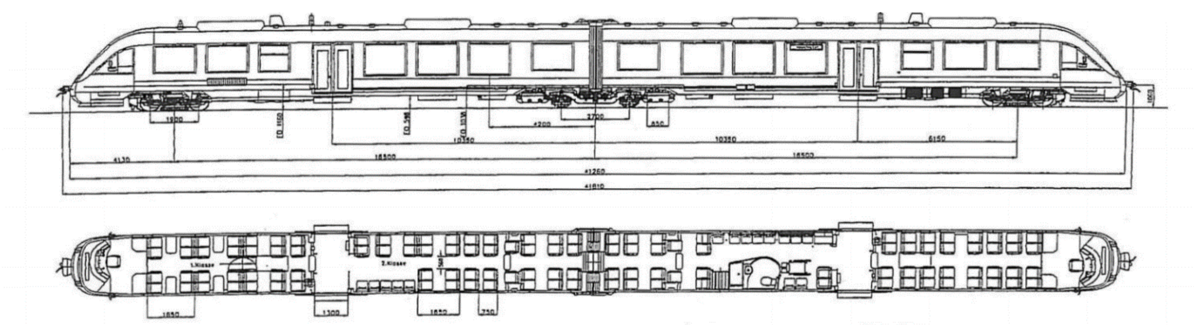
In this sense, the Puglia Region issued *Regional Law n.34 on 23 July 2019* in order to promote "*THE USE OF HYDROGEN*", recognizing it as a effective storage system, energy vector and alternative fuel to fossil sources. With this new law, the Region favors the production of hydrogen through the use of electricity produced by renewable sources to promote a more efficient use of the energy produced, distributed generation and a network of intelligent, eco-sustainable and integrated transport.

Thanks to this provision and to new funds issued, it is therefore possible to start an important decarbonisation of some Apulian railway lines. Our proposal therefore fully reflects the direction indicated by the competent bodies.

Hydrogen train technology e main parameters

The "CORADIA iLINT" hydrogen train

Coradia is the trade name that distinguishes a family of trains produced by Alstom. Coradia iLint is the first hydrogen-powered (fuel cell) passenger train. Developed starting from Lint 54, it is 54 meters long, composed of two car bodies, has a weight of about 120 tons distributed on 4 2-axle trolleys, a capacity of maximum 300 passengers, an autonomy of about 800-1000 km and can reach a cruising speed of 140 km/h.



The iLint is a one-of-a kind train, being the first ever hydrogen train to enter commercial service. From just a prototype, now the iLint rolls along some intercity-regional lines in Germany and is set to be operative in other connections in other countries. In Italy, for example the project “H2iseO”, powered by ENEL and FNM, aims at revamping and improving the Brescia-Iseo railway line, by replacing the current and dated diesel train fleet, with a total of 14 environmentally sustainable Coradia iLint trains (together with 40 hydrogen busses).

The train runs by powering its electric engine via the electricity produced by the chemical reaction between oxygen and hydrogen, which is safely stored under pressure in the fuel cells. This mechanism produces only water vapor and heat, centralizing emissions along the process of hydrogen production, that can be powered by both renewable energy and fossil fuel. More on this energetic topic further in the paper.

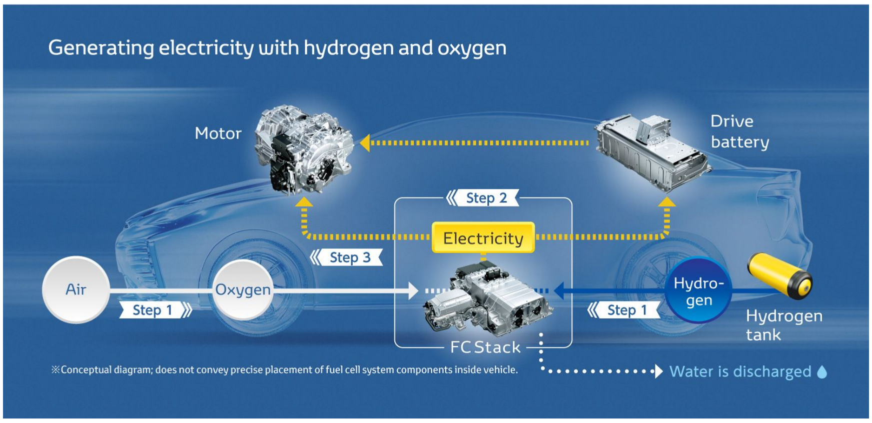


Figure 1 - Summary scheme of the hydrogen powering process of an electric car motor

Upon each of the car bodies, the iLint has a fuel cell pack that provides a total of 200 kW (with a tank consisting of 12 cylinders, positioned on the roof), and a motor trolley. The 24 cylinders in total correspond to 188 kg of fuel, which is equivalent to approximately 624 litres of diesel.

By combining hydrogen with oxygen, the fuel cells produce the electric energy needed to supply the vehicle's operations.

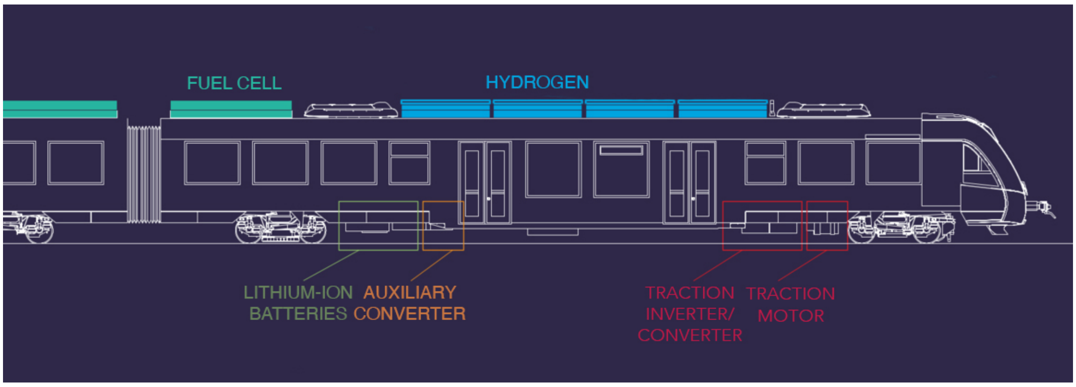


Figure 2 - the Coradia iLint traction system

The total energy available to the train is given by the supply of hydrogen contained in the fuel cells and the lithium ions batteries which help the vehicle thought the phases of acceleration and braking and are used for storing unused energy produced by the fuel cells. The train utilizes regenerative braking, hence it regains energy while braking or coasting downhill.

ENERGY SOURCE	PARAMETERS	AMOUNT OF ENERGY
Fuel Cells	Total Hydrogen Capacity: 188 kg Hydrogen LHV: 120 MJ/kg Motor performance: 50%	3133 kWh
Lithium Ions battery pack	Power density: 1 kW/kg Energy density: 0,4 kWh/kg Mass of the battery pack: 450 kg	200 kWh

Given the calculations above, the total amount of energy available to the train is 3313kWh. The Coradia iLint also consumes an approximated 50kW for the auxiliary elements of the train (heating and cooling systems, lights, sound, panels, etc…).

3. Excel model

Input Values

A,B,C

To extract the parameters A, B, C of the running resistance force " Fr" we have used the formulas below:

- $A = 6{,}4 * mTC + 8{,}0 * mPC$
- $B = 0{,}18 * m + 1 * nTC + 0{,}005 * nPC * P$
- $C = \frac{1}{2} * (8{,}2 + 0{,}057 * l) * \rho$

Where :

- mTC = tot mass of trailer cars in tons
- mPC = tot mass of power cars in tons
- m = tot train mass in tons
- nTC = n. of trailer cars
- nPC = n. of power cars
- P = tot power in KW
- l = train length in m
- ρ = air density in kg/m^3

Eb

To compute The energy battery we have considered the combination of Lithium battery present in the train as reserve energy supplier and the hydrogen fuel cells mounted on the roof of the train

ng

As gear transmission ratio we have choosen an indicative value from the data sheet of IGW company (a company that build gearbox)

Jaxle

As moment of inertia of the motor axis we have considered the combination of axle and wheels

Pr (rated)

As rotor power we have considered the combination of power delivered from fuel cells and from lithium batteries

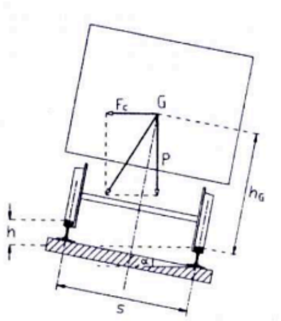
Tr (rated)

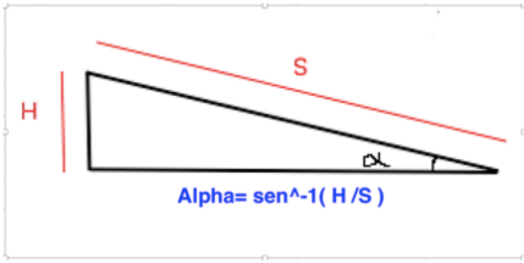
the value of rotor torque we have extracted from Pr (rated) and rpm(revolutions per minute) speed

Cant angle reference (ref)

From a standard table for passengers trains (with non compensated acceleration=0,8) that, given the radius of a curve and the maximum speed extract the value of superelevation (H), we find out the cant angle for each part of our route with the formula below :

$$\alpha = \sin^{-1}\frac{H}{S}$$





Speed

to compute the velocities in each part of our route we adapt a model of regional train to the features of our train

Output Values

cant angle (α)

- $Se\ (\alpha ref - \alpha prev) \neq 0.\ \ \Rightarrow \alpha + 0{,}15 * (\alpha ref - \alpha prev)$
- $Se\ (\alpha ref - \alpha prev) = 0.\ \ \Rightarrow \alpha ref$

Se (ref cant ang.-previous cant ang.)≠0 , allora incrementa il cant ang. di 0,15* (ref cant ang.-previous cant ang.)

Δincr

- $Se\ [o\ (ref\ v\ -\ v) < 0{,}02\ \ o\ \ break = 1] \Rightarrow 0$
- $In\ tutti\ gli\ altri\ casi\ \ \ \Rightarrow 1$

Length to stop

- $0{,}5 * \dfrac{(\frac{speed}{3{,}6})^2}{conf\ acc}$

length to reduce speed

- $Se\ (speed - next\ speed) > 0.\ \ \Rightarrow 0$
- $Se\ (speed - next\ speed) < 0.\ \ \Rightarrow 0{,}5 * \dfrac{\left[\left(\frac{v}{3{,}6}\right)^2 - \left(\frac{next\ v}{3{,}6}\right)^2\right]}{\min\ (conf\ acc; -\ abreak\ av.)}$

Break

- $Se\ (Ref\ speed > speed)\ \&\ Se\ (Ref\ distance - distance) > lenght\ to\ red.sp\ \ \ \Rightarrow 0$
- $In\ tutti\ gli\ altri\ casi\ \ \ \Rightarrow 1$

aLONG

- $\left(\frac{v-prev\ v}{\Delta t}\right)*\frac{1}{3{,}6}$

aLAT

- $Se\ R>0.\ \Rightarrow\frac{v^2}{R*3{,}6^2}$
- $Se\ R<0.\ \Rightarrow 0$

aLAT_NC

- $aLAT*\cos\alpha-9{,}81*\sin\alpha$

TLIMIT_FRICTION

- $\sqrt{[(m*9{,}81*\cos(\theta*cos\alpha)+m*aLAT*\sin\alpha)*\mu]^2-m^2*aLAT^2}$
  - θ= gradient
  - α= cant angle
  - μ= friction coefficient

TT_LIMIT_COMFORT

- $\left(\frac{R}{\frac{\eta}{100}*ng}\right)*\left[\left(m+\frac{Jaxle}{R^2}\right)*aconf+(A+m*9{,}81*\sin\vartheta)+Bv+Cv^2\right]$
  - $aconf$ = comfort acceleration

TT_AVAIL

- $Se\ \frac{v}{3{,}6}*\frac{ng}{R}<1000*\frac{Prated}{Trated}.\ \Rightarrow Trated$
- $Se\ \frac{v}{3{,}6}*\frac{ng}{R}>1000*\frac{Prated}{Trated}.\ \Rightarrow\frac{Prated*1000}{\left(\frac{v}{3{,}6}*\frac{ng}{R}\right)}$

TT_COASTING

- $\left(\frac{R}{\frac{\eta}{100}*ng}\right)*(A+m*9{,}81*\sin\theta+B*vref+C*vref^2)$

TT_BREAK

- $Se\ \frac{v}{3{,}6}*\frac{ng}{R}<1000*\frac{Prated}{Trated}\ \Rightarrow -Trated$
- $Se\ \frac{v}{3{,}6}*\frac{ng}{R}>1000*\frac{Prated}{Trated}\Rightarrow-\frac{Prated*1000}{\left(\frac{v}{3{,}6}*\frac{ng}{R}\right)}$

TT_BREAK_COMFORT

- $\left(\frac{R}{\frac{\eta}{100}*ng}\right)*\left[\left(m+\frac{Jaxle}{R^2}\right)*(-aconf)+(A+m*9{,}81*\sin\vartheta)+Bv+Cv^2\right]$

TT

- $Se\ \ break=0\ \ \&\ \ \Delta incr=1\Rightarrow min(Tlim\ conf\ ;Tava)$
- $Se\ \ break=0\ \ \&\ \ \Delta incr\neq 1\Rightarrow Tcoasting$
- $Se\ \ break=1\ \ \Rightarrow max(Tbrake\ ;Tbrake\_conf)$

T

- $\frac{Tt*\frac{\eta}{100}}{R*ng}$

Rotor Power

- $Tt * \left(\frac{\frac{v}{3,6}*ng}{R*100}\right)$

Energy (Et)

- $prev\ E + \frac{Rot.Power*\Delta t}{3600}$

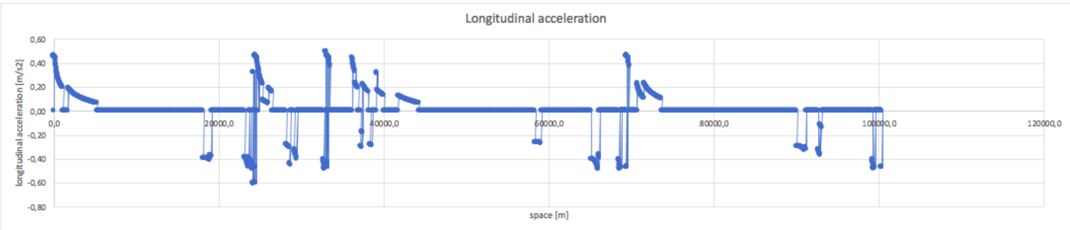
a-break available

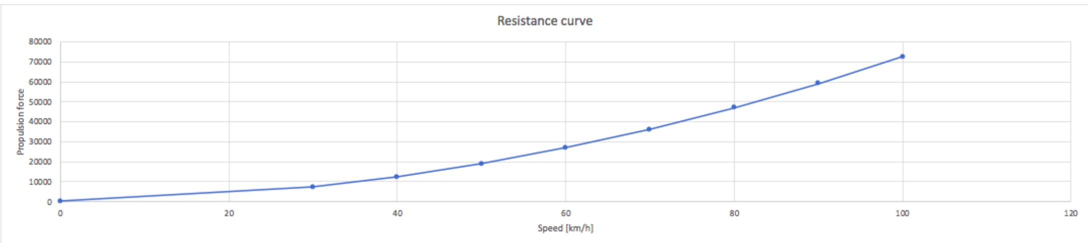
We have computed the equation of T_T_BREAK (that has the same shape of the formula T_T_LIMIT_COMFORT) and we have extracted the accelleration related to breaking

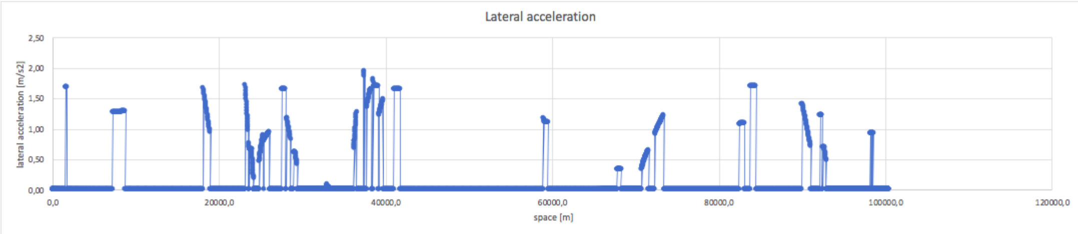
- $\frac{Tbreak*\left(\frac{ng}{\frac{\eta}{100}}\right)-R*\left(A+m*9{,}81*\sin\theta+B*\frac{v}{3{,}6}+C*\left(\frac{v}{3{,}6}\right)^2\right)}{R*m+\frac{Jaxle}{R}}$

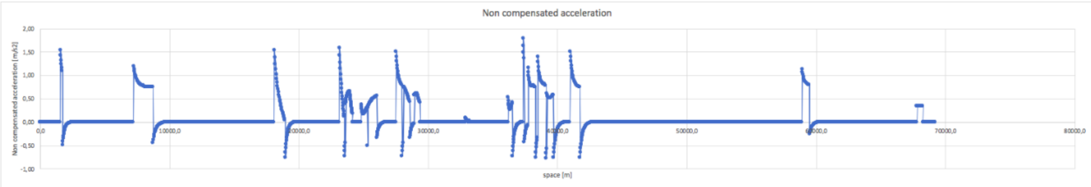
Final Charts

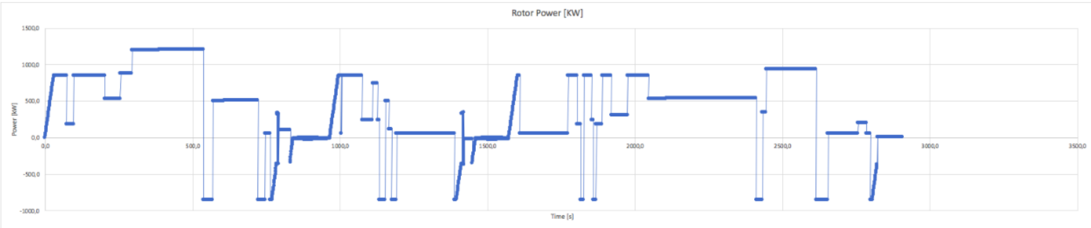
Then we plot the speed-time profile , the speed-distance profile and the behaviour of the most relevant features in time

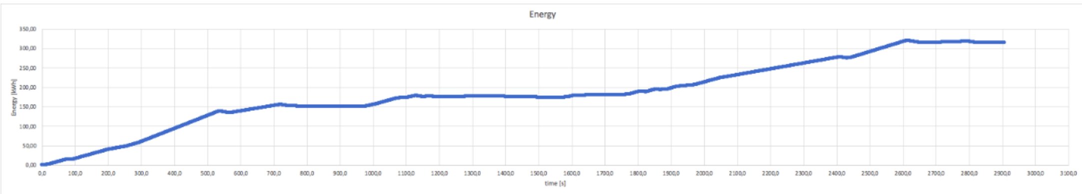





Lateral acceleration
lateral acceleration [m/s2]
space [m]


Non compensated acceleration
space [m]


Rotor Power [KW]
Time [s]


Energy
time [s]

4. Energy Analysis

Energy Consumption of the line

Using our excel model, it was possible to assess the total consumption of energy of a one-way trip:

Total Travel Time [min]	Average Speed [km/h]	
74,55	80,78	
Total Travel Distance [km]	Energy consumption per km [kWh/km]	Autonomy left [km]
100,37	4,01	726,34
Total Energy Consumption (fuel+aux) [kWh]	Hydrogen Consumption [kg]	Specific Hydrogen Consumption [kg/km]
402,21	33,79	0,34
Specific cost of Energy [€/kWh]	Total Cost of Energy [€]	
5,50	2212,18	

From the results above we can see how the train requires a total of 402,11 kWh of energy to run from Monopoli to Matera, which is equivalent to 33,79 kg of Hydrogen "burnt" from the fuel cells. For this calculation, the following considerations were done:

- The braking system has a 60% regenerative efficiency;
- The motor has a 50% efficiency;
- an arbitrary surcharge factor of 1,4 was used, in order to consider the fact that the energy regenerated by braking is not transformed back into hydrogen, but in electricity stored in the batteries.

The specific hydrogen consumption comes at 0,34 kg/km, which is a common value seen in literature.

Objectives and constraints

Given these values of requirements for a one-way trip, the analysis shifts to the design of the energy infrastructure that the train will eventually rely on to operate. It is driven by:

- the **objective** of designing an infrastructure that can sustain in the long term a hypothetical *scheduled service* for travellers
- a perimeter which is framed by **constraints** regarding safety and environmental and operational sustainability.

In this analysis costs were not taken into account, although, in case of a real-world project, this would be a significant constraint, since hydrogen technology is not mature yet. Investment costs, especially, are fairly high, compared to those required for more established technologies.

Hydrogen production technology

This analysis considered only the two most common and technologically mature hydrogen production processes: Steam Methane Reforming (SMR) and Electrolysis. In more detail:

1) The most common production technology is Steam Methane Reforming (SMR) which starts either from natural gas (methane) or bio-methane, a form of methane obtained from biomass. Hydrogen from fossil fuel is called either grey or blue hydrogen, depending on whether the production plant is equipped with a Carbon Capture System (CCS) or not.

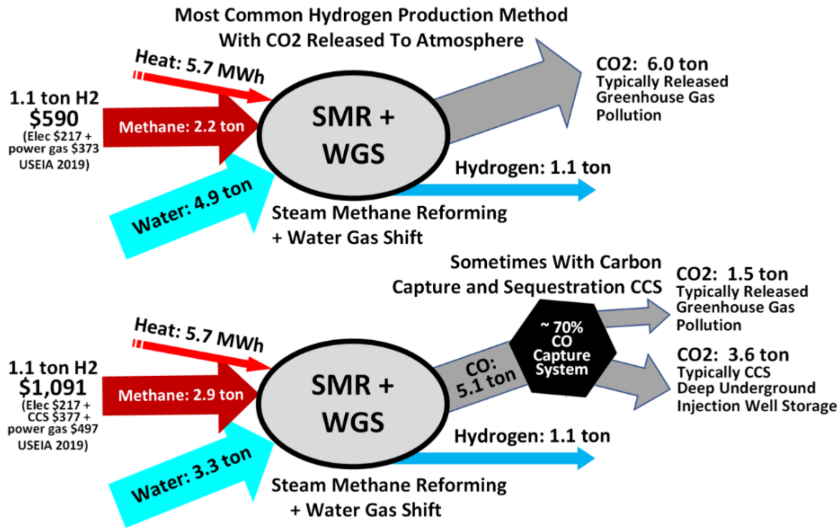


Figure 3 - SMR production processes

2) On the other hand, green hydrogen, the most sustainable kind of fuel in terms of emission, is obtainable through an Electrolysis process which utilizes water as its only reagent. Although the process itself has a neutral carbon footprint, the energy required to power it is relatively high. Indeed, green hydrogen is the most environmentally sustainable, and can only be classified as such, if the production process is powered by renewable energy.

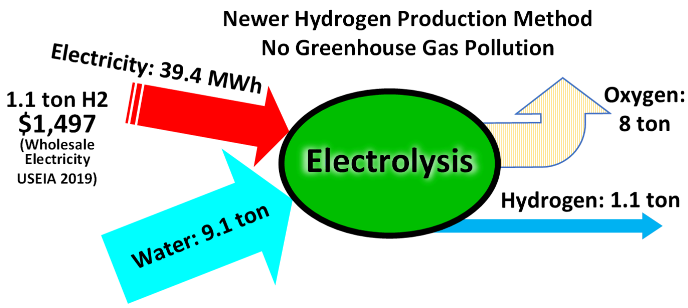


Figure 4 - Electrolysis production process

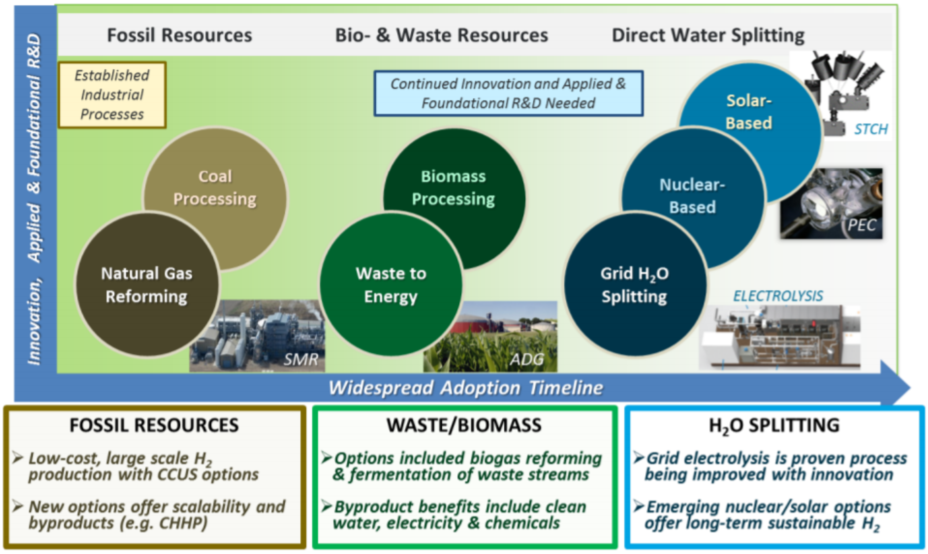


Figure 5 - Summary of Hydrogen production technologies

Production Technology	SMR (with CCS)	SMR (without CCS)	SMR	Electrolysis
Hydrogen class	**Blue**	**Grey**	**N/D**	**Green**
Energy Source	Methane	Methane	Bio-methane	Renewable (solar/wind power)
Energy Consumption [kWh/kg]	41,82	33	33	35,81
Net Average Emissions [kgCO2/kgH2]	3,27	5,45	Very Low*	Very Low*

*= hypothetically, hydrogen production via renewable technology is carbon neutral; practically, a small part of the energy required by the process does not come from renewable sources (es: energy for transportation or auxiliaries).

Hypothetical scheduled service and energy requirement

To correctly design the energetic infrastructure, the chosen approach was the assessment of the amount of available and required energy, at any given time. To do so, a hypothetical timetable can be a useful tool to better understand the demand for hydrogen supply.

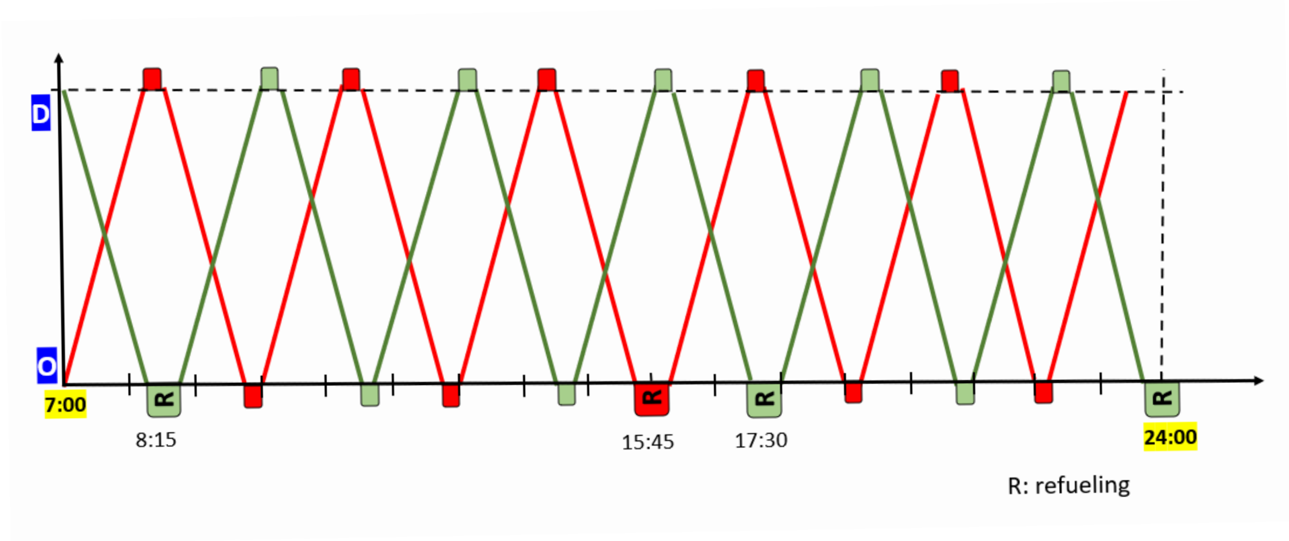


Figure 6 - Hypothetical Timetable of Service of the railway line

For the sake of simplicity, in this timetable only 2 trains (green line and red line) are operating. This choice is also driven by the fact that, since it is a touristic train, the capacity of the line does not have to be as high as the capacity of a regular intercity/regional train line. Also, two trains are enough to have a maximum headway of 1h and 45 mins, an acceptable amount of time, considering it is, as said before, a touristic train.

The timetable shows that a single train can run for 6 consecutive runs (about 600 km) before needing a hydrogen refill. The train could hypothetically run back and forth one more time, adding 2 more runs to the total, but, at this stage, the train would have very little autonomy left. This, in case of unforeseen delays, stops, failures or accidents, could eventually lead to an insufficient autonomy to run on the line. This kind inconvenience could be too risky and unsustainable.

The line was designed making the two trains start rolling respectively from each terminal, in normal operational conditions, from 7:00 to 24:00. The average time spent at the terminal, before operating again, is 15 mins or 30 mins in case the trains require charging its fuel cells. (fonte: American Public Transportation Association e https://www.railjournal.com/in_depth/hydrogen-fuel-of-the-future).

Finally, let's suppose to build the hydrogen production facility, charging station and depot in the Monopoli terminal. These are the results of the analysis of a normal day of operations:

Daily scheduled service operations	
Number of trains on the line	2
Total distance run	2200 km
Runs performed	22
Total Passengers transported	4400
Total charges required	4
Daily Hydrogen requirement	**748 kg**

Energy Infrastructure Dimensioning

The primary constraint of this dimensioning is the limitation of the environmental impact of the train, which can be achieved by providing the system with green hydrogen, hence hydrogen obtained via clean energy electrolysis. Puglia is a region with a high level of production of renewable energy, especially solar power, compared to the rest of the country. Such an available supply could be crucial for powering the production process, while limiting pollutant emissions.

For what concerns operability, in a year (365 days), a fleet of 2 trains would require a total of about 273 tons of hydrogen to operate on the line. This quantity is obtained, as said in the last paragraph, via an electrolysis process which needs 9,78 GWh/year of energy. The Puglia region produces a total of 9940 GWh/year of energy from renewable resources. (fonte: https://www.trenoverde.it/wp-content/uploads/2018/02/ComuniRinnovabili-Puglia.pdf).

In practical terms, to fulfil this demand of energy, the following systems could be used:

- 2 to 3 big size on shore wind turbines (2 MW each; efficiency: 25%), or
- 35530 m^2 of photovoltaic panels (a 15 m^2 3 kW PV system in Puglia produces an average of 4130 kWh/year) equivalent to an area of about 3,5 football pitches

In conclusion the whole train line would consume, only in terms of fuel production, the 0,1% of the annual clean energy produced in Puglia. This piece of data shows how the energetic system of the region could well sustain the implementation of the railway line. Although, it is safe to assume that, in a real-world scenario, the energy requirement could potentially rise to higher values, due to more trains in operations and other secondary factors that were not taken into consideration in this analysis.

In conclusion, to reach a daily requirement of 748 kg of hydrogen, the choice was to equip the production facility with a modular 20 MW Electrolyser unit from thyssenkrup (fonte:https://ucpcdn.thyssenkrupp.com/_binary/UCPthyssenkruppBAISUhdeChlorineEngineers/en/products/water-electrolysis-hydrogen-production/210622-gH2-productbrochure.pdf) that enables a production of 360 kg/h. Production schedule can be optimized to exploit low energy prices, also to produce surplus hydrogen to be stored for future needs, or to be sold on the local market.

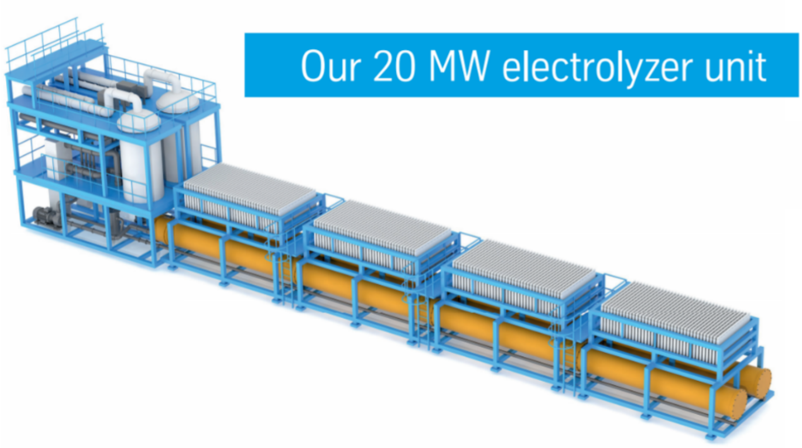


Figure 7 – modular electrolyser unit from thyssenkrup

Environmental Impact

The environmental impact generated by the construction and operation of the train line can be categorized as follows:

- Atmospheric pollution: this aspect is strictly related to the hydrogen production process, in fact CO2 emissions are centralized, and so they depend on the type of hydrogen production process being implemented . The natural gas-SMR process (no CCS) has an average of 5,45 kg of CO2 emitted per kg of hydrogen produced, while the bio methane-SMR and the Electrolysis processes are ideally carbon neutral. In a real scenario it is safe to assume that not all energy that is consumed for the electrolysis process comes exclusively from renewable sources. Some events, like blackouts or energy shortages, may require the supplement of non-renewable energy in order to keep the production plant running. More so, some auxiliary elements of the process may only be able to be powered by energy which is not clean.
  Assuming the absence of these kinds of events, it is possible to hypothesize the complete carbon neutrality of the hydrogen production process.
  For what concerns the vehicle, it does to emit any pollutants during operations: the only products of the reaction that generates electricity from the fuel cells are water steam and heat.

Here is a comparison of the CO_2 emissions of a one way trip (Monopoli-Matera), based on production technology.

Production Technology	SMR (with CCS)	SMR (without CCS)	Electrolysis/SMR (via bio-methane)
CO_2 emissions [kg]	110,5	184,15	Very Low (negligible)

- Visual pollution: the train track would be mostly laid along the countryside, where other tracks have already been present for years. Eventually, the most critical part of the implementation of the project would be the construction of new tracks beside old town centres, such as Alberobello, where there is no railway present to this day. This might give a "punch in the eye" effect considering how peculiar these little towns are, since they have maintained their traditional aspect for years. On the other hand, the Coradia iLint is a good looking and well-designed train and its peculiarity might even increase the attractiveness and reputation of the area, for what concerns sustainability.

- Noise and vibration pollution: this topic will be further developed in chapter 6.

5. Comparison with other vehicles

Purpose of the analysis

Given the peculiarity and the innovativeness of the chosen vehicle, the comparison analysis had to be done considering more traditional types of transportation. The primary objective was to compare the Coradia iLint performances with the ones of the vehicles that a typical tourist would choose as a mean of transport to reach Matera from Monopoli.

The first two obvious choices came down to the car and the diesel engine interurban bus euro 6. Also, a comparison on pollutants emissions with a diesel train of the Coradia family had been done.

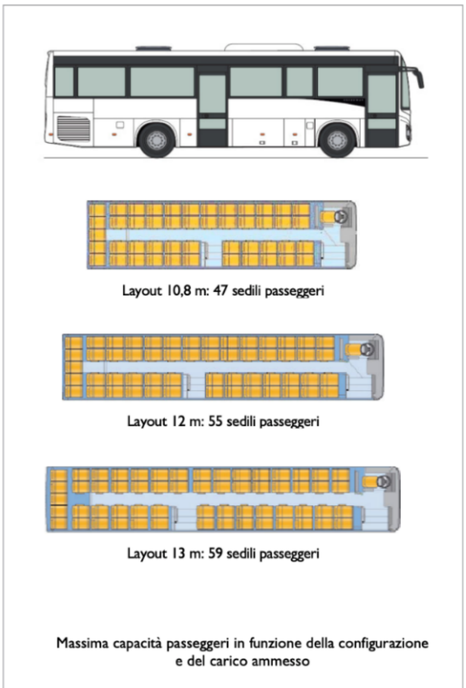
The comparisons will be made analyzing these main aspects:

- Distance travelled
- Total travel time
- Total energy consumption
- Total costs
- Carbon footprint

Diesel Bus

For the comparison between the hydrogen train and a bus, the 13m IVECO Crossway model with approximately 60 seats was chosen.
The technical data sheet is attached below:

Crossway Line 10,8/12/13 m - Diesel EURO VI



LUNGHEZZA	10.757 / 12.097 / 12.962 mm
LARGHEZZA	2.550 mm
ALTEZZA (CON/SENZA A/C)	3.460 / 3.370 mm
PASSO	5.300 / 6.200 / 7.065 mm
SBALZO ANTERIORE / POSTERIORE	2.165 / 3.292 mm (10,8 m) 2.605 / 3.292 mm (12 e 13 m)
ALTEZZA PAVIMENTO	860 mm
ALTEZZA INTERNA	2.280 mm
ALTEZZA ACCESSO PORTA ANTERIORE / CENTRALE	344 / 344 mm
LARGHEZZA PORTA ANTERIORE / CENTRALE (STANDARD)	800 / 800 mm
RAGGIO DI INGOMBRO (TRA I MURI)	9.250 / 10.770 / 11.900 mm
RAGGIO DI VOLTA	7.820 / 8.990 / 10.120 mm
ANGOLI DI ATTACCO / FUGA	8,3°/8°
MTT (MASSA TOTALE TECNICAMENTE AMMISSIBILE)	18.000 kg
CARICO MASSIMO SU ASSE POSTERIORE / ANTERIORE	12.000 / 7.100 kg
VOLUME CAPPELLIERE	2.4 / 2.8 / 3 m^3
VOLUME BAGAGLIAIO	3.3 / 5.4 / 6.2 m^3
MOTORE	Cursor 9 EURO VI / Tector 7 EURO VI
TIPO	6 cilindri in linea, montaggio verticale posteriore, Common Rail
POTENZA MASSIMA	265 kW (360 CV) a 2.200 giri/min / 235 kW (320 CV) a 2.500 giri/min
COPPIA MASSIMA	1.650 Nm a 1.200 giri/min / 1.100 Nm a 1.250 - 1.890 giri/min
CILINDRATA	8,7 / 6,7 litri

CARROZZERIA E ALLESTIMENTO ESTERNO
Trattamento anticorrosione per cataforesi della struttura e della carrozzeria, finitura con rivestimento in resina poliuretanica
Porta anteriore e centrale 800 mm, 1 anta, apertura verso l'esterno
Porte bagagliaio laterale in alluminio
Accesso alle luci anteriori mediante aperture angolari
Specchi retrovisori riscaldati a controllo elettrico
Optional:
- Porta centrale 1.200 mm, 2 ante apertura verso l'esterno, rototraslante o scorrevole
- Predisposizione portasci, predisposizione dispositivo di traino

ALLESTIMENTO INTERNO
Rivestimento pavimento di tipo antiscivolo in PVC
Pareti laterali e padiglione rivestiti con pannelli laminati
Separazioni realizzate con pannelli laminati
4 pulsanti di richiesta "FERMATA"
Sedili passeggeri LINEO fissi
Cappelliere a padiglione
Optional:
- Piattaforma centrale davanti alla porta centrale
- Rampa elettrica per disabili
- Tendine per finestrini laterali
- Frigorifero integrato nella plancia
- Sedili passeggeri LINEO reclinabili, sedili Spacio Line

IMPIANTO ELETTRICO
2 batterie 12V - 225Ah
Alternatori: (C9) 80A + 140A/(T7) 150A + 150A
Protezione elettrica con fusibili nel vano anteriore sinistro
Luci a LED: indicatori di direzione anteriori e posteriori, luci di posizione posteriori, luci di arresto posteriori, luci laterali e luci di ingombro
DRL a LED
Luci interne a LED, luci bagagliaio a LED
Luci anteriori alogene, fendinebbia
Presa da 12V
Sistema di rilevazione incendi
Optional:
- Luci anteriori allo Xenon
- Corner Light (integrate nei fendinebbia)
- Alternatori: (C9) 2x140A
- Luci di emergenza a porte aperte
- Sensori posteriori di parcheggio, telecamera posteriore
- Presa da 24V su plancia

VETRI / CLIMATIZZAZIONE
Vetri oscurati semplici fissi (std), con apertura a Vasistas o scorrevoli (opt)
2 botole a controllo manuale sul padiglione
4 aerotermi per vano passeggeri
Aria condizionata passeggeri 32 kWsenza riscaldamento integrato
Riscaldatore indipendente Webasto Thermo 300
Optional:
- 2 botole a controllo elettrico sul padiglione
- Vetri doppi per finestrini laterali, finestrino autista e porte passeggeri
- Riscaldatore supplementare autista
- Aria condizionata 32 e 38 kW con o senza riscaldamento integrato

POSTO GUIDA
Sedile autista regolabile con sospensione pneumatica, cintura 3 pti
Tendina parasole laterale e anteriore a controllo manuale
Tachigrafo digitale
Vano porta oggetti autista con chiusura a chiave
Optional:
- Sedile autista con sistema di riscaldamento
- Frigorifero autista
- Tendina parasole frontale a controllo elettrico
- Sedile hostess con cintura di sicurezza a 3 punti

MOTORE
Cursor 9 E6 360 CV o Tector 7 E6 320 CV
Sistema di post-trattamento HI-SCR, componenti principali: Catalizzatore di ossidazione diesel (DOC), Filtro antiparticolato diesel (DPF), Riduzione Catalitica Selettiva di NOx con urea (SCR), Catalizzatore Clean Up (CUC)

CAMBIO
C9: cambio meccanico ZF 6S1610 BD / T7: ZF6S1010BO
Optional:
- C9: Voith D864.6, ZF Ecolife 6AP1700, ZF6S1611, ZF12AS1601
- T7: Voith 854.6, ZF Ecolife 6AP1200, ZF6AS1010 con retarder Voith, ZF6S1010 con retarder Voith

PONTE POSTERIORE
Ponte posteriore a riduzione singola ipoidale con quiet ride
Rapporto standard al ponte: (C9) 3,36 / (T7) 5,29

ASSALE ANTERIORE / STERZO
Assale anteriore a ruote indipendenti RI75E
Scatola guida ZF tipo 8098 con servosterzo integrato

SOSPENSIONE
Sospensioni pneumatiche integrali con sensore di autolivellamento
Anteriori: 2 molle pneumatiche combinate / 2 ammortizzatori / 1 sensore di livellamento
Posteriori: 4 molle pneumatiche combinate / 4 ammortizzatori / 1 barra stabilizzatrice / 2 sensori di livellamento
Sollevamento / abbassamento delle sospensioni
Optional:
- Ammortizzatori rinforzati
- Kneeling
- Controllo elettronico delle sospensioni

IMPIANTO PNEUMATICO
Compressore aria bicilindrico da 630 cm^3 (pressione 9,5 bar)
Essiccatore aria integrato: valvole di spurgo sui serbatoi

IMPIANTO FRENANTE
EBS/ESP
Freno di servizio di tipo pneumatico e freno di emergenza con due circuiti aria indipendenti
Dischi freno, anteriori e posteriori, con pinze flottanti e ABS
Freno di stazionamento pneumatico, che agisce sulle ruote posteriori

RALLENTATORE
Freno motore a decompressione (versione Cursor)
Rallentatore elettromagnetico azionato tramite pedale del freno e manettino, rallentatore idraulico integrato nel cambio automatico

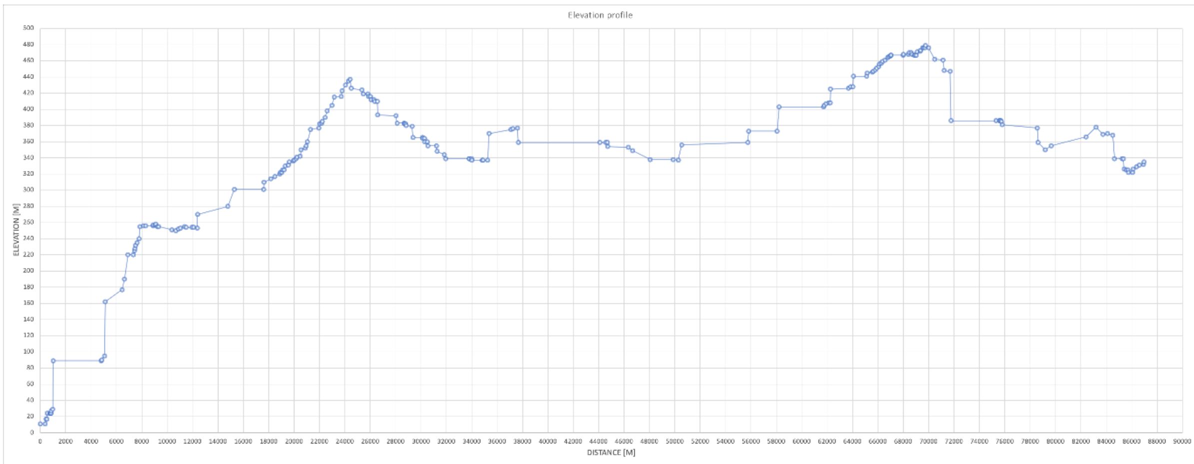
SERBATOIO COMBUSTIBILE
Serbatoio gasolio da 350 litri per Crossway 10,8 m
Serbatoio gasolio da 310 litri per Crossway da 12,1 e 13 m
Serbatoio AdBlue da 80 litri
Optional
- Serbatoio gasolio da 220 litri oppure serbatoio 310+120 litri per 12,1 e 13 m
- Serbatoio gasolio indipendente 35 litri per pre-riscaldatore
- Serbatoio AdBlue da 135 litri

RUOTE E PNEUMATICI
Pneumatici 295/80 R 22,5
Ruota di scorta nello sbalzo anteriore

Iveco Bus opera nell'ottica di una continua evoluzione e si riserva di apportare modifiche al proprio prodotto senza preavviso.

Iveco Bus – Lungo Stura Lazio, 49 – 10156 Torino DTCRL0317

In order to make an adequate comparison, the route was traced as similar as possible to the one taken by the train, passing through the cities of Alberobello, Noci and Santeramo in Colle.



Assuming to travel along state roads, 70km/h on straights and 50 km/h on bends for the extra-urban sections have been chosen as the reference speed, while for those within the city, a speed of 50km/h has been chosen in compliance with the road limits.
The bus takes 86.73 minutes to travel the route while the train takes 74.55 minutes including stops, although the distance travelled by the bus is less than that of the train by 13.1 km.

Total Travel Time [min]	Average Speed [km/h]	Total Travel Distance [km]
86,92	60,26	87,30

Energy consumption per km [kWh/km]	Autonomy left [km]	Total Energy Consumption (fuel+aux) [kWh]
1,41	1316,80	123,25

Total Fuel Consumption [l]	Specific fuel Consumption [km/l]	Specific cost of Energy [€/kWh]
25,60	3,41	0,13

Total Cost of Energy [€]	Carbon Footprint [kg]
16,02	8,73

Diesel Train

The model chosen is Alstom Coradia Lint 54. This type of train has the same features of the hydrogen one. This type of train has the same mechanical characteristics as the hydrogen one. For the comparison, an excel sheet was therefore used to study the performance of a completely dissipative train.

Total Travel Time [min]	Average Speed [km/h]	Total Travel Distance [km]
74,55	80,78	100,37

Energy consumption per km [kWh/km]	Total Energy Consumption (fuel+aux) [kWh]	Total Fuel Consumption [l]
4,92	493,60	83,87

Specific fuel Consumption [km/l]	Specific cost of Energy [€/kWh]	Total Cost of Energy [€]
1,20	0,13	64,17

Impronta di carbonio CO2 [kg]
55,20

Cars

Two different types of cars have been identified for comparison with the hydrogen train:

- Diesel car
- Electric car

The route analyzed is the same of the one run by the bus and the Excel Model gives this results cars:

Diesel Car

Total Travel Time [min]	Average Speed [km/h]	Total Travel Distance [km]
84,98	61,64	87,30

Energy consumption per km [kWh/km]	Autonomy left [km]	Total Energy Consumption (fuel+aux) [kWh]
0,36	1249,25	31,77

Total Fuel Consumption [l]	Specific fuel Consumption [km/l]	Specific cost of Energy [€/kWh]
6,60	13,23	0,13

Total Cost of Energy [€]	Carbon Footprint [kg]
4,13	8,90

Electric Car

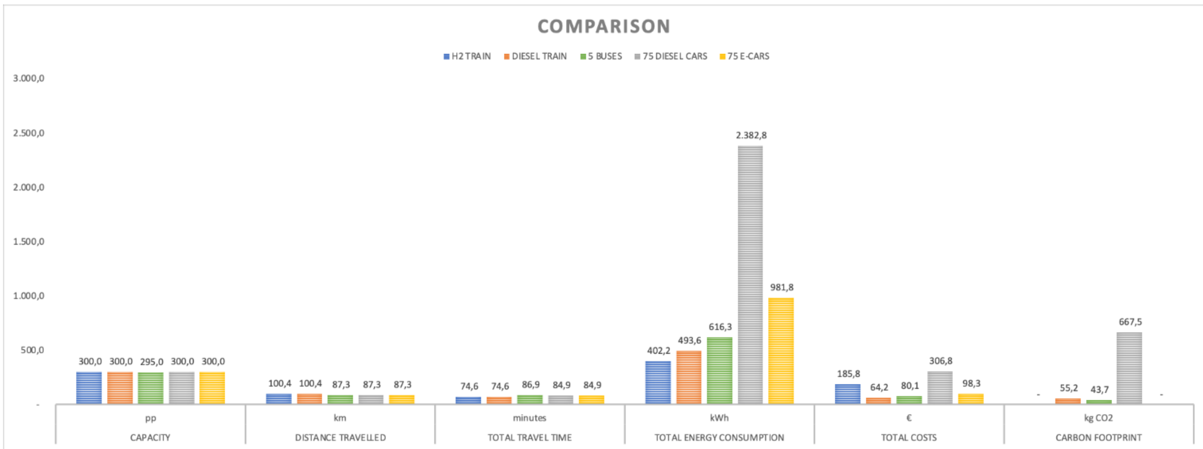
Total Travel Time [min]	Average Speed [km/h]	Total Travel Distance [km]
84,98	61,64	87,30

Energy consumption per km [kWh/km]	Autonomy left [km]	Total Energy Consumption (fuel+aux) [kWh]
0,15	179,37	13,09

Specific cost of Energy [€/kWh]	Total Cost of Energy [€]
0,10	1,31

All comparisons were made analysing these main aspects:

- Distance travelled
- Total travel time
- Total energy consumption
- Total costs
- Carbon footprint



We see a summary diagram that shows how vehicles perform on a one-way trip. To make the comparison more consistent we considered:

1 diesel train

5 buses with 59 passengers each one

75 cars with 4 passengers each one

Each group of these vehicles carries 300 people in total, that is the capacity of the hydrogen train.

- Regarding time and distance it can be notice that trains and automotive vehicle follow two different routes: train route is longer of about 13 km even though this mean of transport can save 10 minutes.

- Regarding energy consumption, diesel cars have the highest consumption: about 6 times bigger than that of Hydrogen train, which represent the best result. However diesel train value is similar to that of Hydrogen solution, while buses and electric cars have much higher values.

- Regarding total costs for transportation it's necessary to distinguish private transportation and public transportation. Cars in general have the higher cost, while Hydrogen Train, in public transportation, is the most expensive choice. This result shows that hydrogen technology has yet to mature and established on the market to become competitive with more traditional technologies.

- For the comparison of Carbon Footprint only local emissions were analysed: the hydrogen and electric choices have no emissions, while diesel bus and Diesel train have a very low carbon footprint compared to the emissions from diesel cars.

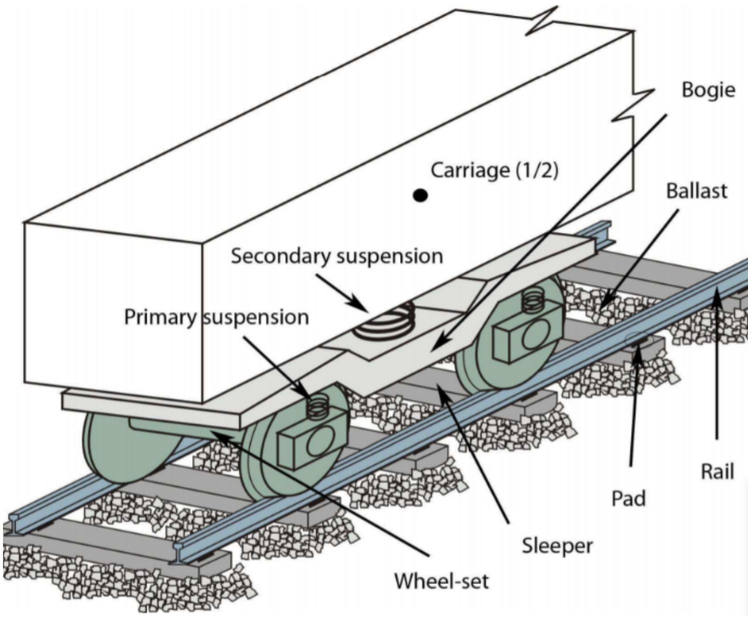
6. Mechanical vibration

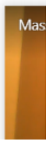
Passenger comfort analysis

This comfort analysis is referred to the entire "above rail" system and so the vibrations that are trasmitted from the track irregularity to the top of the structure, to the body of the passengers.

The analysis starts from the will to find the vertical acceleration on the people placed in the moving railway vehicle starting from input elements like:

- m [kg]= mass, calculated by the ¼ of the total mass of the train (Coradia iLint)
- k_1 [N/m] = primary suspension stiffness coefficient
- k_2 [N/m] = secondary suspension stiffness coefficient
- r_1 [N*s/m] = primary suspension damping coefficient
- r_2 [N*s/m] = secondary suspension damping coefficient
- $\omega_0 = \sqrt{\frac{k}{m}}$ = natural frequency (mainly between 0,8 and 1,2)
- h = $\frac{r}{2*m*\omega}$ = damping ratio
- V [m/s]= vehicle speed

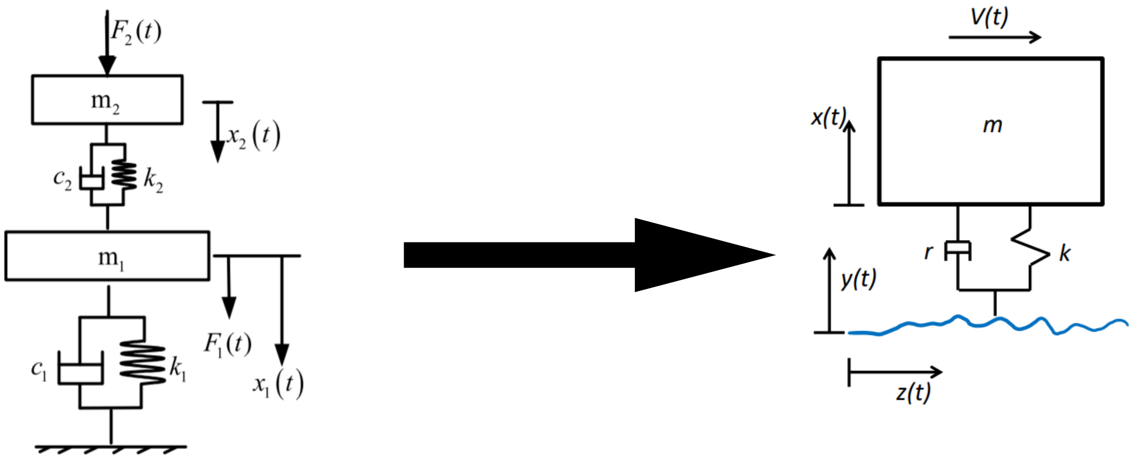




Our train needed a semplification due to its complexity. The image on the left represents the part of the vehicle that has been analyzed.

First of all, the mass is reduced looking only to ¼ of the train so ½ of one of the carriage: m=120000kg/4=30000kg. The purpose of this semplification is to analyze only one bogie and so 4 primary suspension and one top secondary suspension. At first, we tried to sum up the all stiffness/damping coefficient using series/parallel method, but the complexity of this method, and the lack of perfect data (sitffness/damping coefficient are not available and not given by the factory of our train), lead us to using only one k stiffness coefficient (a value that is referred to a suspension of a regional train very similar to our vehicle) and only one damping coefficient.

These changes, are explained and summarized looking at the pictures below:



Data to start the analysis:

M (1/4 train) [kg]	30000
k TOT[N/m]	383094,88
r [N*s/m]	3040
w0	3,5734898
h	0,0141785
V [km/h]	100
V [m/s]	360

Now, calculations have been made on excel program and using as rows the frequencies band numbers (as you can see in the table below) and as columns the various terms that led to the acceleration results.

x (frequency band number)	f [hertz] (1/3 octave)
-17	0,02
-16	0,025198421
-15	0,031748021
-14	0,04
-13	0,050396842
-12	0,063496042
...	...

The calculations starts from finding the columns of $\boldsymbol{\lambda}_k$, Ω_N, "a" and TR.

$$f_k = \frac{V}{\lambda_k} \qquad \Omega_k = \frac{2\pi}{\lambda} V \qquad a = \frac{\Omega}{\omega_0} \qquad TR = \frac{\sqrt{1-(2ha)^2}}{\sqrt{(1-a^2)^2+(2ha)^2}}$$

$$S_{yy} = G_0 \left(\frac{n}{n_0}\right)^{-w}$$

Now on, with the help of Syy (power spectral density Input) (given $G_0=5*10^{-7}$ (power gain, that is tipically between $1*10^{-7}$ and $5*10^{-7}$, that depends on the roughness of the rail and measures the capability to increase the power of the signal from input to output), $n_0=\frac{1}{2}\pi$, cyclic wave number $n = \frac{1}{\lambda}$, w=2 that is the waviness, we can compute the output Sxx with the $S_{xx}(\lambda_k) = S_{yy}(\lambda_k) \cdot TR^2$ formulation:

With the reverse formula of $S_{xx}(\lambda_k) = \frac{x_k^2}{2}\Delta f_k$ you can compute the column of the x_k

that is the single third-octave acceleration RMS.

With this, weighting it with the ponderation filters, you finally can calculate the acceleration on the body with:

$$a_w = \sqrt{\sum_k (W_k x_k)^2}$$

Filters and how they works on the body, are given by the standard: ISO2631-1.

a,wk	a,wd	a,wf
0,08902615	0,18194896	0,5101439

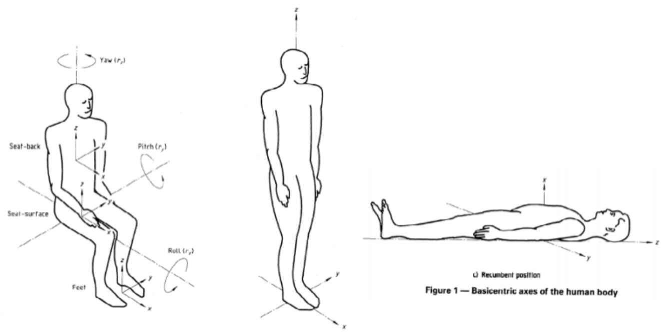


Figure 1 — Basicentric axes of the human body

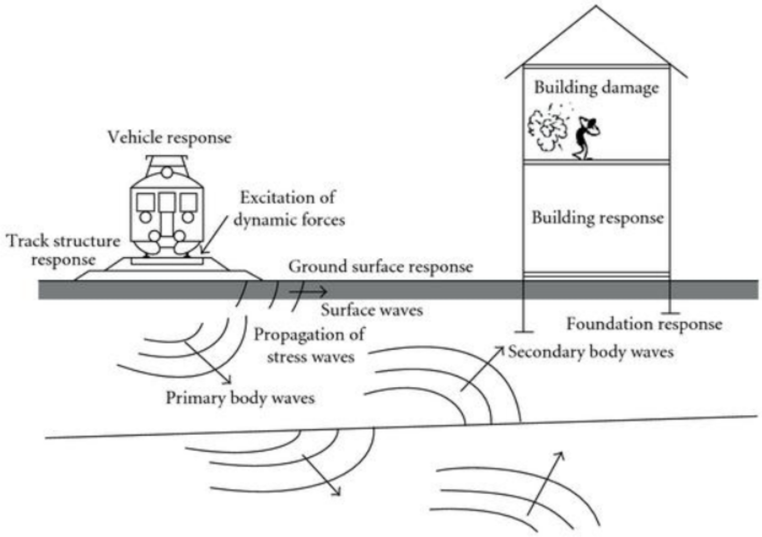
(Wk—Weighting for vertical whole-body vibration, z–axis seated, standing or recumbent person, based on ISO 2631-1
Wd—Weighting for horizontal whole-body vibration, x– or y–axis, seated, standing or recumbent person, based on ISO 2631-1.
Wf—Weighting for vertical whole-body vibration, z–axis motion sickness, seated or standing person, based on ISO 2631-1.)
The 3 accelerations must be evaluated on the table below in order to reach a value that is good for a comfortable travel standing on the vehicle:

Less than 0,315 m/s^2:	not uncomfortable
0,315 m/s^2 to 0,63 m/s^2:	a little uncomfortable
0,5 m/s^2 to 1 m/s^2:	fairly uncomfortable
0,8 m/s^2 to 1,6 m/s^2:	uncomfortable
1,25 m/s^2 to 2,5 m/s^2:	very uncomfortable
Greater than 2 m/s^2:	extremely uncomfortable

Our vehicle, is considered one of the most comfortable train available on the market now, and this analysis (without having exact data, but only approximating it) can show this efficiency in suspensions.

Propagation of vibrations on surrounding environment

In general, vibrations are one of first topic to think about when you're dealing with a train. Noise and the previously explained comfort, depends on the value and importance of the vibrations. The passage of a train can stress the entire railway infrastructure as much as the structures and buildings located adjacent to it.



Vibrations are propagated by the vehicle that runs on the tracks, the transferred to the ground, and consequently to the buildings. They propagates in the ground as volume waves and as waves of surface. Generally, in their path to the receptor, are attenuated by diffusion geometric and by dissipation of energy in the ground.

Since we have also a part of the path in a tunnel, for this section, the presence of the infrastructural work determines a reduction in the load of vibration trasmitted to the ground both for a greater distribution of loads along the route and, above all, due to the presence of the mass of the same work. Also the trasmission of vibration it occurs almost exclusively for body waves that propagate along cylindrical fronts. It follows that in these sections the reduction of the energy introduced by the transit of the railway train is to be attributed both with geometric diffusion and dissipation in the ground. Meanwhile for the viaduct sections there is a reduction in the amount of dynamic loads trasmitted to the soil from the foundations in realtion to the filter effect associated with the first natural frequencies of the eck which are extremely small. In this case it should be considered that, since the entry of vibrations in the geound occurs via the foundation plinths, the type of source is no longer from consider linear but point-like.

All the vibrations depend on several factors:

- Stiffness of the primary suspension
- Condition of alteration of the wheels and rails (corrugation)
- Train speed
- Infrastructure itself (ballast, …)

- Building characteristics (age, materials, …)
- Soil

For what regards the standards, we'll take into account UNI 9614, UNI 9916 and DIN 4150-3 that are the best in this analysis. These standards care about vibrations measurements and distrubance in general to the buildings.

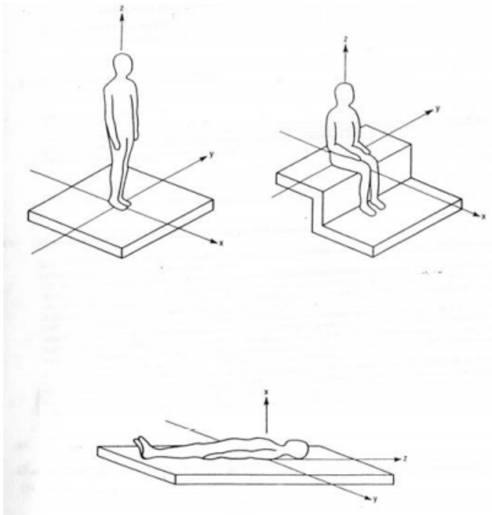
The standards explain how to measure and evaluate the values with limits. Using the root-mean-square of the frequency weighted acceleration you can measure vibrations to the receptor defining the istantaneous value of acceleration suffered by the material-point (a_w).

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w(t)^2\,dt}$$

The a_w function depends on the acceleration during time using the filters explained in the table:

Frequenza (Hz)	Asse z dB	Assi x – y dB	Postura non nota dB
1	6	0	0
1.25	5	0	0
1.6	4	0	0
2	3	0	0
2.5	2	2	0.5
3.15	1	4	1
4	0	6	1.5
5	0	8	2
6.3	0	10	2.5
8	0	12	3
10	2	14	5
12.5	4	16	7
16	6	18	9
20	8	20	11
25	10	22	13
31.5	12	24	15
40	14	26	17
50	16	28	19
63	18	30	21
80	20	32	23

Tabella 2: Attenuazione dei filtri di ponderazione UNI 9614



Filters take into account that the human sensibility to the vibrations depend on the frequency. Furthermore, human sensibility depends also to the propagation direction of the flow, so filters are divided in the x-y / z axis.

As for the threshold values of the freq-weig overall accelerations to do reference (in the case of vibrations of a constant level), the tables are considered separately for x-y / z axis:

Destinazione d'uso	Accelerazione	
	m/s^2	dB
Aree critiche	$5{,}0 \; 10^{-3}$	74
Abitazioni notte	$7{,}0 \; 10^{-3}$	77
Abitazioni giorno	$10{,}0 \; 10^{-3}$	80
Uffici	$20{,}0 \; 10^{-3}$	86
Fabbriche	$40{,}0 \; 10^{-3}$	92

Tabella 3: **Valori e livelli limite delle accelerazioni complessive ponderate in frequenza validi per l'asse z (Prospetto II – UNI 9614)**

Destinazione d'uso	Accelerazione	
	m/s^2	dB
Aree critiche	$3{,}6 \; 10^{-3}$	71
Abitazioni notte	$5{,}0 \; 10^{-3}$	74
Abitazioni giorno	$7{,}0 \; 10^{-3}$	77
Uffici	$14{,}4 \; 10^{-3}$	83
Fabbriche	$28{,}8 \; 10^{-3}$	89

Tabella 4: **Valori e livelli limite delle accelerazioni complessive ponderate in frequenza validi per gli assi x e y (Prospetto III – UNI 9614)**

Vibratory phenomena that are crossing these limits, could be considered objectively disturbing for the person.

Changing to the buildings analysis, these can be damaged by the virbations and the UNI 9916 regulate the standards.

Since our path is passing nearby critical aged buildings (entering cities of Alberobello and Matera) the analysis must be optimal. The standard explain how to deal with structural response of the buildings and evaluate effects of the vibrations. (frequency analized will be in the range 0.1-150 Hz)

The table resume values of the oscillating velocity for the evaluation of the vibration transients of the buildings, where the third row is our focus since we are dealing with "monuments and buildings with particular sensibility to vibrations":

Riga	**Tipi di edificio**	**Valori di riferimento per velocità di oscillazione in mm/s**			
		Fondazioni frequenze			**Ultimo solaio, orizzontale**
		da 1 a 10 Hz	**da 10 a 50 Hz**	**da 50 a 100 Hz ***	**Tutte le frequenze**
1	*Costruzioni per attività commerciale, costruzioni industriali e costruzioni con strutture similari*	*20*	*da 20 a 40*	*da 40 a 50*	*40*
2	*Edifici abitativi o edifici simili per costruzione o utilizzo*	*5*	*da 5 a 15*	*da 15 a 20*	*15*
3	*Edifici che per la loro particolare sensibilità alle vibrazioni non rientrano nelle precedenti classificazioni e che sono da tutelare in modo particolare (monumenti sotto la protezione delle belle arti*	*3*	*da 3 a 8*	*Da 8 a 10*	*8*
(*) Per frequenze superiori ai 100 Hz possono essere adottati come minimo i valori per 100 Hz					

Tabella 5 Valori di riferimento per la velocità d'oscillazione Vi per la valutazione degli effetti di vibrazioni transienti sulle costruzioni

Furthermore, if the case is the one to not have even minor damages in the costructions placed in the third row (in our case the Sassi of Matera), the reference values must be lowered.

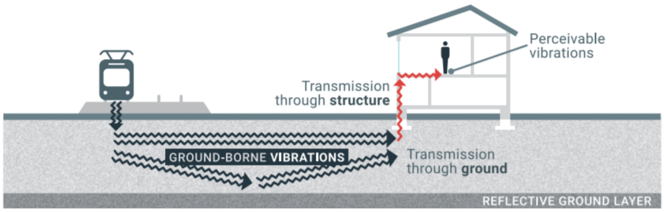
<u>In terms of acoustic annoyance</u> due to the vibrations of the buildings (re-radiated noise), standards refers to equivalent continuous sound pressure levels weighted according to the "A curve". (A-weighted decibels, or "dBA," are often used when describing sound level recommendations for healthy listening. While the dB scale is based only on sound intensity, the dBA scale is based on intensity and on how the human ear responds. Because of this, dBA gives us a better idea of when sound can damage your hearing) Where: values of reference acoustic pressure depends on ISO 1683 and it's equal to 20µPa (p_o). The legislation takes into account 2 time bands that

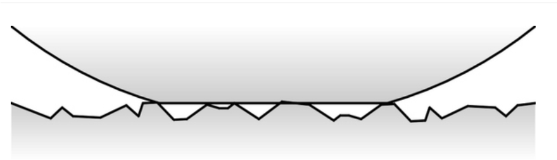
$$L_{A,eq,T} = 10 \times \log\left[\frac{1}{T_2 - T_1} \times \int_{T_1}^{T_2} \left(\frac{p_A(t)}{p_o}\right)^2 \times dt\right]$$

LA,eq = 35 dBA notturno per ospedali, case di cura e case di riposo
LA,eq = 40 dBA notturno per tutti gli altri ricettori
LA,eq = 45 dBA diurno per le scuole

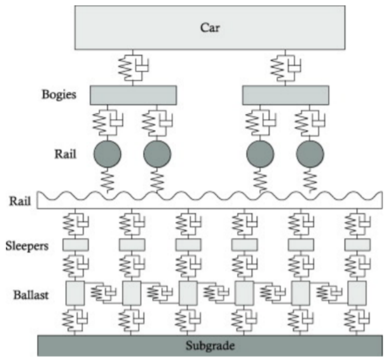
are divided into 16 hours from 6a.m. to 22p.m. that are the light hours and 8 dark hours from 22p.m. to 6a.m and dB limits concercing the different buildings are exposed:

Vibrations that are analized in this section are the Ground-Borne ones:

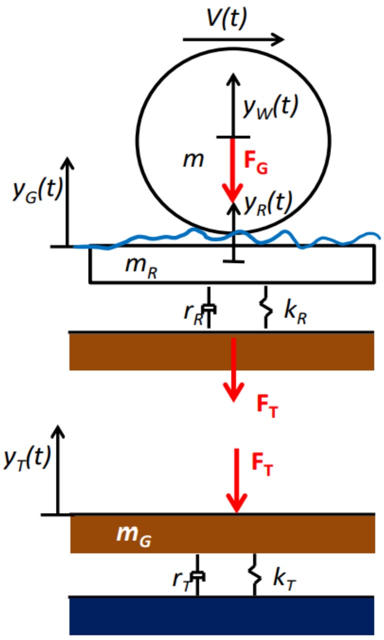




These are trasmitted from the railway vehicle to the rails, continuing to the ballast and so the ground, to finally to the buildings placed nearby the infrastructure. All the components involved are the bogie and the springs/dampers, and their movement depends obviously on the mass of the vehicle. Since the surfaces of the wheel/rail are not perfectly flat but they have peaks and a certain roughness, there is a vertical movement of the various elements. The gound is not stiff and so it moves vertically and so it takes into account the values of stiffness/damping of the sleepers and ballast.



This scheme above represents the whole structurs of elements and springs/dampers involved in a general infrastructure. Notice how the combinations of the values of stiffness and damping can generate different results.



In our case we analized a semplified version of this, including the wheel (mass=m), the irregularity of the track and so the rail (mass= m_R), the sping/damper of the rail (r_R and k_R), leading to the ground (mass= m_G) with the stiffness/damping coefficient given by the terrain (r_T and k_T).

Forces involved are the F_G and the F_T that are:

- F_G=inertial force acting on the wheel
- F_T=force trasmitted through the rail-pad

Furthermore, y_G represents the track irregularity, y_W the wheel center displacedby the rail irregularity, y_R the rail displacement, y_T movement of the terrain/ground (all these are vertically placed and so they act on the y axis, since we are evaluating only 1 grade of freedom).

Calculations starts from the same data of the previous vibrations evaluation. Assuming a f natural frequency as 25Hz, we can find the ω_0=2*3,14*f, and so the portion of the mass analyzed below the vehicle as m=644926 kg. Starting from that, calulation of yG, so yK, and then Fg, TRg, Ft, Trt, yT, aT and finally acceleration to the terrain. From the building side, we can calculate Syy (terrain) and with TRh you can find Syy (h), yHk (buildings). Finally the results of acceleration as the previous analysis with a,wk, a,wd, awf.

<u>This noise (ground-borne noise)</u> is caused by vibrations in frequencies usually in the range of 40–80 Hz, because of the resonance of the building constructions in the tunnel vicinity.

It becomes perceptible as a low-level muffled noise (rumble). Given that the minimum typical limit of the human acoustic capacity is about 20 Hz, vibrations under this frequency become perceptible by the residents of the buildings as vibrations (ground-borne vibrations), while over this frequency they become perceptible both as vibrations and as sound.

Vibrations are primarily expressed in the form of velocity or acceleration. They can, however, be expressed also in the form of noise levels, in dB.

Ground-borne noise and vibrations are caused essentially during train movement at constant speed and acceleration.

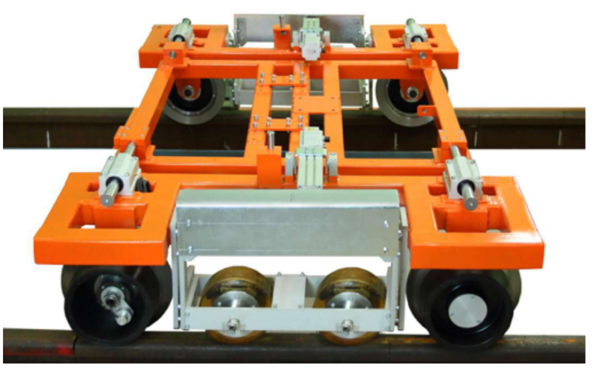
7. Inspection, maintenance, diagnostics

Inspection techniques

Since the Coradia iLint does not need to collect power through contact with an overhead line, the inspection, monitoring, maintenance and diagnostics operations will strictly refer to the vehicle and the track.
As for the inspection, several techniques and devices are used to detect irregularities on track that affects the safety and reliability of railway operations. Here some of those are shown.

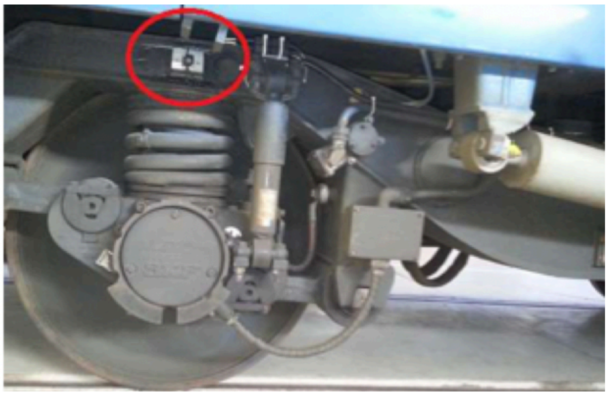
- Ultrasonic Rail Inspection:

A beam of ultrasonic energy generated by a piezoelectric element is transmitted into the rail; the reflected or scattered energy of the transmitted beam is then detected using a collection of transducers.
The reflection of the beam indicates the presence of a structural singularity of the volume of the body we are inspecting.
The type of defects that can be detected: internal defects, web and foot defects, surface defects, defective wheels and bearings, rail wear.
However, this inspection can miss defects at high speed and can miss defects smaller than 4 mm and it is unusable in situations where the surface of rail heads is extremely damaged or extensively worn.

- Accelerometers:

An accelerometer is an electromechanical sensor designed to measure vertical and horizontal acceleration signals derived from vibrational forces in mechanical variables. In railways, these vibration forces can result from the presence of defective wheels, rail wear, damaged switches or track geometry irregularities. By applying a series of mathematical computations, rail defects and track irregularities can be measured from acceleration data. Accelerometers have been used in different railways inspection devices such as wayside detectors, TRV, CMS, axle box measurement, and they have been embedded in smartphones as well. Compared to other sensors, accelerometer sensors can provide more inspection points in a certain length of a track. Furthermore, recently accelerometers have been used for measuring ride comfort in public transportation fleets.

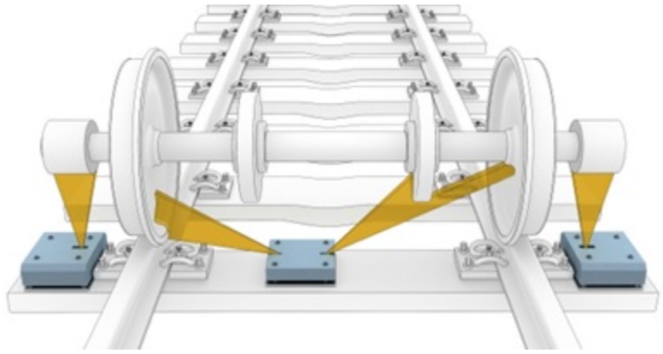


-<u>Hot bearing detectors</u>:

Hot boxes or hot bearing detectors are used to measure the temperature of the journal bearings of a train. They typically consist of two infrared eyes on each side of the tracks looking up at the train's bearings.
They register the radiation from every journal bearing that passes over them. If a bearing reaches the maximum temperature for safe travel, the detector will flag and count it as a defect.

-<u>Acoustic bearing detectors</u>:

Acoustic Bearing Detectors (ABDs) are employed to record the characteristics and quality of the sound made by bearings as the train moves. These detectors are based on the principle that wheel bearings produce noise and excessive vibration when they start to fail. Various measurement techniques, such as sound intensity, sound pressure and AE, can be employed by these detectors. Compared with hot axle bearing detectors, this type of detector is more developed as it is highly sensitive and is able to predict failed bearings in advance. Recent ABDs can detect more than one-third of hot bearing failures.



-<u>Brake Pad Measurement System</u>:

The Brake Pad Measurement System (BPMS) is a type of non-contact detector which functions based on digital images from cameras and machine vision technology. The purpose of this detector is to calculate the thickness of brake pads and identify problems related to brake pads, such as wear rates, uneven wear and missing brake pads. In this type of detector, high-speed digital cameras are installed beneath the track to inspect the condition of the brake pads and provide precise profiles of the components.

Maintenance operations

Planned maintenance

-<u>Vegetation control</u>:
The control of the vegetation can be carried out with a weed-killing train, in order not to grow shrubs that could pollute the embankment; or it can be done with mechanical trimming, to clean the embankment or the trench. And finally, trees that could interfere with the railway line are cutted.

-Tamping:

To make the tracks more durable, a tamping machine or ballast tamper is used to pack (or tamp) the track ballast under railway tracks. Prior to the introduction of mechanical tampers, this task was done by manual labour with the help of beaters. As well as being faster, more accurate, more efficient and less labour-intensive, tamping machines are essential for the use of concrete sleepers since they are too heavy (usually over 250 kg) to be lifted by hand. Whilst also available as a plain tamper with no lifting or lining function this article will focus on the multi function machines.

Early machines only lifted the track and packed the ballast. More modern machines, sometimes known as a tamper-liner or tamping and lining machine, also correct the alignment of the rails to make them parallel and level, in order to achieve a more comfortable ride for passengers and freight and to reduce the mechanical strain applied to the rails by passing trains. This is done by finding places where the sleepers have sunk from the weight of the passing trains or frost action, causing the track to sag. The tamper lifts each sleeper and the rails up, and packs ballast underneath. When the sleeper is laid down again, the sagged rails now sit at the proper level. In cases where frost action has caused adjacent rails to rise higher, ballast tampers can raise rails above their original level to make the line level again. "Lining" rails doesn't involve ballast tamping, it merely ensures the rails are perfectly parallel and straight as possible. Combining tamping and lining into a single machine saves time and money, as only one machine needs to be run over the track to perform both functions.

The tamping process from any type of tamper consists of the following basic steps:

1. Lifting, lining unit moves rail and sleepers under tamping unit into correct vertical and horizontal position
2. Tamping units drive vibrating tines (35 Hz optimum) into the ballast on both sides of the sleeper until squeezing depth is achieved
3. Vibrating tines are pushed together to pack ballast under lifted, lined sleeper to ensure it holds position when released by the lifting, lining unit
4. Tamping unit retracts to rest position slightly above railhead, track is released by lifting, lining unit
5. Machine moves to the next sleeper and begins a new cycle

-Leveling and alignment:
Leveling is the set of operations that allows to re-establish the correct elevation position of the track. Alignment, on the other hand, consists in bringing the track to its correct planimetric position. For both operations, if the machine detects defects, both planimetric and altimetric, it corrects the section that does not respect the set values, returning the track to its correct planimetric and altimetric configuration.
This procedure is also done by the tamping machine.

-Ballast profiling:
The lateral profiling of the ballast is carried out to bring the ballast back to its design condition, in particular as regards the lateral slopes (generally equal to ¾). Thanks to lateral, frontal and leveling plowshares, they move piles of rubble with the aim of filling the track inside and out. After arranging the ballast, the machine brushes, to remove any crushed stone left over the rails. In case of need, the profiling machine can be followed by a refueling wagon of the crushed stone to integrate it if needed in specific areas of the track.

Extraordinary maintenance

-Rehabilitation of the ballast:
The rehabilitation is the operation that allows to restore the efficiency of the degraded embankment. The operations are carried out by removing the existing ballast, through chain members, and then the new ballast is formed. The crushed stone removed is screened by means of special screens on the machine and, if still suitable, it is reused for the formation of the new ballast, otherwise it is completely replaced with new crushed stone. The last 10 cm layer of crushed stone in contact with the crossbars should preferably consist of new crushed stone.
The rehabilitation operation is carried out with special machines, called rehabilitation machines, which allow the work to be carried out in an automated way and act without removing the rails and sleepers, lifting them in the affected section.

-Track renewal:
Track renewal consists of removing and replacing the ballast, sleepers and rails. The machine, proceeding on the line to be renewed, disassembles the attachment parts (which connect the rails with the sleepers), removes the rails and sleepers through fully automated operations, and then replaces all the removed elements.
Sleepers and rails are generally replaced with new elements, while the crushed stone, as in the case of the rehabilitation machine, is screened and, if suitable, is reused.

Hydrogen Maintenance and Safety Concerns

Hydrogen technology is critical, under certain points of view, because it creates a set of safety and maintenance concerns that has to be highly considered when designing a train line like this one.

For what concerns production, highly pure water is needed to fuel the electrolysis process to avoiding electrode corrosion. This can lead to impure hydrogen output. A potential solution to this matter could be the combination of the hydrogen production plant with a de-salinization plant: costs may significantly rise, but the supply of pure distilled water would be always available.

For what concerns stocking and distribution, hydrogen is a gas with a very low volumetric energetic density (compared to other traditional fuels, like methane), so it requires to be either compressed or frozen to be effectively used by the train. Compression has to reach levels of 700 to 800 bars, which is energy intensive and can also create safety issues. Compression cycles can lead to wear, fatigue and eventually failures of components. To make the mater "worse" hydrogen tends to accelerate the corrosion of materials. A plausible solution could be to adopt cryogenic hydrogen, which is safer stock and distribute, and can also reach higher values of volumetric energy density.

For what concerns safety, hydrogen is a hazardous material to handle: it is highly reactive, it has a low flashing point, it has no odor and its flame is almost invisible. This can cause the impossibility to detect a possible tank leak, also given the fact that traditional odorizing agents (like the ones used for kerosine and other fossil fuels) cannot be mixed with hydrogen, because they would freeze solid and become useless and even dangerous for the fuel cell functioning. So, a big focus has to be put on safety, especially in the production plants where there would be the highest concentration of the gas. Alarms, protection and mitigation measures have to be implemented to minimize risk.

FONTI

https://uic.org/IMG/pdf/uic-railway-induced-vibration-report-2017.pdf

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