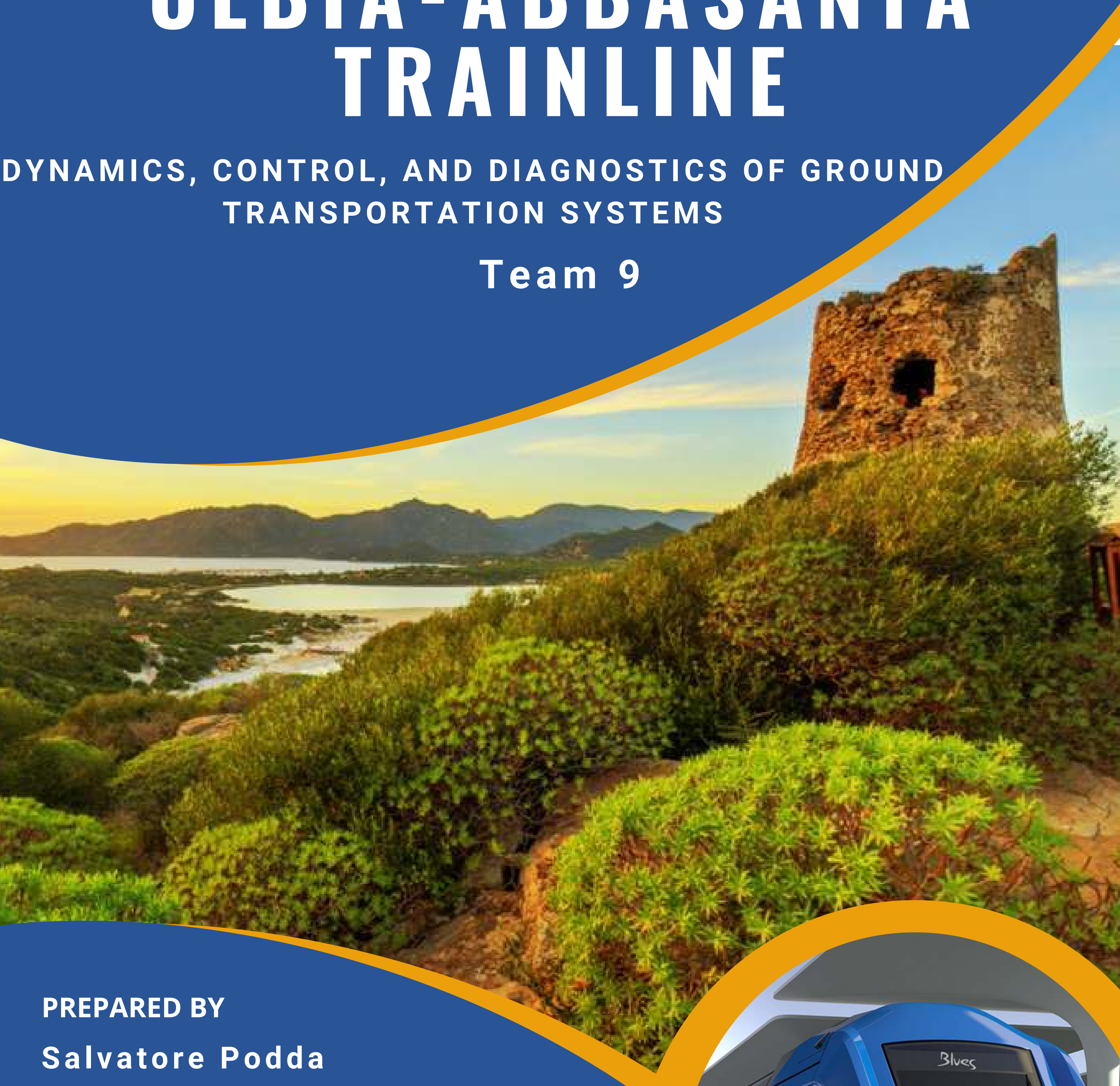
POLITECNICO
MILANO 1863

OLBIA-ABBASANTA TRAINLINE

DYNAMICS, CONTROL, AND DIAGNOSTICS OF GROUND TRANSPORTATION SYSTEMS

Team 9



PREPARED BY

Salvatore Podda
Leonardo Nava
Giovanni Zanotto
Luca Sforzin
Amirhassan Darvishzade

INDEX

Abstract

This technical report examines the proposal for a new railway line connecting Olbia to Abbasanta in Sardinia. This infrastructure aims to significantly enhance regional mobility by providing a direct link between the northeastern coast and the central part of the island. The area affected by the new railway line includes different populations, from the urban areas of Olbia, a major tourist and commercial center, to the rural areas of Nuoro.

The construction of this new railway line offers numerous benefits. Foremost is the reduction in travel times between the two cities, thereby promoting economic and social integration across different parts of Sardinia. Additionally, the new infrastructure will help alleviate road congestion, reducing the environmental impact of road traffic and promoting a more sustainable public transport system. The railway line will also open new opportunities for tourism by facilitating access to historical and natural attractions along the route.

Economically, the construction of the new railway line will create jobs during the building phase and subsequently contribute to the economic development of the areas involved by encouraging investment and commercial activities. Furthermore, the improvement of the public transport network will strengthen the social fabric, enhancing the quality of life for residents.

This technical report provides a detailed exploration of several critical aspects of the project, including analysis of train vibrations, passenger comfort, environmental impacts, diagnostics, and maintenance. These comprehensive studies highlight how the new Olbia-Abbasanta railway line represents a significant step toward a future of sustainable mobility and balanced development for Sardinia.

Introduction

In response to the urgent need for efficient and eco-friendly transportation solutions in Sardinia, we are proud to present the Olbia-Abbasanta Trainline project. This initiative marks a significant shift from conventional transportation methods, such as buses, to a more sustainable and accessible mode of travel across the region.

At the heart of the Trainline is our commitment to environmental stewardship. By replacing existing bus services with a modern train line, we aim to significantly reduce greenhouse gas emissions and ease road congestion, particularly during tourist seasons. This project will mitigate the strain on Sardinia's challenging and often hazardous roads, offering travelers a safer and more reliable alternative.

The benefits of this new railway extend beyond environmental impact. Train travel presents a more affordable option compared to private car ownership or rental, eliminating costs associated with fuel, parking, and maintenance. This cost-effectiveness is especially appealing to visitors, making the train line a smart choice for both locals and tourists.

Economically, the Olbia-Abbasanta Trainline is set to be a catalyst for regional growth and development. By enhancing connectivity between key locations such as Olbia Airport and Nuoro, the train line will facilitate trade, boost tourism, and stimulate business activities. The reliable and efficient transportation it provides will attract more tourists, leading to increased spending on local accommodations, dining, and attractions. This surge in tourism revenue is essential for strengthening local economies and promoting sustainable development.

We acknowledge the unique challenges of this ambitious project, including Sardinia's low population density and seasonal travel fluctuations. Nevertheless, we are dedicated to overcoming these obstacles to deliver a transportation solution that meets the region's needs.

In summary, our proposal represents a visionary step towards addressing Sardinia's transportation challenges. By prioritizing sustainability, affordability, and enhanced connectivity, we are paving the way for a brighter, more prosperous future for the island and its residents.

1-STATE OF ART

Aware of the beauty and magnificence of the east coast of Sardinia, and considering the lack of a train line here, we highly believe proposing a new train line will enhance the quality of life of residents and passengers.

Currently, the existing train lines in Sardinia include key stops such as Cagliari, Oristano, Sassari and Olbia. By proposing a new line from Olbia to Abbasanta, and from there the railway interchange with Cagliari-Sassari line, this plan aims to enhance accessibility and provide a vital link between the northeastern, central, and southern parts of the island, improving transportation options for residents and tourists alike.

1.1 Preliminary Analysis

The Sardinian Island system is divided between coastal areas with high daily traffic and inland areas with low service centralization. Combined with significant economic disparity between these areas, this results in demographic shrinkage and, more importantly, population aging, leading to alarming depopulation estimates for many villages.

For these reasons, it is essential to focus on improving public transportation across the island's areas. A considerable part of Sardinia's population commutes daily from their towns of residence to the island's most developed cities, predominantly using private automobiles for employment, education, or other purposes. Unlike residents of the island's main centers, which are supplied with all necessary services, those in smaller towns are forced to travel daily, incurring extra time and financial costs.

These locations, particularly those along the coasts, are popular for daily commuting because they provide superior services that attract residents of nearby towns for work, secondary education, or healthcare. Additionally, during the summer, these coastal areas become major tourist destinations.

Tourist demand in Sardinia is disproportionately centered along the coast, neglecting the potential of the interior regions. This has a significant impact on the transport sector, as over 92% of tourists travel by private car due to shortcomings in public transport infrastructure and organization.

A broader vision of the territory is therefore needed, aiming to integrate vocational and structural diversities to contribute to the development of weaker areas through a rational organization of infrastructures.

Tourists can reach the Costa Smeralda through various modes of transportation, primarily via the Olbia-Costa Smeralda Airport, from where they can rent cars, take taxis, or use bus services to the coastal towns. Other airports include Cagliari-Elmas, Alghero-Fertilia, and Tortolì-Arbatax. Additionally, ferries to Porto Torres and Olbia connect Sardinia with mainland Italy and other islands. Many tourists opt to rent cars to explore the region independently.

However, there are several mobility issues. Traffic congestion is common during summer weekends and holidays. Public transportation availability can be limited, especially between smaller towns and beaches. The high costs associated with this luxury destination affect transportation, accommodation, and tourist activities. Moreover, maritime connections are reduced in the winter months due to decreased tourism. Tourists should consider these logistical challenges and costs when planning their visit to the Costa Smeralda.

The purpose is to implement a physical structure of the road network and functional services to ensure accessibility to various regions, at least during the main daily rush hours.

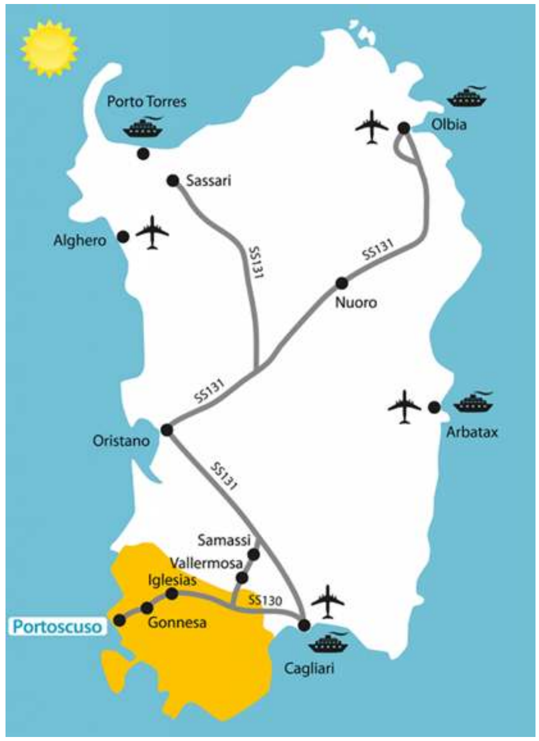


Figure 1.1: Sardinian main roads and network nodes

1.2 Current service analysis

This section focuses on the analysis of local public transport services from the perspective of their usage level and user satisfaction. The data used in the analysis were obtained from the territorial indicators for development policies by Istat.

Figure 1.2 shows the trend of the indicator related to the use of public transport by commuter users for the period 2012-2021. The public transport means considered are: trains, trams, buses, coaches, and intercity buses. The reference population includes employed individuals over 15 years old and students up to 34 years old who left their homes to go to work, university, school, or kindergarten.

Between 2012 and 2021, the percentage of commuters using public transport in Sardinia showed an overall increasing trend until 2017, then decreased in the following years, reaching its lowest point in 2021. In the last year, 12.6% of the reference population used public transport in Sardinia, a value lower than both the Mezzogiorno (13%) and the Centro-Nord (15.9%).

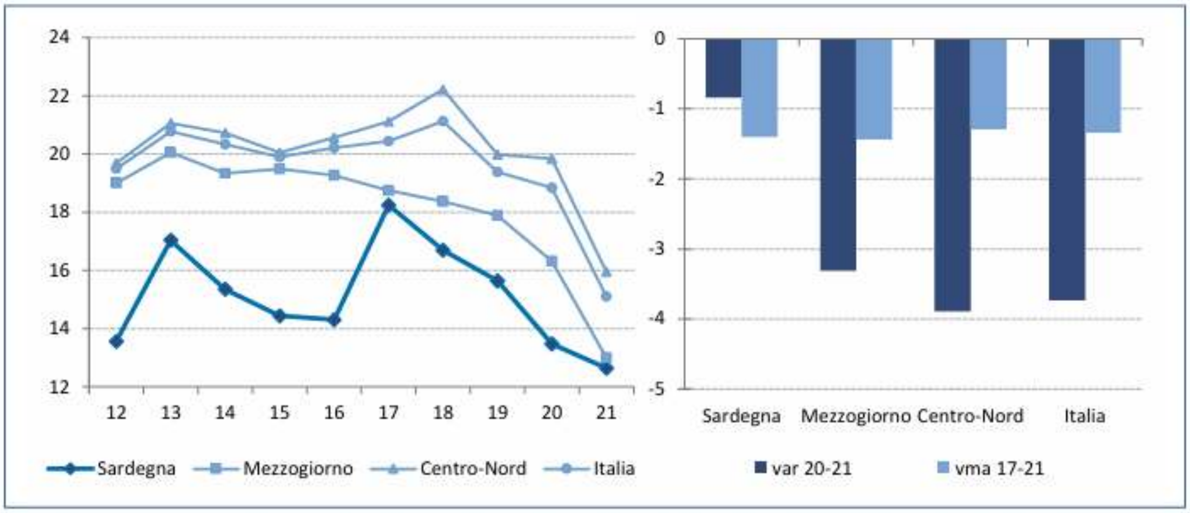


Figure 1.2: Use of Local Public Transport (%)

Figure 1.3 shows data related to the railway transport usage index, calculated as the percentage of individuals over 14 years old who used the train at least once during the year between 2012 and 2021.

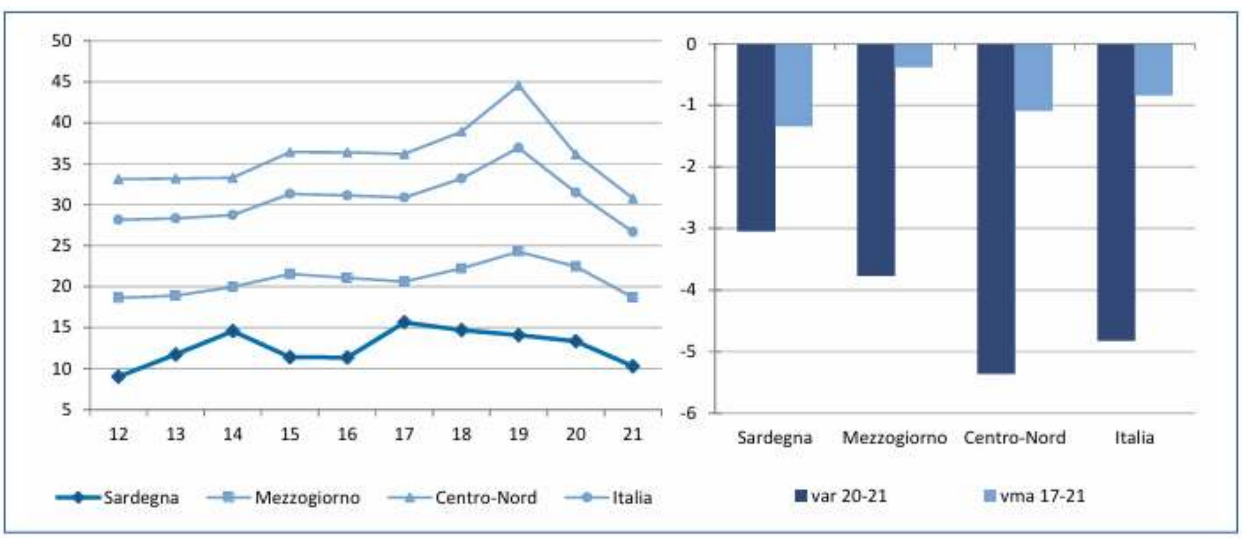


Figure 1.3

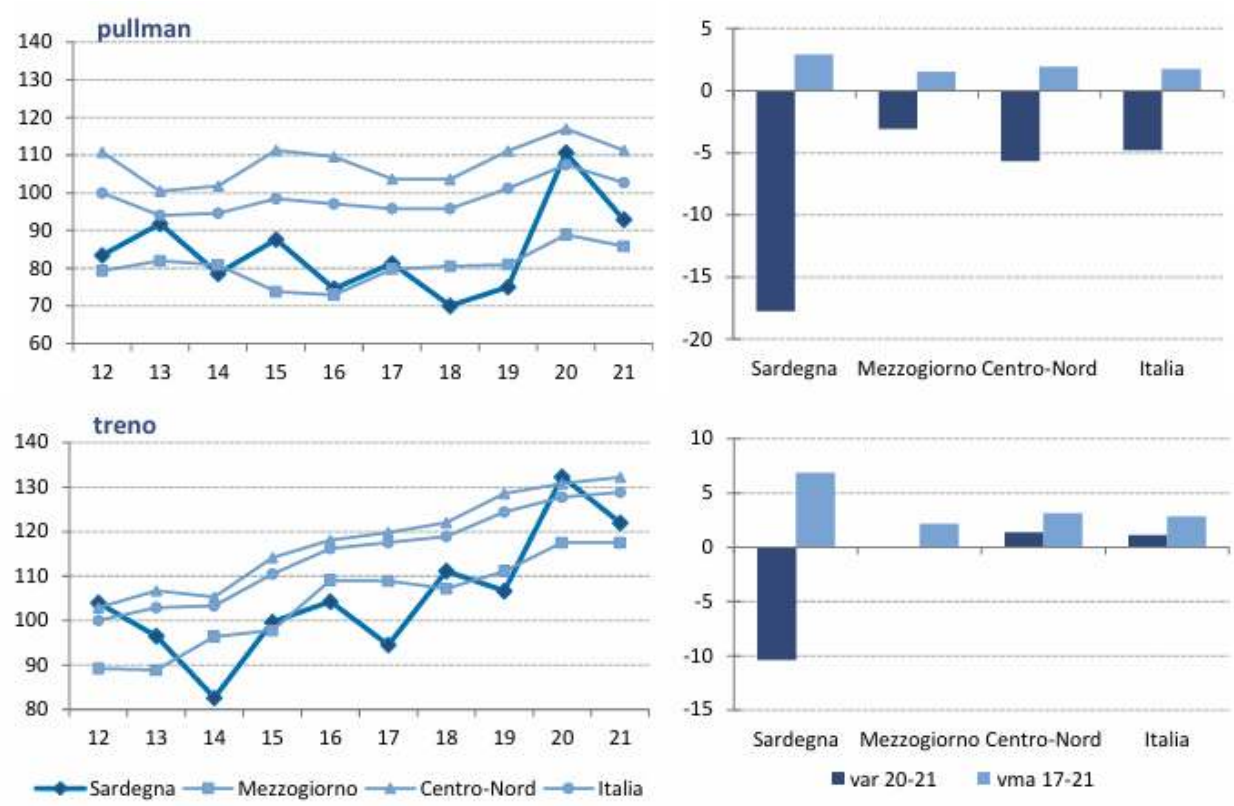
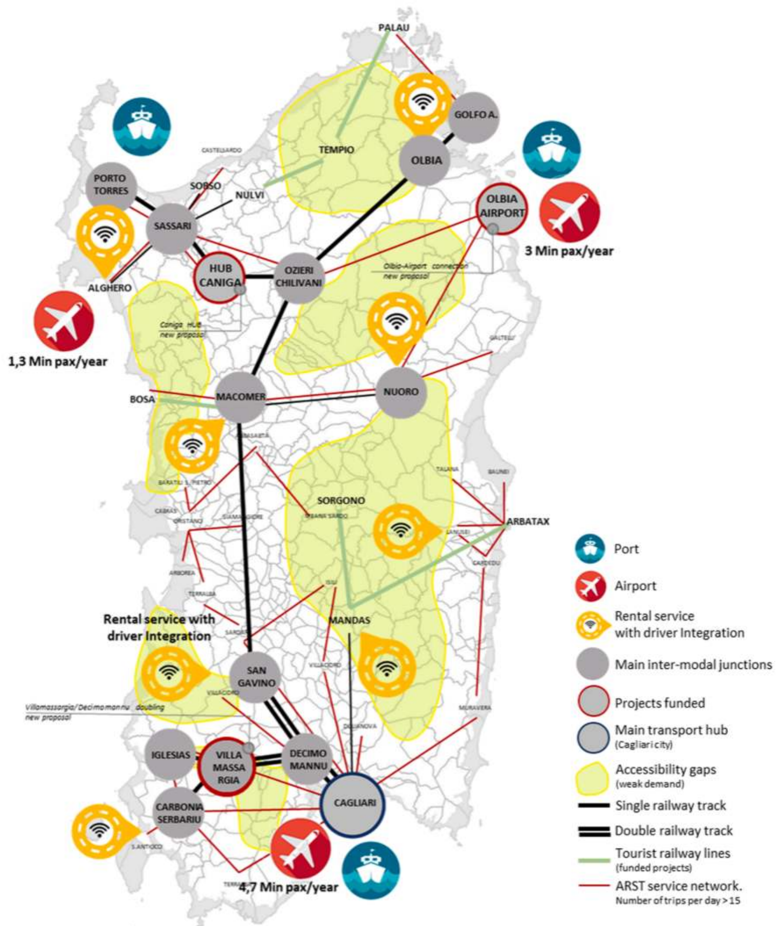


Figure 1.4: Public Transport Services User Satisfaction Index

Figure 1.4 shows data related to user satisfaction with transportation services between 2012 and 2021. Specifically, satisfaction levels were calculated from the Istat Multiscopo survey on aspects of daily life for families, focusing on two types of public transportation: trains and buses. The available data includes the number of users and the number of people who are fairly or very satisfied with various indicators.

The graph highlights the almost parallel trend between the series for Central-Northern Italy and the overall Italian series. This parallelism is because 76% of train users in Italy are concentrated in the Central-Northern regions. When compared to the railway transport usage index, this element underscores the national disparity in service provision between the Central-Northern regions and the Southern regions.

This is one of the reasons why we chose to analyze the Sardinian scenario.



[Accessibility and Public Transport Mobility]

One could be traffic congestion. During the summer months, especially on weekends and holidays, roads along the coast can become very congested, causing delays and inconvenience. Furthermore, transport availability, if not traveling with your own car, it can be challenging to find availability on public transportation, especially for travel between smaller towns and beaches. Also, high costs could be a problem, this area is known as a luxury tourist destination, which can be reflected in the high costs of transportation, accommodation, and tourist activities. Finally, some transportation services, particularly maritime connections, may be limited during the winter months when tourism is less frequent. In any case, while the Smeralda coast is one of the most beautiful and exclusive destinations in Sardinia, tourists should consider the logistical challenges and costs of reaching this region.

Actual bus service

The bus service in Sardinia is primarily operated by several companies, **including ARST** (**Azienda Regionale Sarda Trasporti**), which has most of the lines of the island.

TRASPORTI REGIONALI DELLA SARDEGNA

Corse e orari

Cerca per data: gg/mm/aaaa Cerca

Linea 9342 NUORO - CAGLIARI

Condizione pianificazione	GIO	GIO
Numero corsa	1	3
CAGLIARI AUTOSTAZIONE ARST	15:30	18:15
CAGLIARI VIALE TRIESTE-ASS.TO TURISMO	15:33	18:18
CAGLIARI V.LE TRIESTE FR. EE.LL.	15:34	18:19
CAGLIARI V.LE SANT'AVENDRACE 291	15:37	18:22
CAGLIARI PIAZZA SAN MICHELE-ANG.VIA REDIPUGLIA	15:40	18:25
AEROPORTO ELMAS ARRIVI	15:50	18:35
OTTANA VIA ITALIA-DANCING	17:34	20:19
NUORO VIA MANNIRONI 62 - OSPEDALE	18:00	20:45
NUORO STAZIONE ARST	18:05	20:50

Linea 9342 NUORO - CAGLIARI

Condizione pianificazione	FER	GIO	FEST
Numero corsa	2	4	102
NUORO STAZIONE ARST	07:10	14:20	07:10
NUORO VIA MANNIRONI 62 - OSPEDALE	07:15	14:25	07:15
OTTANA VIALE GHITTI 18		14:53	07:43 **07:47**
AEROPORTO ELMAS PARTENZE	09:28	16:39	09:33
CAGLIARI PIAZZA SAN MICHELE-LATO VIA ABRUZZI	09:37	16:48	09:42
CAGLIARI V.LE SANT'AVENDRACE 252	09:42	16:53	09:47
CAGLIARI V.LE TRIESTE-EE.LL.	09:44	16:55	09:49
CAGLIARI VIA ROMA 86	09:47	16:58	09:52
CAGLIARI AUTOSTAZIONE ARST	09:51	17:02	09:56

Time tables line 9342 ARST

It’s evident that the service offered by ARST, **from and to Cagliari**, is not competitive due to very low bus frequency and total travel time. (Only **two buses** per day). In this case, price of the single ticket is 14€.

The idea is that a railway **Nuoro-Abbasanta-Cagliari** can seriously decrease total travel time and the accessibility for all those people coming from internal Sardinia’s areas that need to move to the capital for various reasons.

Smeralda coast

The bus service is the only available option for traveling on the east coast of Sardegna.

In addition to the ARST **Line 514 Nuoro-Orosei-Siniscola-Olbia**, we have also Deplano Bus that connect Nuoro with Olbia Airport.

[Deplano Bus at terminal point in Olbia Airport]

The bus transit services between **Olbia** and **Nuoro**, provided by the private operator **Deplano** and the public company ARST, appear to be inadequate for meeting contemporary transportation needs. Both services operate on the same roads, which suffer from insufficient infrastructure, leading to **safety concerns** and **potential disruptions** in service. Deplano, a private company, while marginally better in frequency, faces issues such as delays, lack of data recording, and reliance on the same substandard road infrastructure.

The ARST service, being public, exhibits lower frequency, an aging fleet, and additional uncertainty at intermediate stops. This results in longer travel times and higher unpredictability, further exacerbated by the necessity for drivers to manually validate tickets at each stop, contributing to delays and a lack of real-time information for passengers. Both services collectively fall short of meeting the demands of commuters, thus not providing a viable alternative to private travel. This inadequacy is particularly pronounced along the Olbia-Nuoro route, which lacks any train service, emphasizing the urgent need for a more efficient and reliable transportation solution to serve both resident and seasonal demand.

This is a table with characteristics (are same) for both companies:

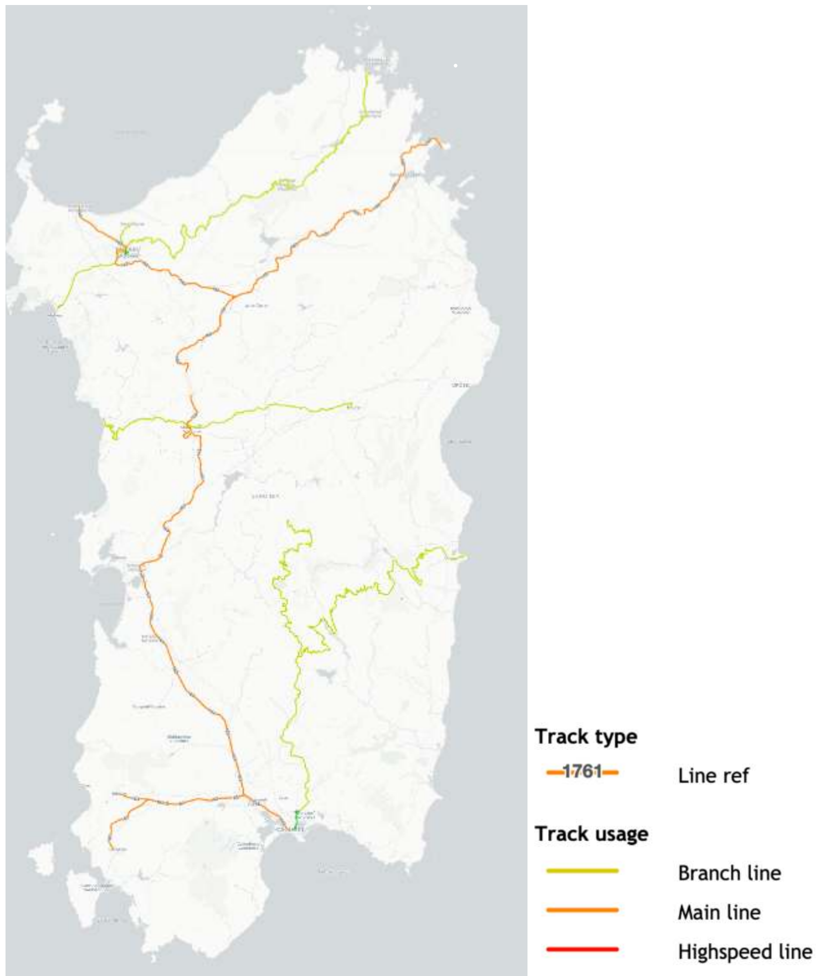
STATIONS	TIME FROM OLBIA (Time from last stop)	PRICE FROM OLBIA (Price from last stop)
Olbia Terranova	-	-
Olbia Aeroporto CostaSmeralda	11 min	1.30€
Porto SanPaolo	26 min (15min)	1.90€ (1.90€)
San Teodoro	54 min (28min)	1.90€ (1.90€)
Budoni	1h 14 min (20min)	3.10 €(1.90€)
Posada	1h 21min (7min)	3.70€ (1.90€)
Siniscola	1h 54 min (33min)	4.30 €(1.30€)
Orosei	2 h 30 min (36min)	6.10 €(3.10€)
Nuoro	2 h 25 min (50min)	8.10€ (3.70€)
Ottana	2 h 56 min (31min)	8.10 €(2.50€)
Abbasanta	3 h 52 min (56min)	10.6 €(3.70€)

[Google Maps data]

Railway service

Regarding trains, the railway network in Sardinia is managed by Trenitalia. It includes, at first, the Cagliari - Golfo Aranci line, connecting the city of Cagliari with the tourist resort of Golfo Aranci, passing through Sassari and Olbia. For second the Cagliari - Sassari line, connecting the capital with the city of Sassari via several towns inland. The technical standards of the railway infrastructure in Sardinia are adapted to local needs, with stations offering basic services such as ticket offices, bars, and restrooms. Cagliari - Golfo Aranci and Cagliari – Sassari are Standard-Gauge Lines, and passe across the island from the southern city of Cagliari to the north, passing through major towns like Oristano, Abbasanta, and Olbia.

There are also narrow-Gauge Lines. One of them is the Mandas – Arbatax, known for the scenic "Trenino Verde" tourist route.
Macomer - Nuoro connects the central town of Macomer to Nuoro. Finally Isili – Sorgono, that is another scenic route utilized primarily for tourism.



Technical Characteristics of Trains and Infrastructure

Due to the lack of electrification, most of the rolling stock consists of diesel multiple units (DMUs) and locomotives. The modernized DMUs offer improved comfort and efficiency compared to older models. Regarding the narrow-gauge trains, these are designed for the unique tracks and include both historical and modernized units used primarily on tourist routes.

Regarding infrastructure, it is predominant single-track lines, which limits the frequency and flexibility of services. All standard-gauge and narrow-gauge lines in Sardinia are non-electrified, relying entirely on diesel traction. Many stations are historic and have seen various degrees of modernization. The facilities range from well-equipped urban stations to more basic rural stops [1].

Key Characteristics and Challenges

Single-track lines necessitate careful scheduling and can cause delays if not managed efficiently. The reliance on diesel engines increases operational costs and environmental impact compared to electrified lines. While main routes have regular services, some areas suffer from limited frequencies, impacting accessibility and convenience for residents and tourists.

Recent Developments

There are ongoing projects aimed at renewing tracks and upgrading facilities to improve safety and efficiency. Furthermore, there is an introduction of newer, more efficient trains to enhance service quality. Joint efforts between Trenitalia and regional authorities aim to address existing challenges and enhance the overall rail service.

1.3 Current situation analysis

While several candidates are available to be chosen as a station, we should consider the tourism popularity of the proposed regions to check if they are suitable candidates. By checking the number of people who came to Sardegna we can identify the more popular areas as tourist destinations [2].

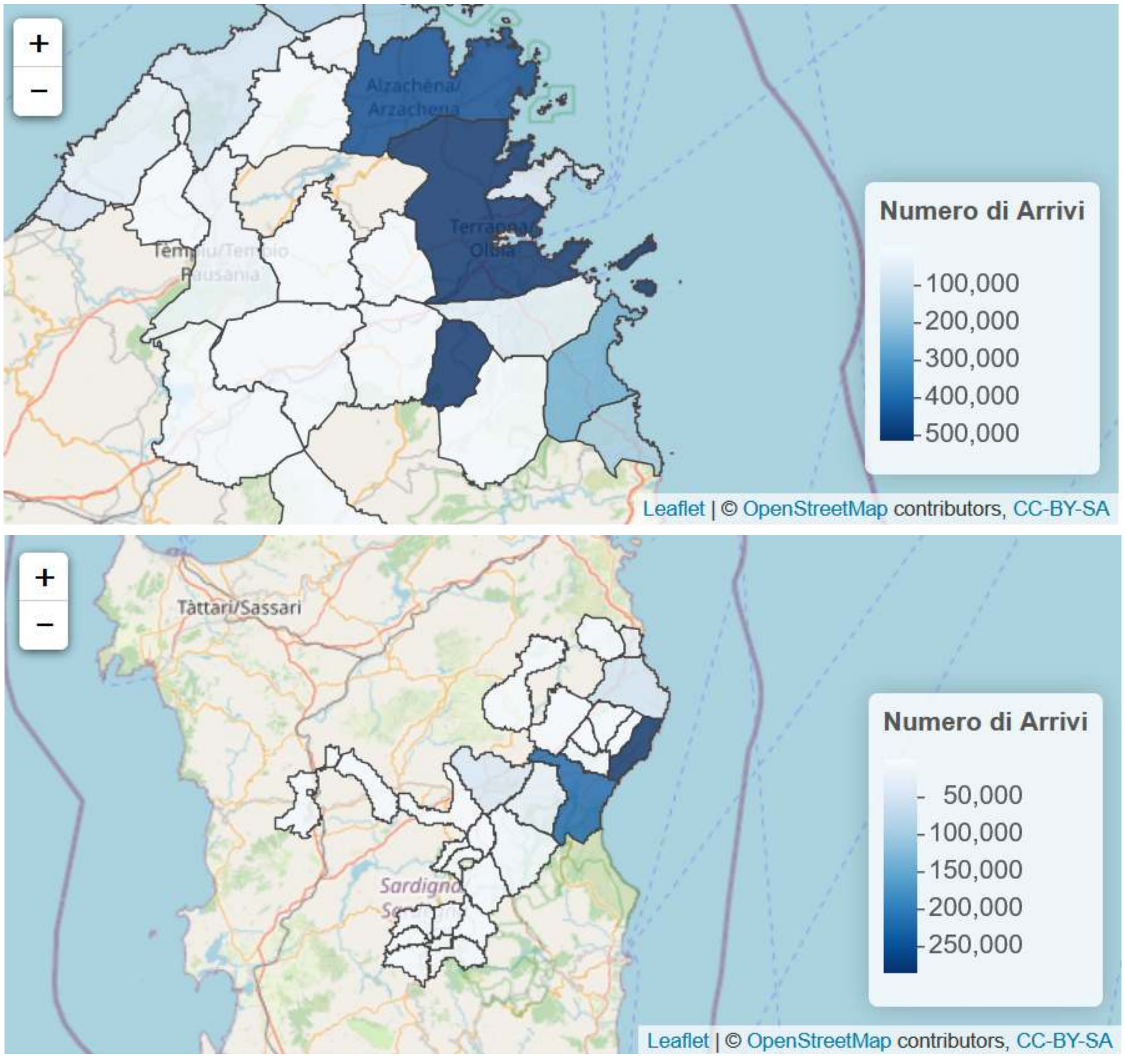
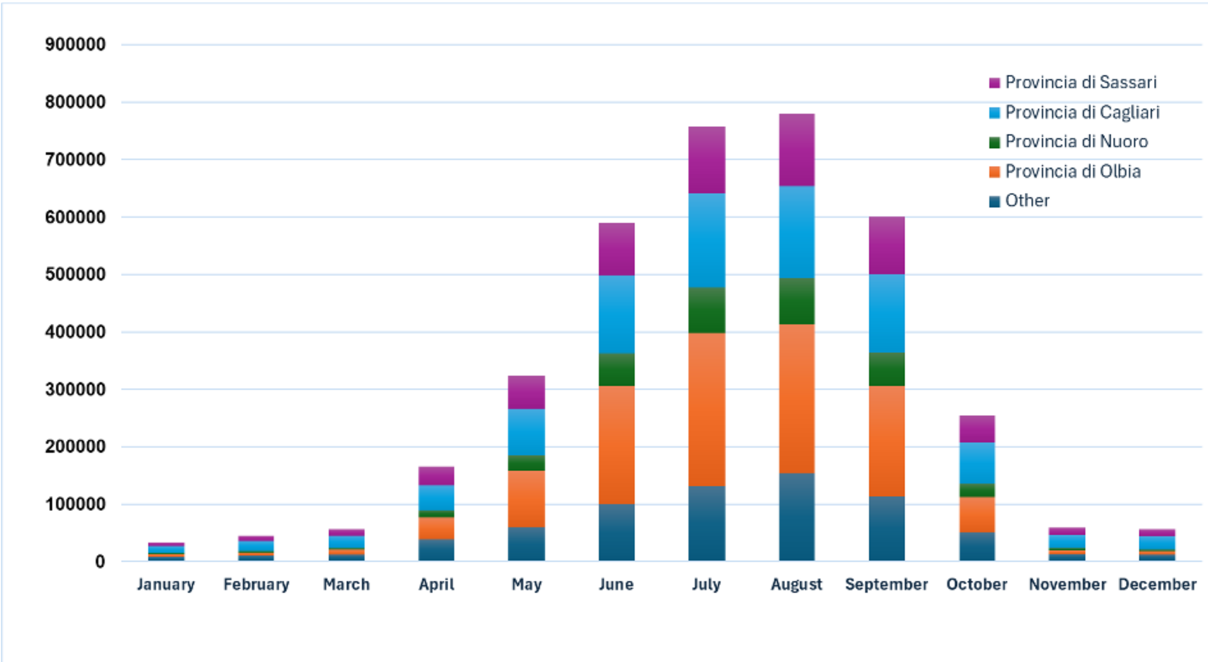


Figure 1.6: Total arrivals during year 2022

The tourism data indicates a substantial influx of visitors to the northeastern and eastern regions of Sardinia, particularly around Olbia and along the eastern coast. To cater to this significant tourist traffic and enhance accessibility, a new railway line connecting Olbia, Nuoro, and Cagliari is proposed. This strategic route would include stations at major tourist destinations such as Olbia, San Teodoro, Budoni, Siniscola, Nuoro, Oristano, and ultimately Cagliari. The proposed railway line aims to improve connectivity between these key tourist hubs, thereby enhancing the overall travel experience for visitors. Additionally, it would support the regional economy and promote sustainable tourism development by providing an efficient and environmentally friendly mode of transportation.



Graph 1: Monthly arrivals in Sardinia during year 2022 by province

There is a big difference between arrivals in the summer season compared to the winter season, which implies that the service must be ready to meet this variable demand [2]. In addition, people of all ages arrive, but especially people between 45 and 65 years of age who, unlike younger users, may prefer convenience over price and therefore the train over the bus.

As can be seen from the graph, with the increase over the years, there has been a profitable growth in the number of tourists coming to Sardinia, which means a greater need for mobility and therefore greater use of alternative transport units to provide good connections to areas of interest.

2-ROUTE DEFINITION

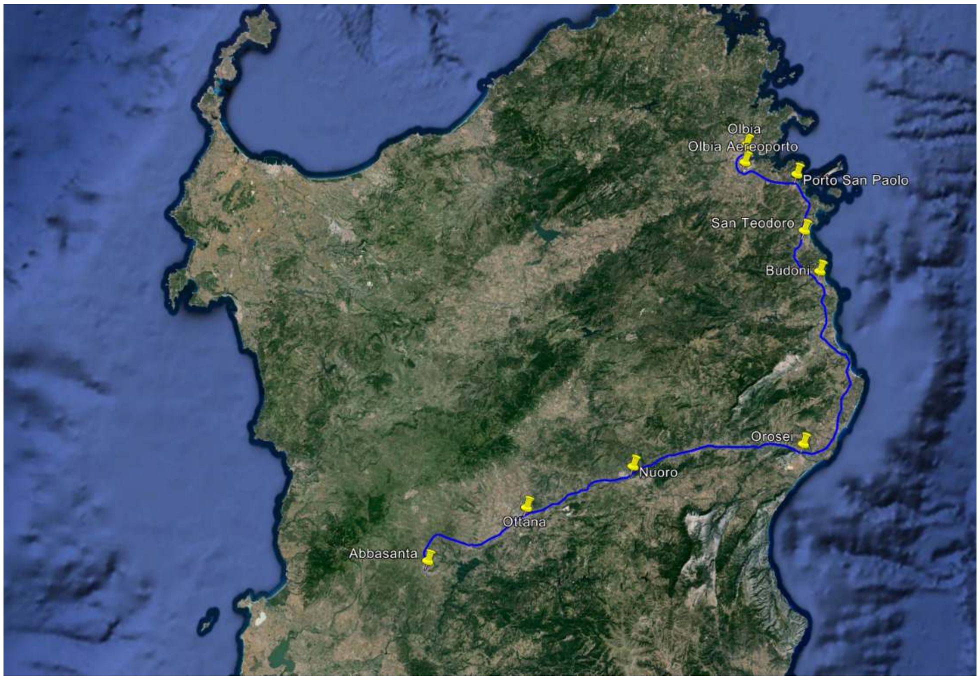
The line was chosen in this way because it follows the SS131, which is one of the main arterial roads and therefore indicates a large flow of people. A small diversion was chosen to go through Orosei instead of going directly to Nuoro, because Orosei is one of the most attractive and populated centres in the central area of Sardinia.

Integration with existing railway

The route we have designed creates a valid alternative for crossing Sardinia by train, connecting places where there is no railway line.

In red we can see the current railway line, while in blue the new one that we projected.

2.1 Reference Path



Path proposed

The stops are:

- Olbia station, which already exists.
- Olbia Airport allows a direct connection between the airport and the railway network, the connection to the Emerald Coast will be immediate.
- Maritime stops such as Porto San Paolo, San Teodoro Budoni and Orosei.
- Inland stops to rejoin the existing railway line such as Nuoro, Ottana and Abbasanta;

Figure 1(The line starts from Olbia station and diverges from the existing regional line. From there, it will connect to the airport and head south.)

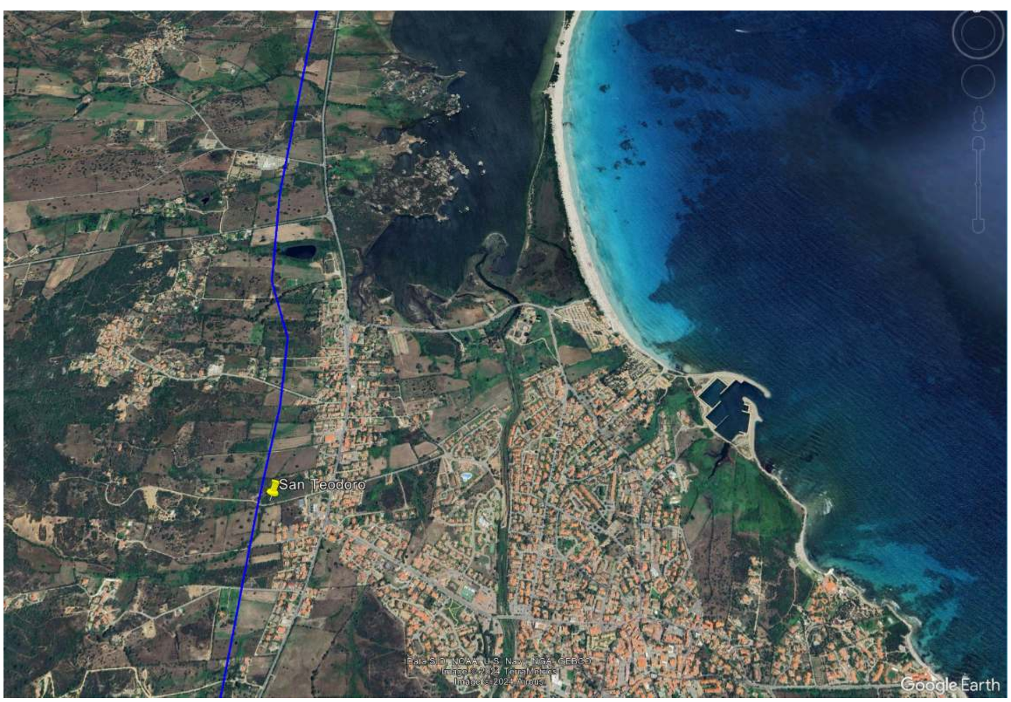


Figure 2 (The first towns encountered will be the seaside towns of the Costa Smeralda. In the photo, you can see San Teodoro and where the station could be located.)

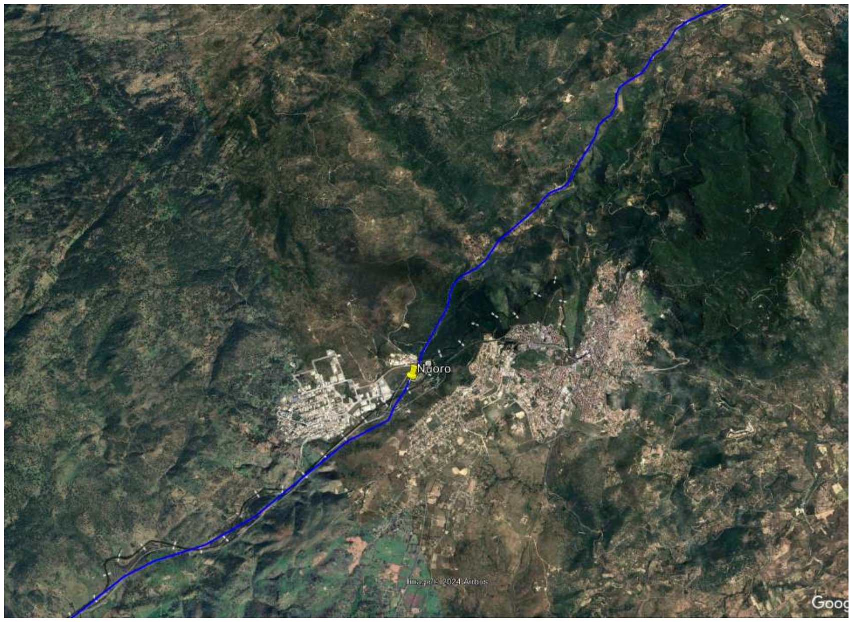


Figure 3 (The line then moves inland, passing through some interior cities such as Nuoro)

Nuoro's existing railway is narrow gauge (black line), which means that the distance between tracks is less than the standard gauge used in most main railways. This type of gauge is often used in secondary or local railway lines where ground conditions or construction and maintenance costs require a more economical and flexible solution.

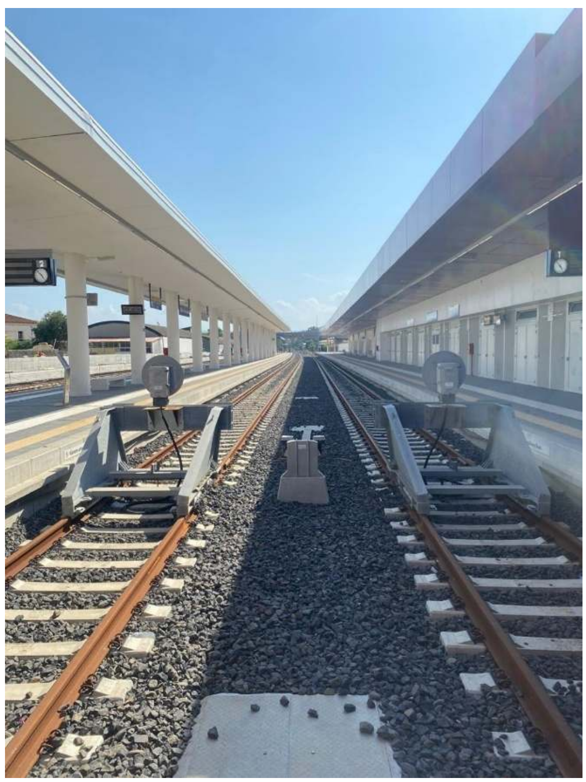
In our project, we plan to replace the existing narrow-gauge railway with a new rail line. It will be designed to improve efficiency and transport capacity, providing a more modern and reliable service to passengers

Figure 4 (Finally, it reconnects at Abbasanta with the route that continues to Cagliari.)

2.2 Infrastructure design

The speed limits set along the route reach a maximum of 160 km/h in the less urban sections and decrease significantly in urban centers. Given all the innovative processes that have occurred in recent years and the attempt at decarbonization, the initial hypothesis is to use a pair of tracks, one for each direction, with catenary. Since the current network is not electrified, it will be necessary to have trains that can travel on both the non-electrified sections and the proposed electrified sections.

The stations have been conceptually designed as intermodal hubs. It is very important that they are served by other efficient means of transportation, such as buses, and that they are accessible to the public by car with parking facilities. If the stations are efficient, it is possible that even those living in inland towns will rely on trains as a means of transport, reaching the stations by bus or car and subsequently reaching coastal destinations. Some major stations, such as Olbia Airport or Nuoro, could become polycentric locations and be equipped with shops and restaurants. This would allow the stations to expand their user base, attracting not only travelers but also people visiting these places for reasons unrelated to mobility. Generally, this type of approach, which is becoming very popular in Europe and Italy, can generate immense economic and social benefits.

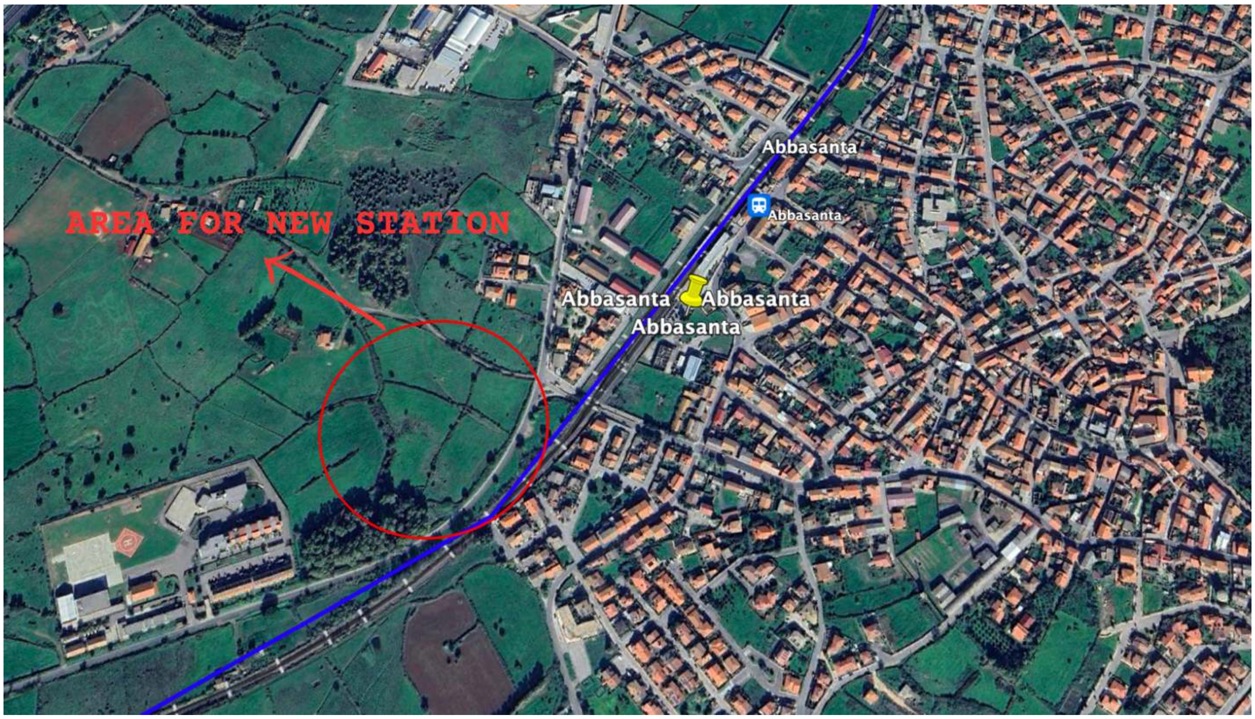


Figures: Olbia Terranova station and its platform

Specific Case Study – New station in Abbasanta

In our project, we planned to build a new station in Abbasanta. Its central position facilitates the integration of different transportation modes, including road and rail networks.

This station will not only serve as a terminal for passengers but will also function as a depot, for vehicles maintenance, and central point for the distribution of other types of transport. The facility will be designed to integrate with existing transport networks, such as scheduled buses, improving the overall efficiency and connectivity of the region.



By moving the existing single-track Abbasanta station to a neighbouring area, a more complete infrastructure can be created, considering the availability of space and the need to expand the capacity and frequency of vehicles, given the demand for travel.

An area of 50,000 km^2 was chosen based on several technical characteristics that make it ideal for this development:

1. Topography and Soil Location: Abbasanta is located in the heart of Sardinia and is easily accessible from the main highways and existing roads, making it an optimal point for connecting the various regions of the island. The chosen area has a relatively flat topography, which simplifies construction processes and reduces the need for extensive land levelling.

2. Accessibility: The site is easily accessible from major highways and existing roads.

3. Environmental assessment: the project has a strong focus on environmental sustainability. The station will incorporate green building practices, including photovoltaic installations for energy and green spaces to enhance the local ecosystem.

The new station will be provided with a series of shops and points of interest to meet the needs of travelers and the local community.

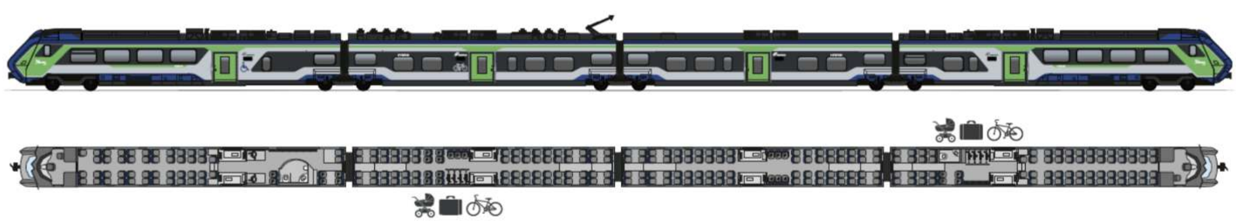
This development aims to develop Abbasanta into a key logistics and commercial center, supporting local businesses and enhancing the travel experience for all who use the new railway line.

2.3 Train design

Our chosen vehicle is the Hitachi Blues, which has various configurations. The first EMU configuration was considered for the study because the entire new section would be catenary-powered. There are also other configurations that would allow traveling on tracks other than the one proposed.

1) Electric (EMU) – Power supply from 3kV DC overhead line (prepared for 25kV AC 50Hz // 15kV AC 16⅔Hz).
2) Diesel-Electric (DEMU) – Power supply from onboard Diesel Engine.
3) Hybrid (HMU) – Power supply from onboard Diesel Engine and Traction Batteries; Battery (BEMU) – Power supply from Traction Batteries.

The train can consist of 3 or 4 carriages, in which, in addition to the passenger compartments, various service areas for travelers are distributed: standard and PRM toilets, wheelchair areas, multifunctional areas (bike rack, ski rack, luggage stack, stroller areas). [3]



Vehicle Capacity	Number
Total Fixed Seats	**275**
Total Tip-Up Seats	**23**
Total PRM Positions	**2**
Total Seating Positions	**300**
Total Bicycle Spaces	**8**

3-VEHICLE MODELLING AND SIMULATION RESULT

3.1 Traction force (locomotive)

Hitachi Blues has an innovative vehicle architecture offering 4 modes of operation:

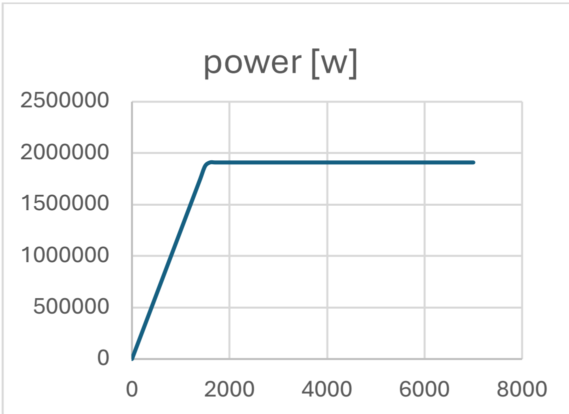
- Electric (EMU): catenary power supply 3kVdc (prepared for 25kVac 50Hz // 15kVac 16⅔Hz)
- Diesel Electric (DEMU): powered by an onboard Diesel engine.
- Hybrid (HMU): powered by onboard Diesel engine and traction batteries.
- Battery (BEMU): power supply from traction batteries

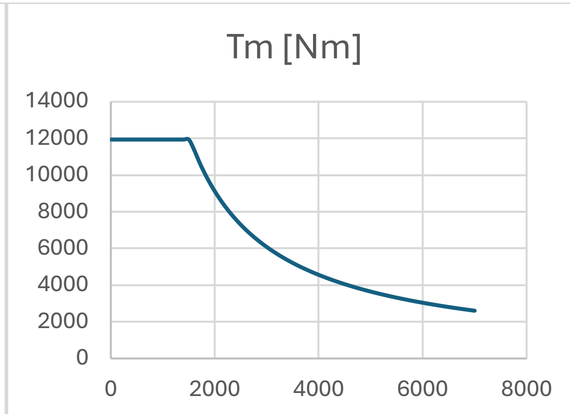
In this discussion, the EMU solution (4-car configuration: 2 locomotives, 2 carriages) has been chosen; a comparison will then be made in terms of greenhouse gas emissions with the DEMU solution.

4-car	EMU	DEMU
Length [mm]	86080	
Width [mm]	2800	
Seats	300	
Max power [kW]	1910	890
V max [km/h]	160	160
Acceleration [m/s^2]	1,08	0,78
max configuration	2 trainsets	

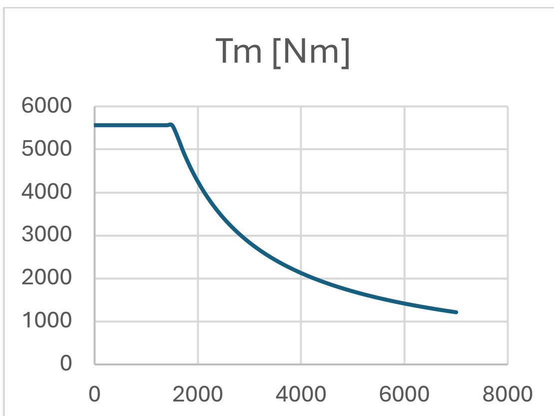
The electric motor operates in two distinct modes: constant torque mode, where power increases with speed, and constant power mode, where power remains constant while torque decreases. The rated speed is set at 160 rad/s.

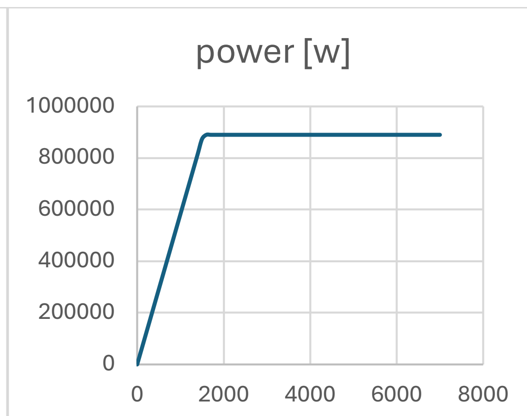
EMU





DEMU





During the braking phase with the traction motor, the torque is considered with its sign reversed.

Power Balance (Kinetic Energy Theorem)

By applying the kinetic energy theorem, which relates the change in kinetic energy to the work done on a system, the instantaneous acceleration value for the railway case study can be determined. This approach allows for a precise calculation of acceleration at any given moment, taking into account the dynamics of the railway system

$$P_{motor} + P_{diss} + P_{res} + P_{brake} = \frac{dE_c}{dt}$$

Motor power:

$$P_{motor} = T_m \omega_m \rightarrow >0 \text{ traction mode}$$

<0 braking mode.

Power dissipated from the transmission:

$$P_{dissipated} = -(1-\eta_{\frac{d}{r}})|P_{in}| \rightarrow \text{Direct flow: } P_{in} = T_m\omega_m - J_m\omega_m\dot{\omega}_m$$

$$\text{Reverse flow: } P_{in} = |P_{res}| - mva - J_w\omega_w\dot{\omega}_w$$

Power due to resistance and dissipative forces:

$$P_{resistances} = P_{areo} + P_{curve} + P_{weight} + P_{roll}$$

$$P_{weight} = -mgsen(\alpha)v \qquad \alpha = \text{slope}$$

$$P_{aerodynamic} = -\frac{1}{2}\rho C_d S v_{rel}|v_{rel}|$$

$$P_{rolling} = -vf_r mgcos(\alpha)\frac{\omega_w}{|\omega_w|}$$

$$P_{curve} = -vmr_c \qquad \text{Sachs formula: } r_c = (1{,}6a + 1{,}62)/R_c$$

$$R_c = curvature\ radius$$

a = distance between the axles of a bogie

Mechanical brakes:

$$P_{brake} = -T_{b,tot}\omega_w \rightarrow \text{value to reach a=-1,5 m/s^2}$$

Total kinetic energy:

$$E_c = \frac{1}{2}m^* v^2 + E_{c,motor} \qquad m^* = m_{tot} + \frac{J_{w,tot}}{r_w^2} \quad \text{(20 wheelsets)}$$

$$\frac{dE_c}{dt} = m^* va + J_m\omega_m\dot{\omega}_m$$

From the power balance, acceleration can be computed. Speed and displacement can then be determined by integrating with respect to time.

FRICTION LIMIT

Through the Coulomb friction model for the wheel-rail contact, the maximum torque limit was calculated to assess wheel adhesion in the longitudinal motion model.

$$T_{max,adhesion} = \frac{\left(\mu_{rail} F_{n,w} r_w + F_{n,w} f_r r_w + \dot{\omega}_w J_w\right) n_{w,t} \tau_g}{\eta}$$

COMFORT LIMIT

Considering the maximum acceleration values from the datasheets of the two solutions and the assumptions of paper [9], the thresholds for maximum acceleration chosen to calculate the maximum torque, through the power balance, capable of being delivered to meet the limit, were set at:

- $a_{max} = 1{,}07 \frac{m}{s^2}$ (EMU)
- $a_{max} = 0{,}78 \frac{m}{s^2}$ (DEMU)

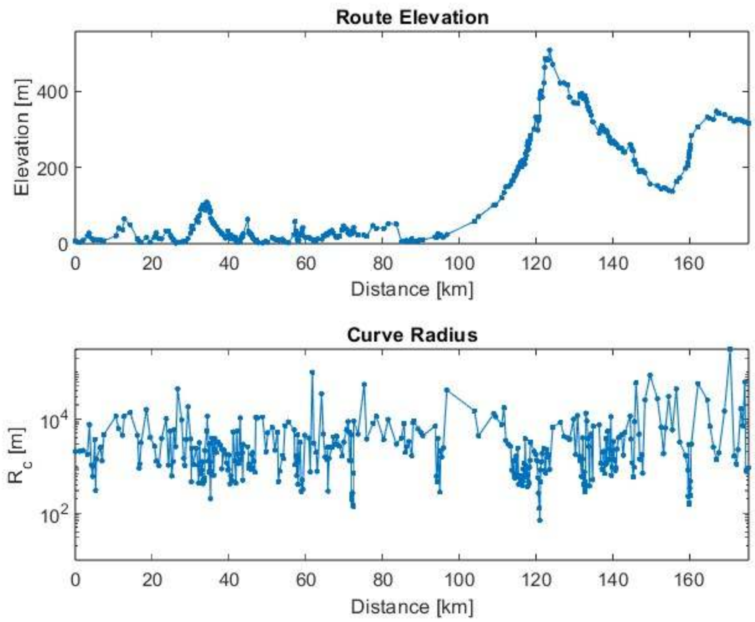
Model

HTR 412	Bo'2'2'2'Bo'		4-car	Motor				
v max	160	km/h		T m,r	11937,5	Nm	rated torque	
2 dc motors	1910	Kw/mot		ω m,r	160	rad/s	rated speed	
locomotive	2			P m,r	1910000	w	rated power	
carriages	2			τ g	0,380435		transmission ratio	
gravity	9,81	m/s^2		η d	0,975		transmission direct efficiency	
J m	10	kgm^2	motor inertia moment	η r	0,95		transmission reverse efficiency	
J ws	90	kgm^2	wheelset inertia moment					
r w	0,445	m	wheelset radius	n	8		wheels in traction	
n loco	2		number of locomotives	n w	20		wheels	
n car	2		number of carriages	m*	203118,9			
Resistance forces				m tot	198574	kg		
fr	0,008		rolling friction coefficient	μ rail	0,35		friction coefficient	
S	7,8	m^2	vehicle cross section	a	2,6	m	axles bogie distance	
Cd	1,05		drag coefficient	P aux	80	kW	auxiliary systems	
ρ air	1,25	kg/m^3	air density					

References [3], [4].

3.2 Speed limits, Curvature Radius and Slope Angle

From the MATLAB script, we extract the data for gradient and radius of curvature:



$$\alpha = \arctan\left(\frac{\Delta elevation}{\Delta distance}\right)$$

The maximum speeds of curves, which refer to the highest velocities at which a vehicle can safely navigate through a curved section of track, can be computed as follows:

$$v_{max} = \sqrt{\frac{\Delta hRg}{2s} + a_{NC}R} \qquad a_{NC} = 0{,}7\,\frac{m}{s^2} \quad 2s = 1{,}435 \quad \Delta h\,\text{max} = 0{,}16\ m$$

After entering the equation for calculating acceleration into the model and integrating it to obtain velocity and displacement, the Excel model uses the SEARCH.VERT function to select the correct velocity limit:

speed limit					
start [km]	finish [km]	**limit [km/h]**	start [km]	finish [km]	**limit [km/h]**
0	1,17	50	72,51	93,7	160
1,17	5,48	80	93,7	95,13	80
5,48	12,71	160	95,13	112,71	160
12,71	16,78	140	112,71	123,52	90
16,78	24,26	150	123,52	131,36	130
24,26	30,02	110	131,36	132,61	100
30,02	34,93	100	132,61	134,86	80
34,93	36,27	60	134,86	143,13	120
36,26	43,73	100	143,13	147,52	110
43,73	51,27	130	147,52	158,94	120
51,27	56,98	100	158,94	160,44	50
56,98	66,06	80	160,44	172,19	160
66,06	71,97	160	172,19	175,36	140
71,97	72,51	50			

The slope and radius of curvature data are linearly interpolated to obtain intermediate values between two consecutive readings:

```
Function INTERPOLATE:

  For i = 1 To x_range.Count - 1

    If x >= x_range(i, 1) And x <= x_range(i + 1, 1) Then

      x1 = x_range(i, 1)

      x2 = x_range(i + 1, 1)

      y1 = y_range(i, 1)

      y2 = y_range(i + 1, 1)

      Exit For

    End If

  Next

  INTERPOLATE = y1 + (x - x1) * (y2 - y1) / (x2 - x1)

End Function
```

After selecting the interval, the function calculates the line between two points.

Comparing the computed speed value with the speed limit, 3 braking modes are set:

- No (direct power flow)
- Yes_df (direct flow, mechanical brake)
- Yes_rf (motor brake, reverse flow)

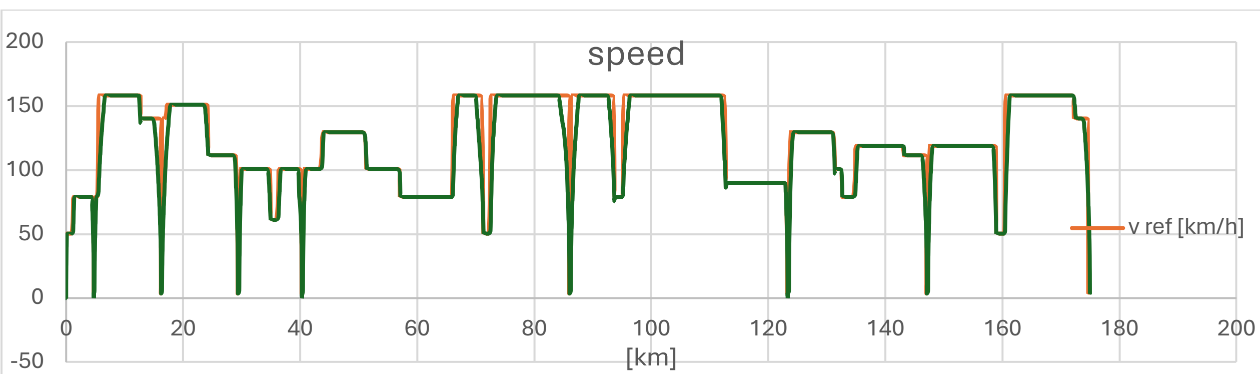
The acceleration values for both direct and reverse flow are computed, and the appropriate acceleration value is then selected.

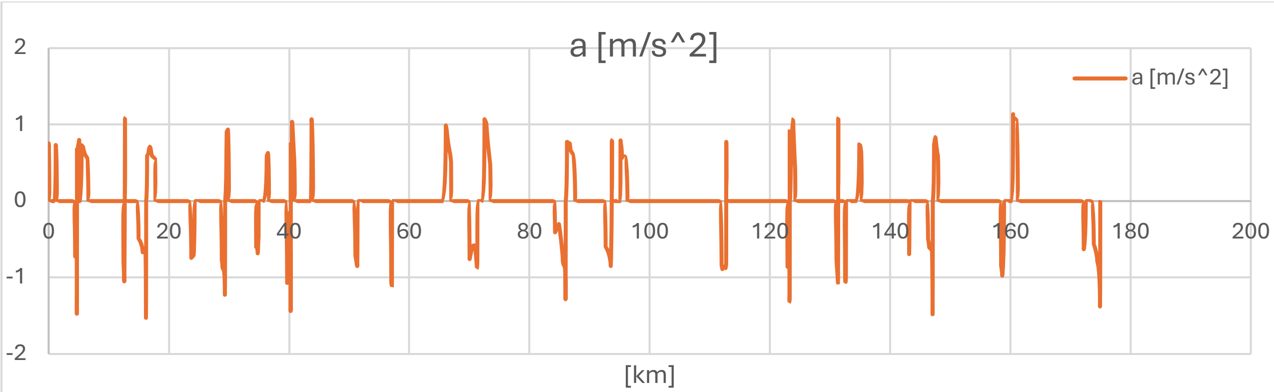
Four modes correspond to them:

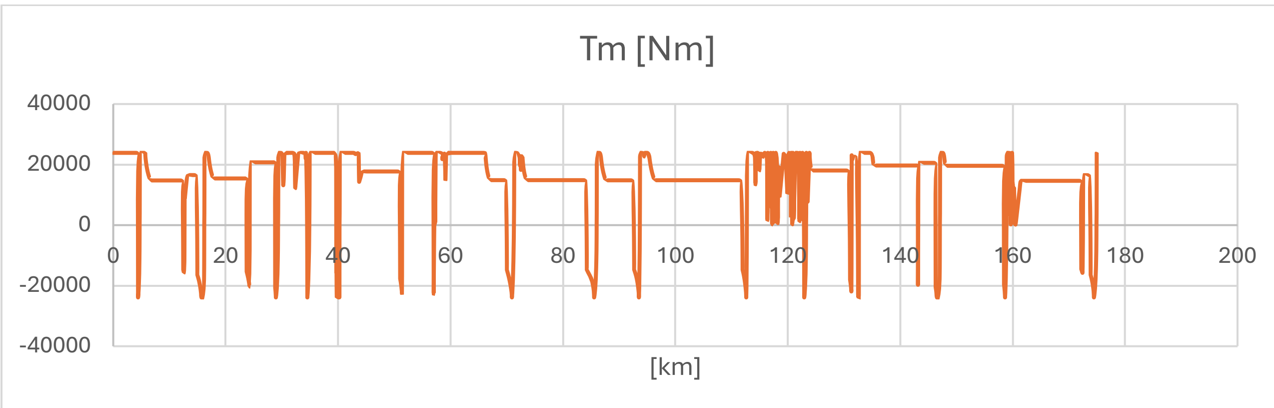
- Accelerating (if v limit > v computed)
- Constant speed (if v limit = v computed)
- Coasting (motor braking until 10 m/s)
- Brake (to stop)

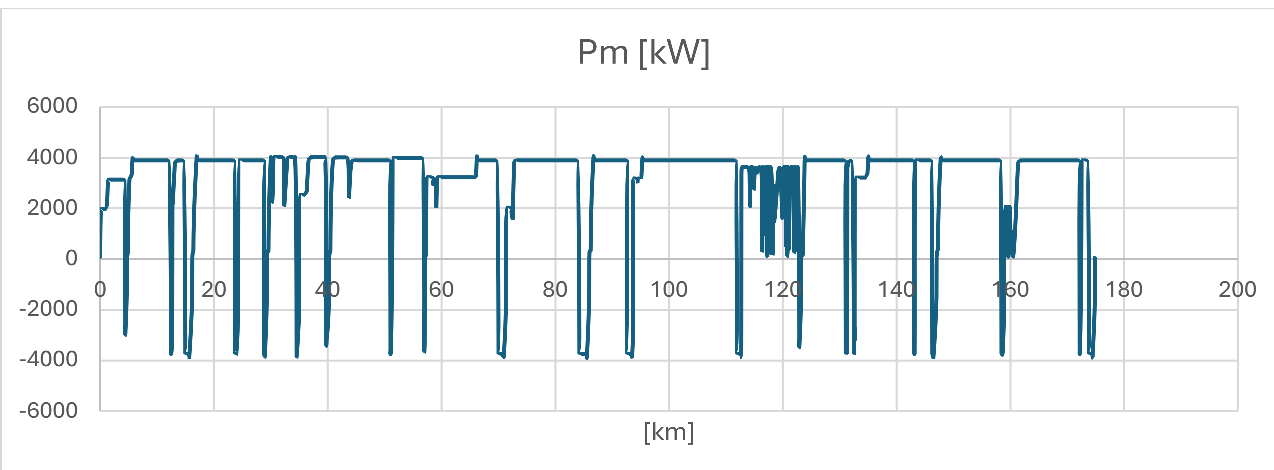
The torque value is determined by selecting the lowest value among the torque available from the engine, the torque limited by adhesion, and the torque constrained by comfort limits.

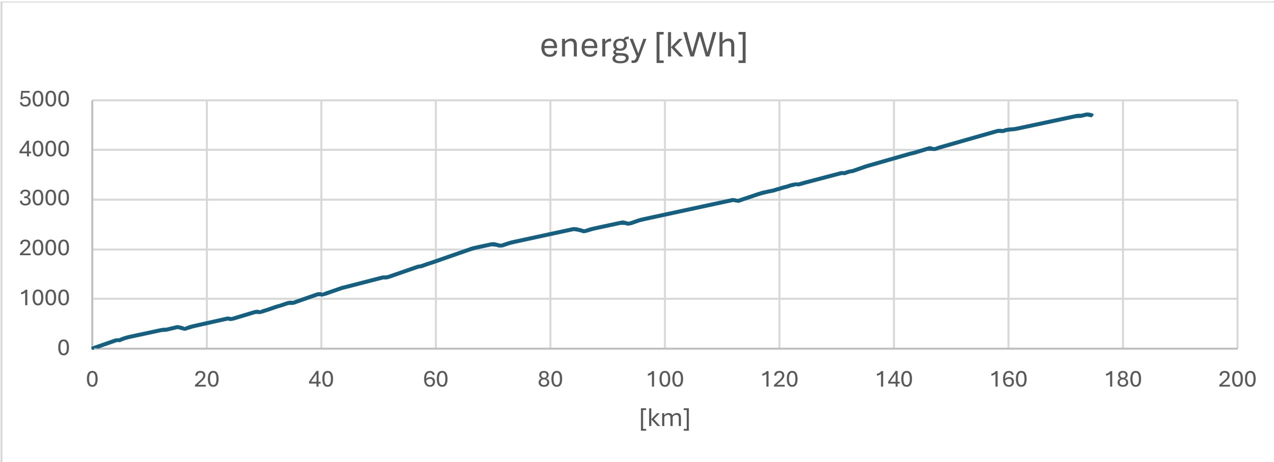
Below there are the final computed values for velocity and acceleration for both direct and reverse flow, as well as the required motor torque, power, and energy, considering the contribution of the auxiliaries as a function of displacement. Additionally, the speed as a function of time.




a [m/s^2]
a [m/s^2]
2
1
0
-1
-2
0
20
40
60
80
100
120
140
160
180
200
[km]


Tm [Nm]
40000
20000
0
-20000
-40000
0
20
40
60
80
100
120
140
160
180
200
[km]

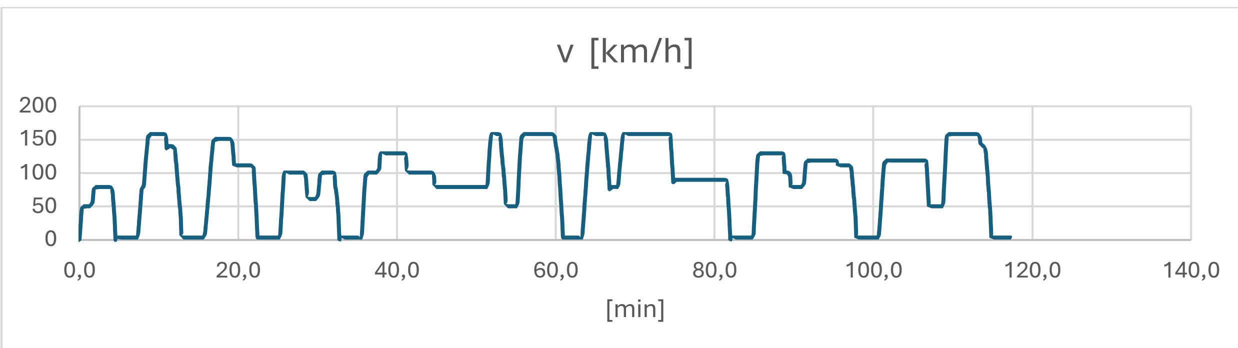

Pm [kW]
6000
4000
2000
0
-2000
-4000
-6000
0
20
40
60
80
100
120
140
160
180
200
[km]



Energy is computed as the integral of the power: $E = \int P_m \, dt$

and divided by 3600 in order to convert from J to kWh.

Travel time: 117 min



The model has been run also for the diesel configuration.

3.3 CO2 Emissions and Environmental impact

The Statistical Office of Terna, a member of the National Statistical System, is legally responsible for compiling official statistics in the electricity sector and oversees the entire data collection process. This includes data acquisition, checking and correcting inconsistent data, processing, and final publication. In 2022, the electricity demand in Italy was 315 TWh, a decrease of 1.5% compared to the previous year. The electricity demand was met by 86.4% from domestic production for consumption, amounting 272 TWh (-1.8%), and the remaining 13.6% was covered by net imports from abroad, amounting to 43 TWh. Gross domestic production was 283.9 TWh, registering a decrease of 1.8% compared to 2021.

Non-renewable thermoelectric sources covered most of the demand, representing 63.9% of production (an increase of 6.4% compared to 2021). Among renewable sources, there was a historical record for photovoltaic production, amounting to more then 28 TWh in 2022 (+12.3% compared to 2021). In contrast, there was a historical low in hydroelectric production, which decreased by 36.2% to 30.3 TWh. Other renewable sources also declined: wind by -2.1%, geothermal by -1.3%, and bioenergy by -7.6% compared to 2021. The main factor contributing to the decrease in bioenergy, which recorded the most significant negative delta in recent years, was the production obtained using crude vegetable oils as fuel, which fell by 24.8%.

When analysing thermoelectric production by fuel, the following trends were recorded: an increase in production from solid fuels by 61% (22.6 TWh), a decrease in production from natural gas by 2% (which continues to cover 71.0% of thermoelectric production with 141.4 TWh), an increase in production from petroleum products by 29% (4.9 TWh), and an increase in production from other fuels by 8.5% (30.2 TWh). [7], [8].

In Sardinia, against a gross efficient electric power capacity of 4,744 MW, the thermoelectric component is 2,501 MW.
The island produces thermoelectric energy from coal, diesel, fuel oil, syngas and biomass.

In 2017, the net electricity generated in the region was more than 40.8% of the island's net demand. [9]

Energy mix 2022 in Italia (Terna data)					
Thermoelectric (70,2%)	Production %	CO2 [mln ton]	CO2 %	prod [GWh]	gCO2/kWh
Natural gas	71,0	49,8	53,1	141444,9	352,0805628
Bioenergy	14,0	18,09	19,3	27887,99	648,6663255
coal	11,3	21,76	23,2	22606,7	962,5465017
Petroleum	2,5	3,16	3,4	4953,3	637,9585327
other	1,2	1,06	1,1	2309,9	458,8943244
Res (29,8%)					
hydroelectric	10,7				
Photovoltaics	9,9				
Wind power	7,2				
Geothermal	2,1				

Energy mix 2022 in Sardegna (Terna data)					
Thermoelectric (74,3%)	Production %	CO2 [mln ton]	CO2 %	prod [GWh]	gCO2/kWh
Natural gas	0,1	0	0	7,9	0
Bioenergy	47,6	2,32	33,5	4735,74	489,89
coal	47,4	4,44	64	4713,1	942,05
Petroleum	3,1	0,17	2,4	309,7	548,92
other	1,9	0	0	185,1	0
Res (25,7%)					
hydroelectric	3,2				
Photovoltaics	10,1				
Wind power	12,4				
Geothermal	0				

Fossil source (Italia)	
561,63	[gCO2/kWh]
Fossil + RES (Italia)	
394,26	[gCO2/kWh]

Fossil source (Sardegna)	
780,98	[gCO2/kWh]
Fossil + RES (Sardegna)	
580,27	[gCO2/kWh]

Below there are the characteristics of the fuels, taken from SNCF [5] and Minister of Natural Resources Canada, 2014 [6]:

kgCO2/l	Diesel
3,160	off-road diesel
1,21	B100

Gasoline	
2,312	kgCO2/l
0,63	kg C/l
3,67	kg CO2/kg C

WELL TO WHEEL ANALYSIS

well to wheel			
EMU		DEMU	
feed cable	0,95	engine	0,4
transformer	0,95	generator	0,92
control systems/ power electronics	0,975	rectifier	0,98
		motors	0,92
		transmission	0,95
electric motors	0,95	traction auxiliaries	0,95
transmission	0,95		
traction auxiliaries	0,95		
power at rails	0,79	power at rails	0,79

energy consumption		
EMU [kWh]	DEMU [l]	
5906,99	779,19	
CO2 kg		
EMU (Sardegna)	DEMU	B100
3427,66	2462,24	942,82
EMU (Italia)		
2328,94		
CO2 kg/pass/km		
0,065	0,047	0,018
0,044		

car [gasoline]	
15	km/l
9,933	l
149	km
22,966	kg CO2
0,154	kg/pass/km

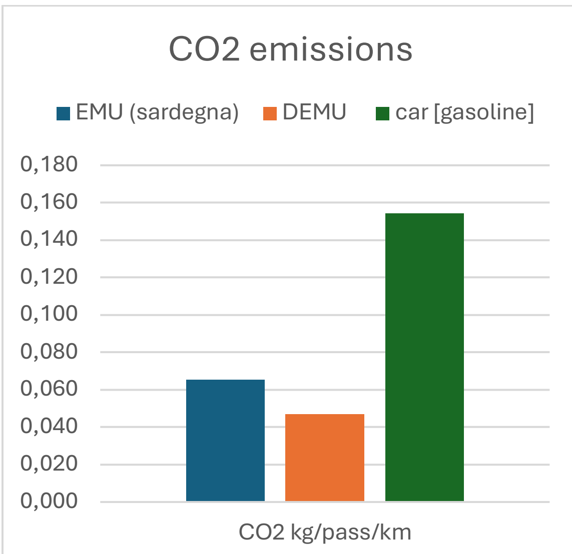
The EMU consumption in kWh is then divided by the efficiency obtained.

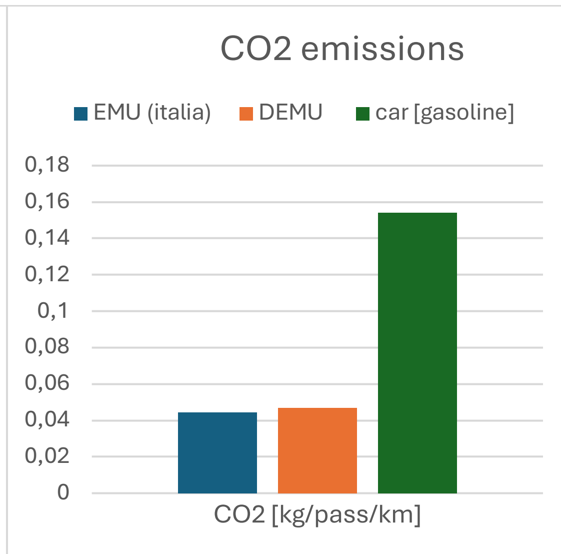
DEMU Consumption in J gives the litres of diesel consumed.

$$P_{fuel} = \frac{P_m}{\eta_{diesel,gen}} \qquad Flow\ rate = \frac{P_{fuel}}{LVH} \text{ (positive part only)}$$

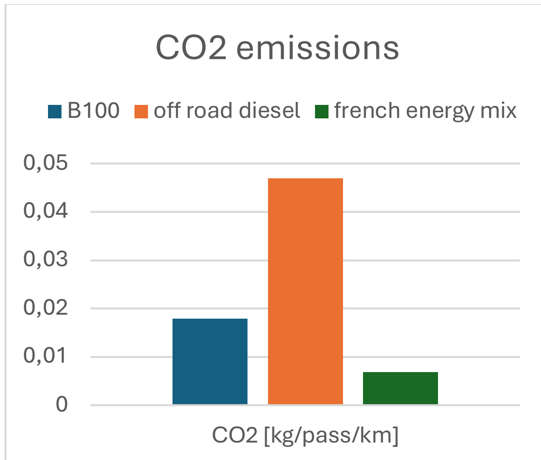
$$fuel\ mass = \int flow\ rate\ dt \qquad litre = \frac{fuelmass}{fueldensity}$$

The Italian and Sardinian energy mix, due to the preponderance of coal and natural gas, in the case of the characteristics of this route and the train chosen, does not allow the electric solution to be helpful in terms of greenhouse gas emissions. The EMU configuration does, however, make it possible to reduce local pollution. Anyway, the advantage over the private vehicle is still significant, for which the route via the SS131 road was considered with an average travel time between 1.5 h and 2.0 h:





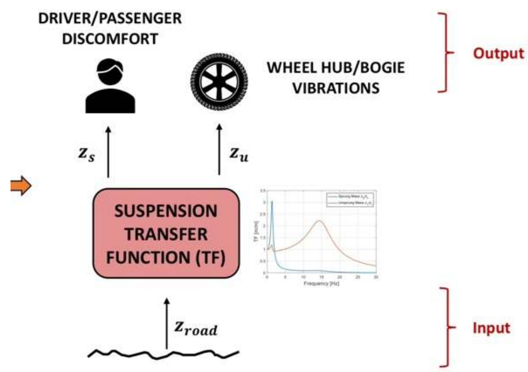
On the other hand, for instance taking the French energy mix, in which there is a strong production of electricity by means of nuclear power plants and not natural gas or coal, the environmental impact is significantly lower, even compared to a more virtuous fuel such as biodiesel B100. French electricity for transport use has an emission factor of 60.7 gCO2/kWh in 2019 and 59.9 gCO2e/kWh in 2020; 60 gCO2e/kWh has been taken into account, with a final CO2e emission of 0.007 [kg/pass/km]:



4- NOISE AND VIBRATION

4.1 Comfort

Railway tracks are uneven due to manufacturing imperfections and wear over time, which can provoke defects and irregularities. When rail vehicles cross these tracks, the suspension system plays a crucial role by transferring the vibrations caused by track irregularities to the car and passengers. This process can be understood through a Transfer Function, a mathematical representation that models how input (track irregularities) affect output signals (vibrations felt by the vehicle and passengers).



In this context, the input (road irregularity) produces vibrations (z_{road}) that pass through the suspension system, resulting in wheel hub/bogie vibrations (Zu) and driver/passenger discomfort (Zs). The transfer function of the suspension system describes how these vibrations are filtered before reaching the passengers.

For analyzing track irregularities in the railway sector, we use analytical models to define the Power Spectral Density (PSD) of these irregularities. The PSD measures the power distribution of a signal across different frequencies, providing a detailed understanding of how irregularities are spread over the track. In this case, the signal is considered random, with its power continuously distributed across frequencies.

The PSD is generally expressed in terms of power density, which represents the average power of the signal per unit frequency. For our analysis, we utilized the formula for track irregularity PSD, assuming the track is characterized by minor defects:

$$G_d(\Omega) = \frac{A_v \Omega_r^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)}$$

Where:

Ω_r = 0.0206 [rad/m]

Ω_c = 0.8246 [rad/m]

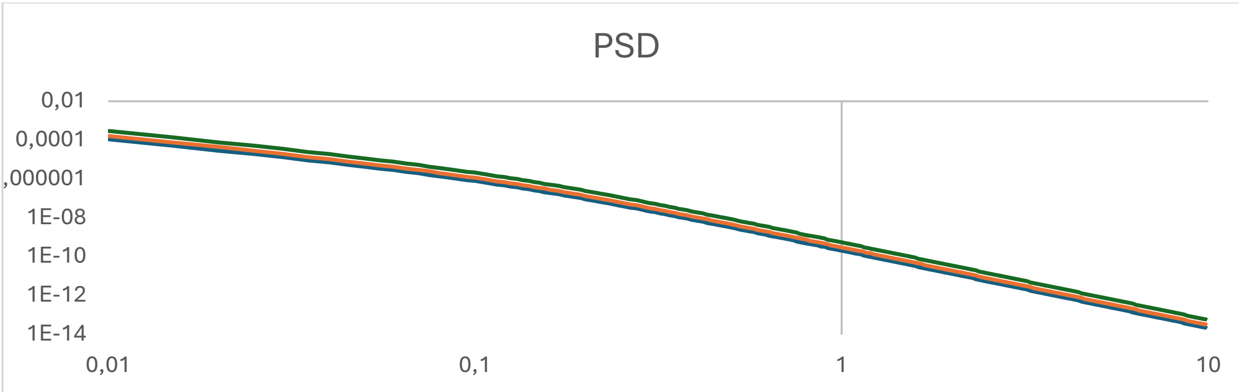
A_v = 4.0320 * 10^{-7} [m/rad]

The constant A_v is a parameter that refers to the defects of the track. It's selected for tracks with minor defects to have minimal irregularities.

However, we calculated the track irregularities for medium and big defects too, to better illustrate the potential effect of the A_v on PSD.
To calculate the angular frequency Ω, we used the formula $\Omega = 2\pi n$, with the frequency (f) defined ($\frac{v\Omega}{2\pi}$). Here, *v* is the maximum velocity of the train, and n represents the spatial frequency. We considered the maximum velocity of 160 km/h (as for the HTR 412 Blues technical data sheet) to analyze the worst-case scenario, where the train experiences maximum discomfort. For our analysis, we chose n values ranging from 0.01 to 10. This range results in frequency ranges from 2.792526 Hz to 2792.526803 Hz. This approach provides a comprehensive view of all significant frequencies, allowing us to calculate $G_d(\Omega)$ using the formula. Using the track irregularity PSD, we can calculate the Spectrum of the Road Irregularity. This represents the vertical displacement of the wheels at different excitation frequencies. The formula used to compute the spectrum is:

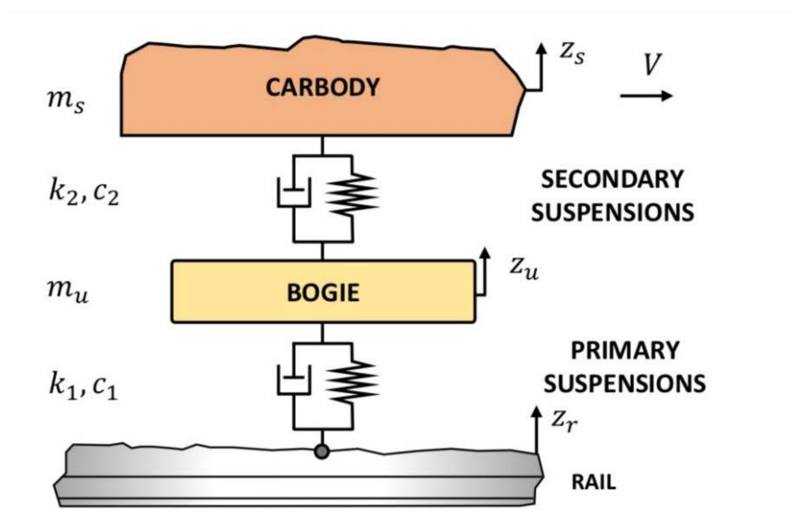
$$Z_r(\Omega) = \sqrt{2G(\Omega)\Delta\Omega}$$

The resulting spectrum illustrates how the road irregularities are distributed across different frequencies.



The graph indicates that the level of track defects significantly impacts the vibration spectrum experienced by the train. Tracks with small defects show less power across all frequencies, resulting in smoother rides. Meanwhile, as the defect size increases, the power in the lower frequency range increases, which aligns with the resonant frequencies of the suspension system, potentially leading to higher vibrations transmitted to the carbody.

Transmission of Vibrations to the Bogie and Carbody



To understand how these vibrations affect the bogie and carbody, we can use simplified models. One such model is the Quarter Car Model. This model is effective in analyzing the performance of suspensions by considering parameters such as stiffness and damping. The Quarter Car Model represents only a quarter of the vehicle and simplifies the analysis of vertical dynamics.

Parameters for the Analysis

For a comprehensive analysis, it is essential to start with several known parameters:

m_s = 9000 kg Sprung mass (the carbody)

m_u = 1400 kg Unsprung mass (the bogie)

k_1 = 340000 N/m Primary suspension stiffness

k_2 = 1950000 N/m Secondary suspension stiffness

c_1 = 13000 Ns/m Primary suspension damping

c_2 = 16000 Ns/m Secondary suspension damping

For these parameters, we used values compatible with the HTR 412 Blues train, which is the train under analysis.

In our analysis, the goal of applying the Quarter Car Model is to determine the vertical displacements z_s and z_u, representing the sprung mass (carbody) and unsprung mass (bogie), respectively. These are derived from the equations of motion in the frequency domain, leading to the following transfer functions:

For the road-sprung mass transfer function:

$$H_{sr(\omega)} = \frac{z_s}{z_r} = \frac{(c_1 s + k_1)(c_2 s + k_2)}{D(s)}$$

For the road-unsprung mass transfer function:

$$H_{ur(\omega)} = \frac{z_u}{z_r} = \frac{(c_1 s + k_1)(m_s s^2 + c_2 s + k_2)}{D(s)}$$

Where $D(s)$ is the denominator polynomial, representing the dynamic characteristics of the system:

$$D(s) = m_s m_u s^4 + [m_s(c_2 + c_1) + m_u c_1]s^3 + [m_s(k_2 + k_1) + m_u k_2 + c_2 c_1]s^2 + (k_1 c_2 + k_2 c_1)s + k_2 k_1$$

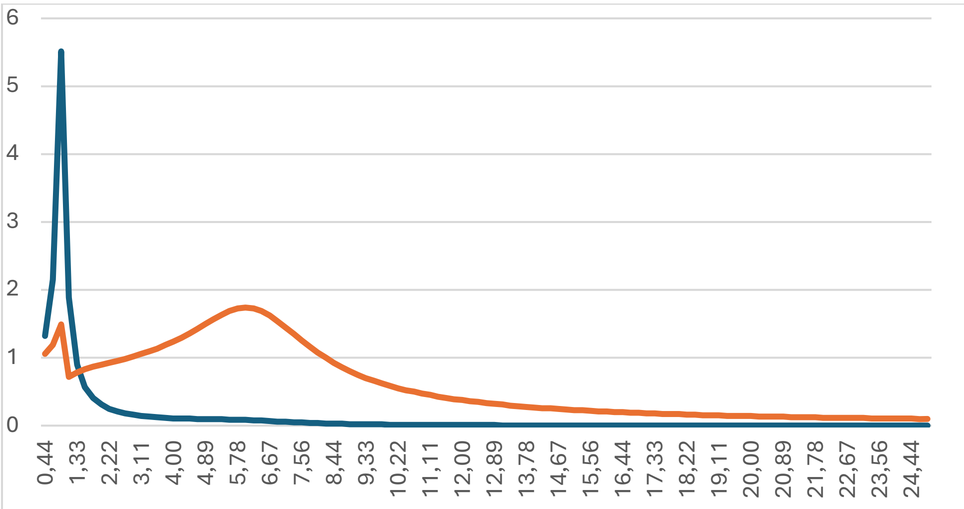
Here s = jω is the complex frequency variable.

Using these parameters and equations, we computed the frequency domain responses of the sprung and unsprung masses as follows:

$$Z_s(f) = H_{sr}(f) Z_r(f)$$

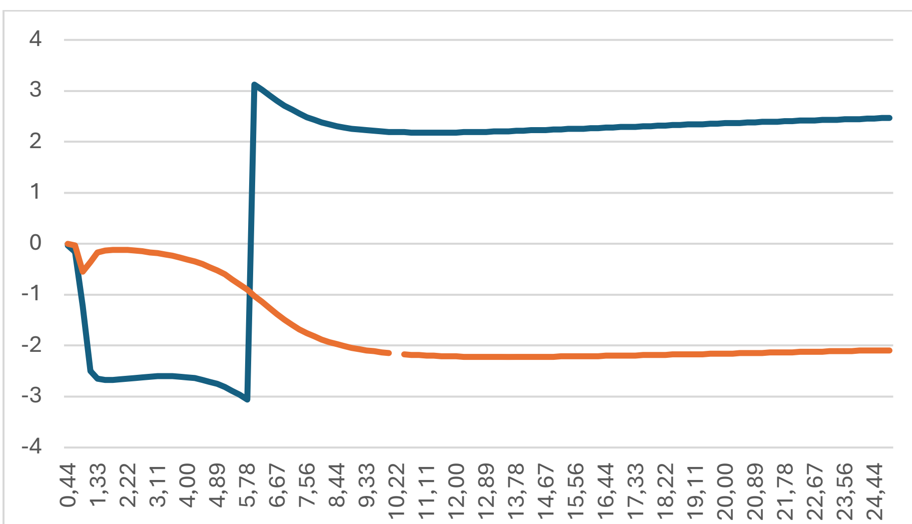
$$Z_u(f) = H_{ur}(f) Z_r(f)$$

These expressions represent the responses of the sprung and unsprung masses, respectively, in the frequency domain.



Transfer Function Magnitude for Sprung and Unsprung Masses

The carbody (blue line) shows strong damping at high frequencies, with a peak near 1 Hz. The bogie (orange line) displays greater response amplitude at higher frequencies.

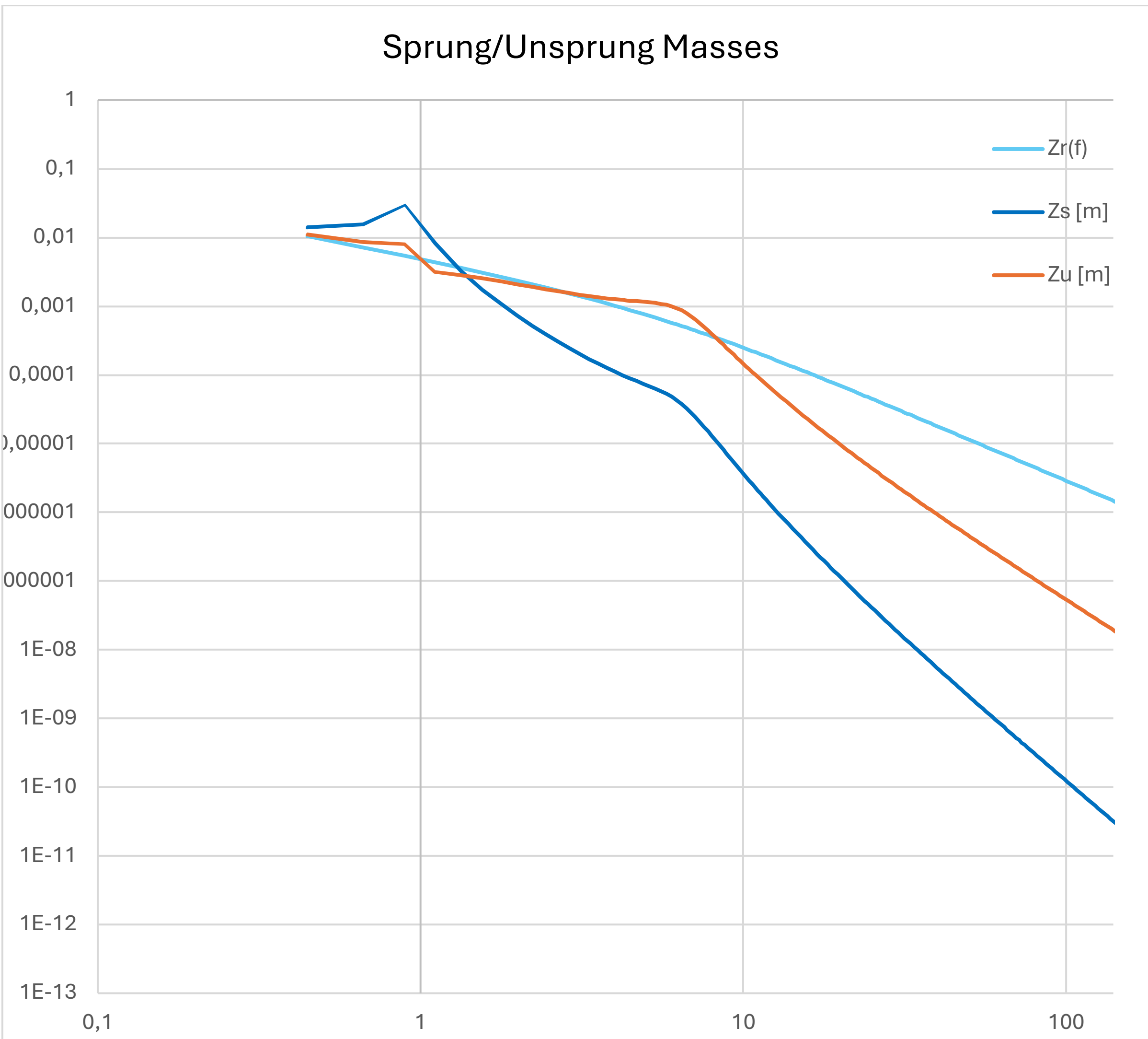


Transfer Function Phase for Sprung and Unsprung Masses

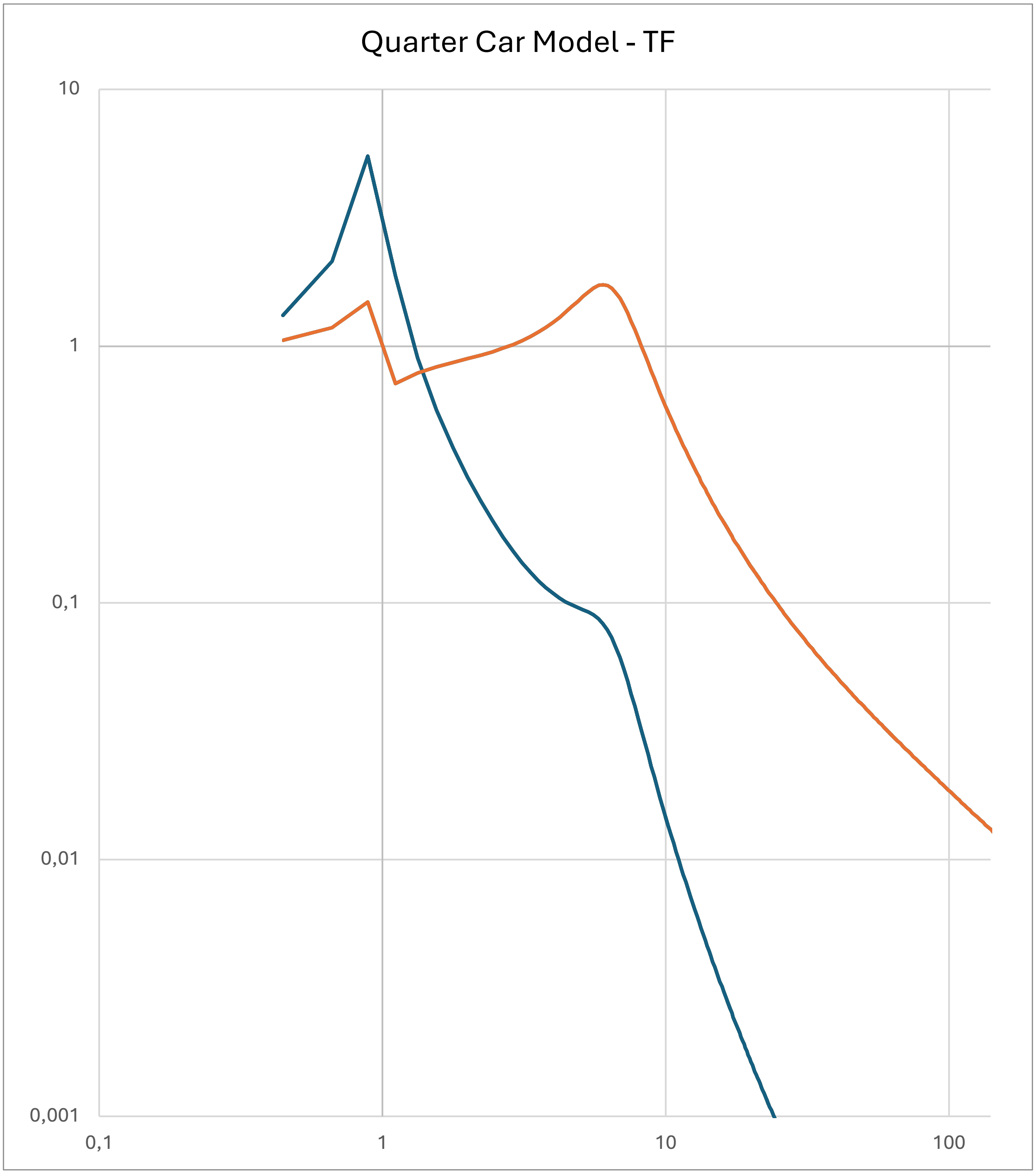
Carbody (blue) and bogie (orange) phase shifts show major changes near the system's natural frequency.

Analysis of Transfer Functions and Mass Responses

The graphs below show the transfer functions for the sprung and unsprung masses and their corresponding responses to the road irregularity spectrum in the frequency domain.



The graph illustrates the frequency response of the sprung mass (carbody) and unsprung mass (bogie) in relation to road irregularities. The blue line represents the carbody's response, showing significant attenuation at higher frequencies due to the damping effects of the secondary suspension system ($c_2$and k_2), with a peak around 1 Hz indicating the natural frequency of the sprung mass system. The orange line shows the bogie's response, which has higher amplitude at higher frequencies, indicating the unsprung mass is more affected by high-frequency inputs due to less damping and stiffness. The light blue line represents the road input spectrum, providing a baseline for comparison.



The graph shows the transfer function of the quarter car model, illustrating how road irregularities are transferred through the suspension system. The blue line indicates the transfer function from the road to the carbody, with a peak around 1 Hz reflecting the natural frequency of the primary suspension (k1 and c1). The orange line represents the transfer function from the road to the bogie, showing higher gains at higher frequencies, indicating that the bogie is less effective at damping high-frequency vibrations compared to the primary suspension.

Comfort is described as "the well-being of a person or the absence of mechanical disturbance concerning induced movement." Various physiological and environmental factors can influence comfort, with vibration being a significant source of discomfort for passengers. On-board vibrations can result from wheel/rail interactions, engine vibrations, aerodynamic effects, or forces from vehicle dynamics.

Vibrations also result in noise problems, as the vibrating surfaces generate waves in the surrounding air. Thus, vibration mitigation measures can reduce both vibrations and noise emissions.

According to the ISO 2631 standard, the primary quantity for evaluating vibration magnitude is acceleration a [m/s2].

In our project, starting from the carbody displacement spectrum $Zs(f)$, obtained as shown in the previous chapter, we derived twice in the frequency domain and computed the carbody acceleration spectrum $z_{\ddot{S}}\ (f)$:

$$z_{\ddot{S}}\ (f)=j(2\pi f)\ z_{\dot{S}}\ (f)=-\ (2\pi f)^2 z_s\ (f)$$

Then, we proceeded to turn the narrow band signal power spectrum in third-octave bands, obtaining the third-octave band carbody acceleration $z_{\ddot{S}}$ (i):

$$\frac{z_{\ddot{S}}\ (\mathrm{i})^2}{2} = \Sigma_{fmin,i}^{fmax,i}\ \frac{z_{\ddot{S}}\ (\mathrm{f})^2}{2}$$

$$\mathrm{i} = 1{,}2{,}\ldots,\ \mathrm{n_{bands}}$$

We then computed the Root Mean Square of the third octave bands carbody acceleration:

$$z_{\ddot{S},RMS}\ (i) = \sqrt{\frac{{z_S}^2}{2}}$$

Finally, applying the ponderation filter W_k (i) to each of the $\ddot{z}_{S,RMS}$ (i): and summing up all of them, we obtained the weighted acceleration $a_{W,RMS}$ corresponding to a top speed of 160 km/h.

$$a_{W,RMS} = \sqrt{[\,\Sigma\,(W_k(i)\ddot{z}_{s,RMS}\,(i)\,)^2]}$$

By following the above steps we reached the final $a_{W,RMS}$ in our 3 categories as below:

$a_{w,RMS}$	
small defect	0.4431
medium defect	0.5371
big defect	0.7252

Comparing the obtained $a_{W,RMS}$ with the standard ISO 2631 we see:

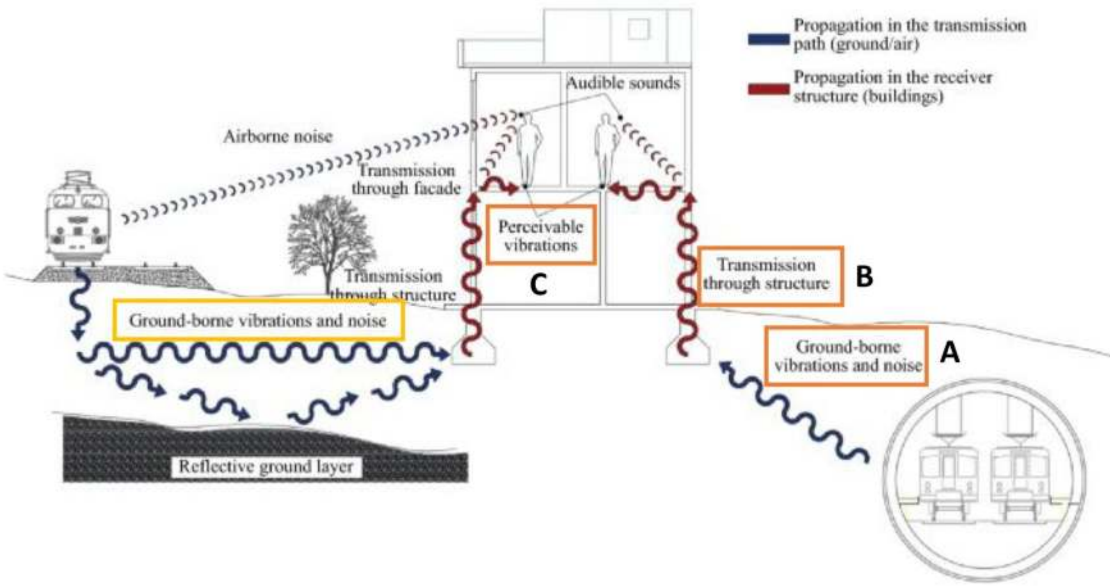
$a_{w,RMS}$		
	Less than 0,315 m/s^2:	not uncomfortable
	0,315 m/s^2 to 0,63 m/s^2:	a little uncomfortable
	0,5 m/s^2 to 1 m/s^2:	fairly uncomfortable
	0,8 m/s^2 to 1,6 m/s^2:	uncomfortable
	1,25 m/s^2 to 2,5 m/s^2:	very uncomfortable
	Greater than 2 m/s^2:	extremely uncomfortable

Even with big defects, we are not in an uncomfortable area, even though it's not our case. We can say in our project we are a little uncomfortable, so we should take a look at techniques to enhance the ride experience.

4.2 Ground borne vibration

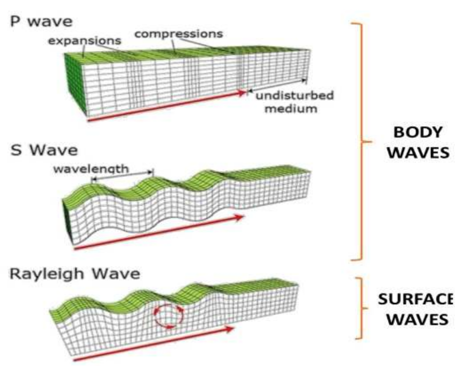
Vehicles that run on the rails are responsible for the vibrations transmitted through the ground and to the foundations of the buildings.

Due to this, we analyzed the effect of vibrations on the nearby infrastructures.



The vibration propagation doesn't concern only the transport unit, but there are also vibrations through the track and soil, affecting neighboring buildings and people.

When we analyze wave propagation in soil, there are different types of waves can be recognized:



1. P-WAVES: or primary waves, the first to arrive at observation point, causing dilatation/ compression.
2. S-WAVE: or secondary waves, the second arrive at observation point, causing shearing motion.
3. RAYLEIGH WAVES: running on the surface, causing dilatation/ compression and shearing motion.

Far from the source, Rayleigh waves are predominant and lead to much stronger vibrations with respect to P or S waves.

The difference in vibration strength can be attributed to the “geometrical damping” effect, which affects the rate of energy decay. Rayleigh waves, being confined to the surface, exhibit slower energy decay compared to P and S waves, which propagate through the volume of the medium with a spherical wavefront, leading to a faster decay of energy as the distance from the source increases.

It's possible to analyze the transmissibility of vibration through the track in the frequency domain.

Track super and sub-structure can be modelled as several viscoelastic layers of material with different mass, stiffness, and damping properties per unit length/area. Each of these layers has its own capability of transmitting/filtering the vibration induced by vehicle/track interaction.

The vibration propagation through the soil cannot be reduced acting on the soil properties, thus, the only way to prevent the vibration propagation from the vehicle to the surrounding infrastructures is to isolate the vibration by properly designing the track superstructure.

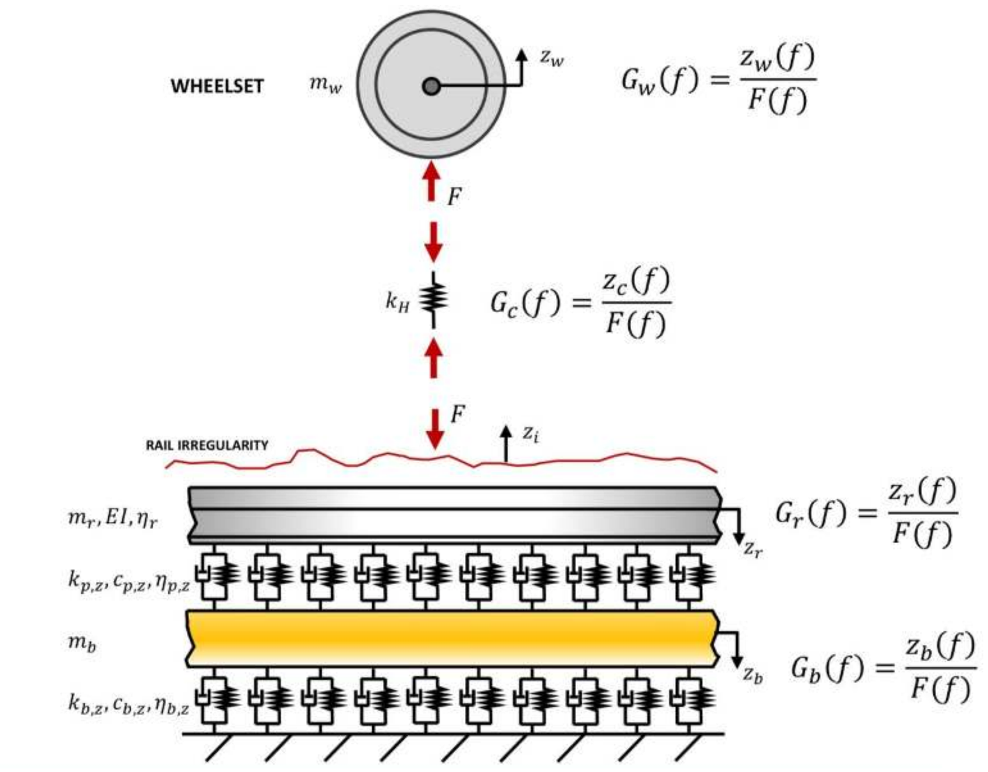
The principal vibration isolating track designs we considered are:

- **Ballasted track**, in which a layer of crushed stone, known as ballast, is laid on the subgrade (the natural formation or prepared foundation) to create a stable and resilient track bed. The track components, such as sleepers/ties and rails, are then placed on top of the ballast.

- **Floating slab track**, in which a solid concrete slab is constructed directly on the subgrade. The track components, including rails and sleepers/ties, are embedded or mounted on the concrete slab.

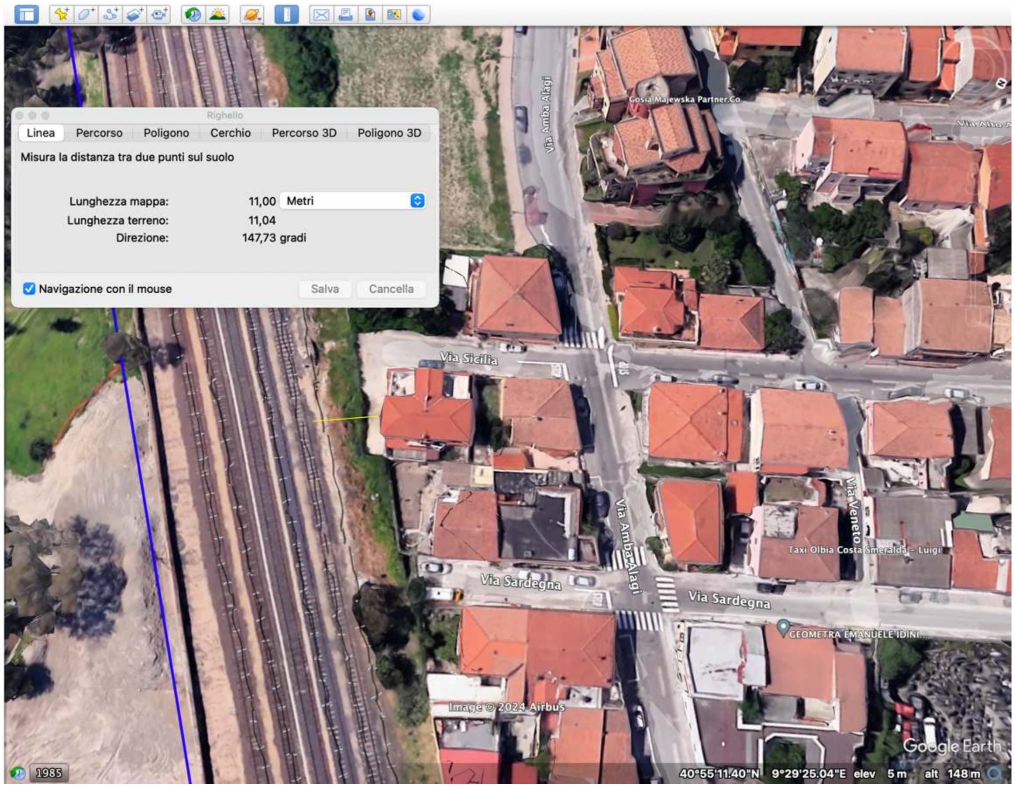
In general, slab tracks offer superior stability and vibration isolation compared to ballasted tracks. This is due to the stiffness and rigidity of the solid concrete slab, which reduces the dynamic response of the track system. However, constructing slab tracks incurs higher upfront costs due to extensive concrete works and specialized installation methods. Nonetheless, reduced maintenance and increased lifespan can result in long-term cost savings.

For our project, we have chosen to implement a slab track, owing to its superior performance in terms of stability and vibration isolation, as well as its low maintenance costs, despite the higher initial investment compared to ballasted tracks. Considering the frequency range of 0.22-200 Hz, the primary and secondary suspensions isolate the bogie and car body from the track. The model can be simplified to a single wheelset running on the rail.



[Model as a single wheel]

Now, we want to analyze the most critical situation that happens in Olbia, where the distance between the nearest rail and the nearest house is 11 and the train has a speed of 80 km/h.



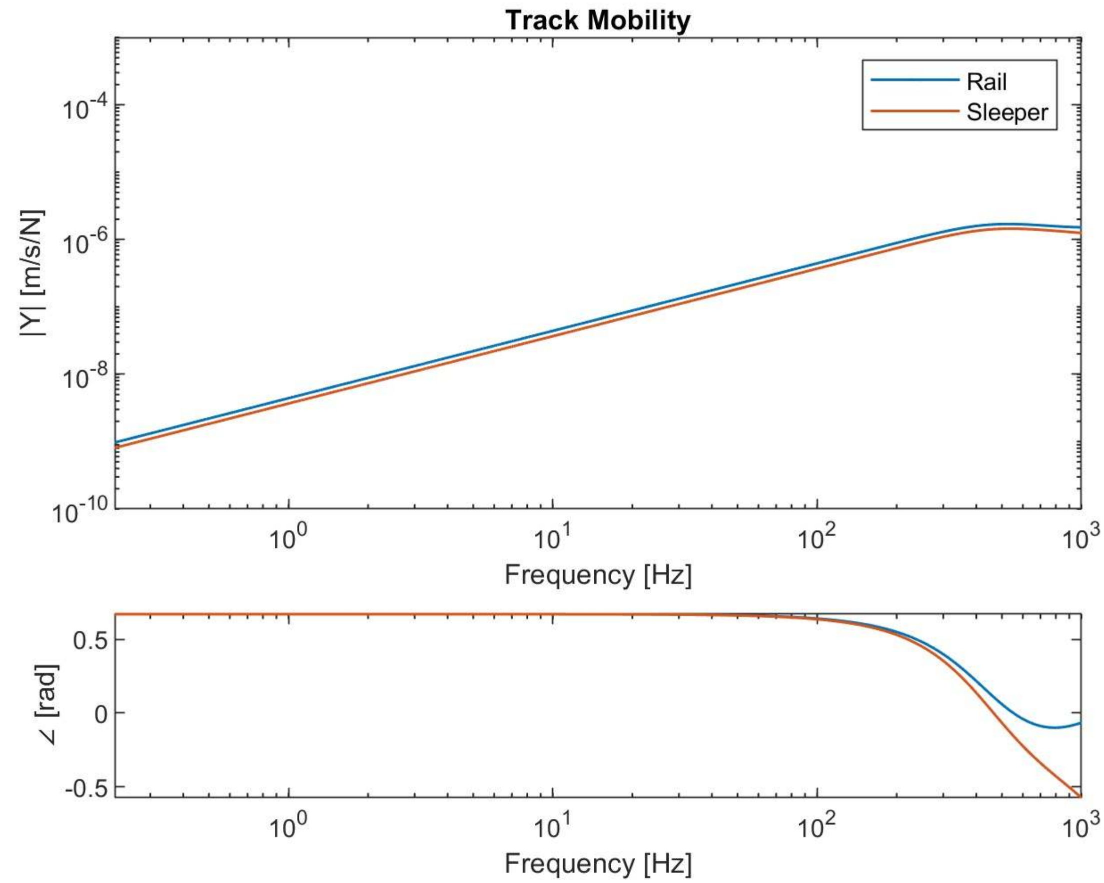
In this image, we have the most critical situation, within Olbia city.

So, the first step of our analysis involved computing the transfer function of vibrations on the wheel G_w (f) as:

$$G_w \text{ (f)} = \frac{-1}{(m_w * \omega^2)}$$

where m_w = 1000 kg (the mass of the wheelset).

Next, we obtained the transfer functions G_r (f) and G_b (f), which are the transfer functions of vibrations on the rail and slab, respectively. This was done through a MATLAB function.



applying a Timoshenko Double Layer using the below data we obtained the transfer functions, the spectrum of vibration of rail and ballast, and overall forces transmitted to the ground:

- f_{track}= (0.22: 0.001: 200) Hz – frequencies vector
- m_r= 60 kg/m – rail mass
- m_s= 1110 kg/m – slab mass
- k_1= 3 × 10^8 N/m^2 – rail pad stiffness
- k_2= 6 × 10^7 N/m^2 – slab stiffness
- η_1= 0.35 – rail pad loss factor (structural damping)
- η_2= 0.35 – slab support loss factor (structural damping)
- EJ_r= 6.95 × 10^6 Nm^2 – rail bending stiffness

Once obtained the transfer functions, we could compute the spectrum of the wheel, rail, and slab vibrations, respectively zw, zr and zs, as:

$$\mathrm{Z}w = GwF = = \frac{\mathrm{Gw}*\mathrm{zi}}{\left(\left(\frac{1}{\mathrm{kH}}+\mathrm{Gr}+\mathrm{Gw}\right)\right)}$$

$$\mathrm{Z}r = GrF = \frac{\mathrm{Gr}*\mathrm{zi}}{\left(\left(\frac{1}{\mathrm{kH}}+\mathrm{Gr}+\mathrm{Gw}\right)\right)}$$

$$\mathrm{Z}s = GsF = \frac{\mathrm{Gs}*\mathrm{zi}}{\left(\left(\frac{1}{\mathrm{kH}}+\mathrm{Gr}+\mathrm{Gw}\right)\right)}$$

F= Elastic force
Z_i=$road\ irregularity$ ($computed\ in\ road\ irregularity$)
kH=3∗109 $Nm-Hertzian\ contact\ spring$

Finally, we computed $Fsoil$, the overall force that, after being filtered by the two beams, reaches the ground:

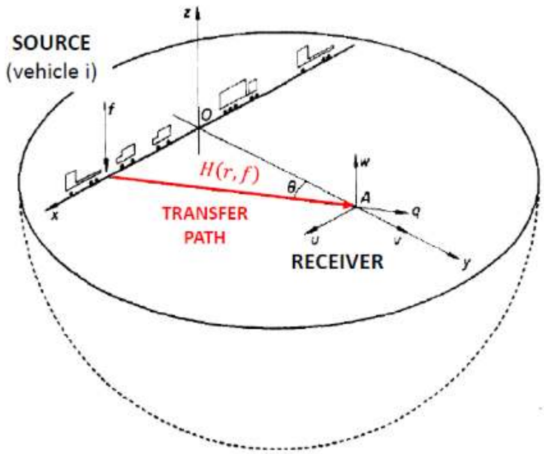
$$Fsoil=k_2 Zb(f)\Delta L$$

Where ΔL is two times the spacing between two consecutive fastenings. $\mathrm{L} = 0.6\ \mathrm{m}$

Surface waves (Rayleigh waves) generated by train/rail interaction result in ground-borne vibrations that may affect nearby buildings and residents. The Hunt model is a simplified way to analyze traffic-induced ground-borne vibrations. The model is formulated to estimate the vibration generated by a series of vehicles (a train, in our case) that produce soil excitation due to wheel/track interaction.

The Hunt model represents the train (vibration source) as a sum of the contributions of all the wheel/rail forces generated by all the wheels running on the rail. The vibration at the receiver location is computed by evaluating the soil transfer function for each relative source/receiver position. This approach allows for assessing the cumulative impact of the train's wheelsets on the surrounding environment.

By computing the vibration contributions from each wheelset and considering the relative distances, the model provides a comprehensive view of the ground-borne vibrations generated by train traffic, helping to predict and mitigate their effects on nearby structures and residents.



The first step is calculating the relative distances between the receiver and the wheelsets of the coaches. The relative distances are 44 m from the head and the end of the locomotives, and 11 m from the train's center to the nearest house.

After providing our vector of source-receiver relative distances as input, we ran a MATLAB function to compute the Hunt model. We calculated the Power Spectrum of the vibration of the receiver due to the contribution of each single source,

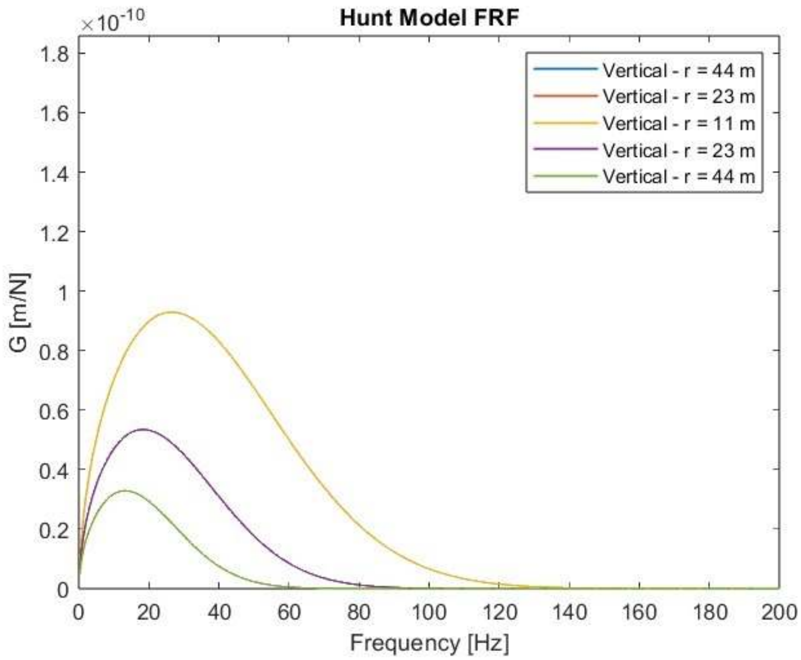
$$PS_d{}^i(r,f)=|G(r_i, f)|^2 PS_F{}^i\,(f)$$

$$PS_F{}^i(r,f)=\frac{|f_{Soil})|^2}{4}\text{ - } power\ spectrum\ of\ Fsoil$$

Summing each one of these components we can compute the Power Spectrum of the vibration of the receiver due to the overall contribution of the train and consequently, we turned this Power Spectrum of the vibration (displacement) of the receiver into the Power Spectrum of acceleration:

$$PS_d{}^{tot}(f) = \Sigma|G(r_i, f)|^2 PS_F{}^i\,(f)$$

$$PS_a{}^{tot}(f) = \omega^4 PS_d{}^{tot}(r,f)$$



The final step involves processing the vibration spectrum at the receiver location through Third-Octave Bands, applying a Ponderation Filter, and computing the weighted RMS acceleration. For this, we follow these steps:

$$\frac{{PS_a}^{tot}(i)}{2} = \Sigma_{fmin,i}^{fmax,i} \frac{{PS_a}^{tot}(f)}{2}$$

$$i = 1,2,\ldots, n_{bands}$$

$${PS_{a,RMS}}^{tot}(i) = \sqrt{\frac{{PS_a}^{tot}(i)}{2}}$$

$$i = 1,2,\ldots, n_{bands}$$

$$a_{W,RMS} = \sqrt{[\, \Sigma\, (W_k(i){PS_{a,RMS}}^{tot}(i))^2]}$$

This weighted RMS acceleration is then compared with the following standard values.

Area Type	Acceleration a [m/s²]
Critical areas	$5*10^{-3}$
Residential areas (night)	$7*10^{-3}$
Residential areas (day)	$10*10^{-3}$
Office	$20*10^{-3}$
Factories	$40*10^{-3}$

Following the mentioned steps through a MATLAB code finally, our result was:

$$a_{W,RMS} = 0.1357 \text{ [m/s^2]}$$

This number suggests we should take into consideration some actions to reduce the weighted RMS acceleration.

MATLAB code for the analysis:

Matlab Code

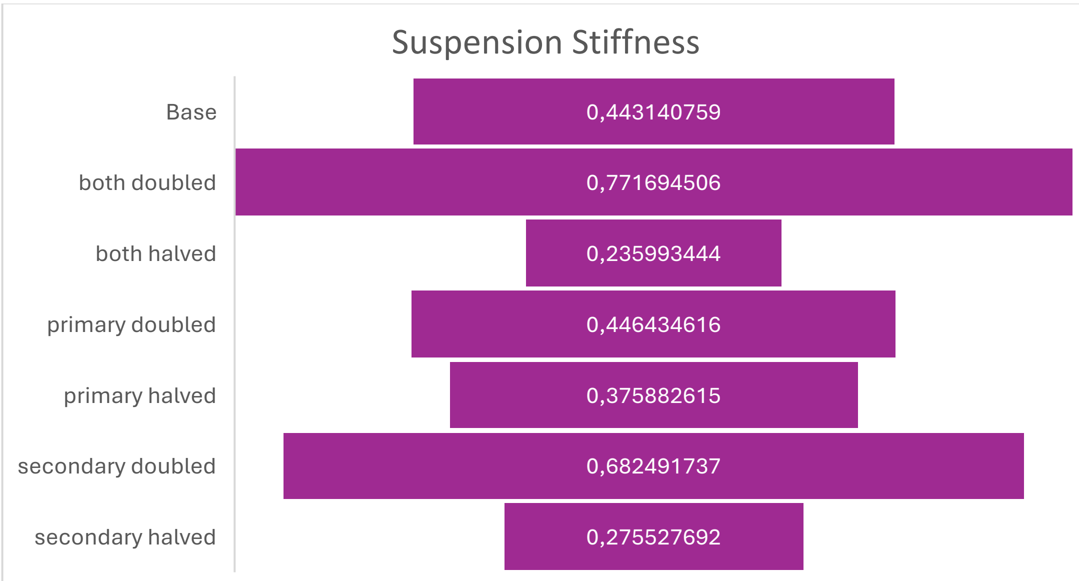
```
%% Ground Borne Vibration - Main

clear
close all
clc
% Frequency vector (track models)
f_track=(0.22:0.001:200)'; % [Hz]
size(f_track)
w=2*pi*f_track;
m_w=1000;
fp=0.6;
Gw=-1./(m_w*w.^2);
fc = [0.02, 0.025, 0.0315, 0.04, 0.05, 0.063, 0.08, 0.1, 0.125, 0.16, 0.2, 0.25,
0.315, 0.4, 0.5, 0.63, 0.8, 1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16,
20,25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400];
fl = [0.018, 0.022, 0.028, 0.035, 0.045, 0.056, 0.071, 0.09, 0.112, 0.14, 0.18,
0.224, 0.281, 0.354, 0.449, 0.561, 0.707, 0.898, 1.12, 1.4, 1.8, 2.24, 2.81, 3.54,
4.49, 5.61, 7.07, 8.98, 11.2, 14, 18, 22.4, 28, 35, 45, 56, 71, 90, 112, 140, 180,
224, 281, 354, 449];
fu = [0.022, 0.028, 0.035, 0.045, 0.056, 0.071, 0.09, 0.112, 0.14, 0.18, 0.224,
0.281, 0.354, 0.449, 0.561, 0.707, 0.898, 1.12, 1.4, 1.8, 2.24, 2.81, 3.54, 4.49,
5.61, 7.07, 8.98, 11.2, 14, 18, 22.4, 28, 35, 45, 56, 71, 90, 112, 140, 180, 224,
281, 354, 449, 561];
Wkk = [0, 0, 0, 0, 0, 0, 0, 31.2, 48.6, 79, 121, 182, 263, 352, 418, 459, 477, 482,
484, 494, 531, 631, 804, 967, 1039, 1054, 1036, 988, 902, 768, 636, 513, 405,
314, 246, 186, 132, 88.7, 54, 28.5, 15.2, 7.9, 3.98, 1.95]/1000;
% Vehicle Dynamics (wheelset)
kH=2*1.5e9; % Hertzian Contact Spring (N/m)
fp=0.6; % distance between the fastenings (m)
k_fast=50e6; % vertical stiffness of one single fastening (N/m)
k1fast=2*k_fast/fp ; % vertical stiffness of the fastenings per unit track length
(N/m/m)
k2fast=3.8e9; % soil vertical stiffness per unit track length (N/m/m)
deltal=fp*2;
%% 1. Ballast (double Rail)
m_r=2*60; % rail mass [kg/m]
m_s=2*120; % sleeper mass [kg/m]
k1=2*3e8; % railpad stiffness [N/m^2]
k2=2*6e7; % ballast stiffness [N/m^2]
eta_1=2*0.35; % railpad loss factor (structural damping) [-]
eta_2=2*0.35; % ballast loss factor (structural damping) [-]
EJ_r=6.95e6; % rail bending stiffness [N/m^2]
% run function
[G1_Ballast,G2_Ballast]=TrackModel_Timoshenko_DoubleLayer(k1,k2,eta_1,eta_2,m_r,m_s,E
J_r,f_track); % [G1,G2]: Track Vertical Receptances (displacement/force) [m/N]
%%
```

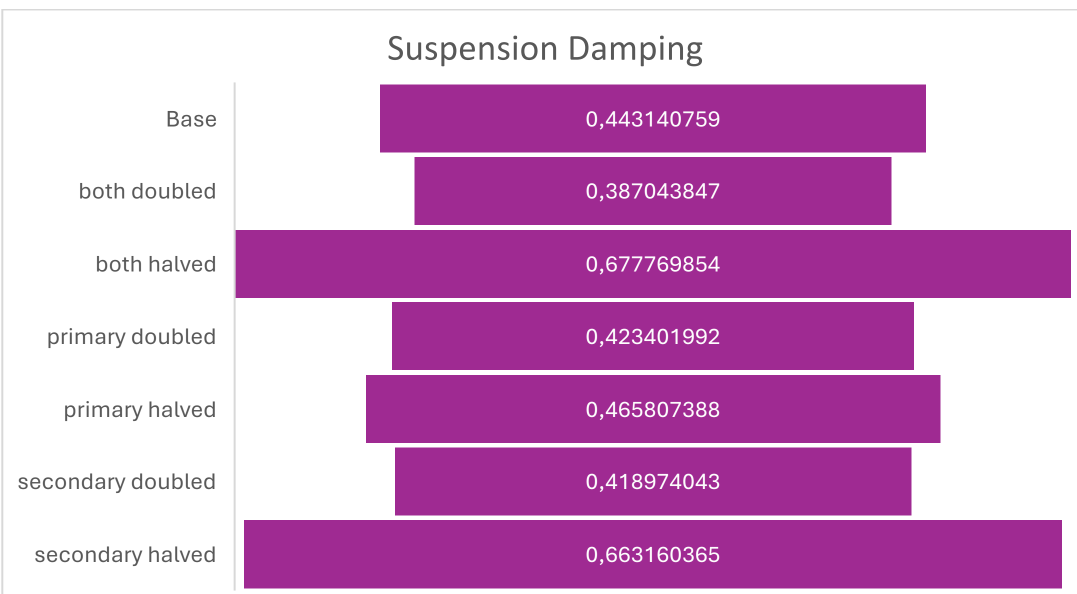
```
% Distanza relativa tra sorgente e ricevitore
R = [44, 23, 11, 23, 44];
% Velocità del treno
v = 22.22;
n=f_track/v;
%Gd
omegac=0.8246;
omegar=0.0206;
Av=5.9233e-7;
omega=2*pi*n;
deltaomega=omega(2)-omega(1);
g1babs=(G1_Ballast);
g2babs=(G2_Ballast);
d=((omega.^2+omegar^2).*(omega.^2+omegac^2));
Gd=(Av*omegac^2)./d;
Z=sqrt(2*Gd.*deltaomega);
Zabs=abs(Z);
kh2=1/(kH);
F=Zabs./(kh2+g1babs+Gw);
Zb1=g1babs.*F;
Fsoil=k2fast*Zb1*deltal;
PSF = abs(Fsoil).^2 / 2 * 2; % 2 wheelset per bogie !!
f_Hunt = n * v;
[G_Hunt] = SoilModel_Hunt(R, f_Hunt);
%%
Psd = abs(G_Hunt).^2 .* PSF;
PSd_tot = sum(Psd,2);
PSa_tot=(2*pi*f_Hunt).^4.*PSd_tot;
%% Third Octave Bands
PSa_third_octave = zeros(size(fc));
for i = 1:length(fc)
f_low = fl(i);
f_high = fu(i);
indices = find(f_Hunt > f_low & f_Hunt <= f_high);
%if ~isempty(indices)
PSa_third_octave(i) = sum(PSa_tot(indices));
%end
end
PSa_RMS_third_octave = sqrt(PSa_third_octave);
weighted_PSa_RMS_third_octave = Wkk .* PSa_RMS_third_octave;
aw_RMS = sqrt(sum(weighted_PSa_RMS_third_octave.^2))
aw=sqrt(weighted_PSa_RMS_third_octave.^2);
aw_RMS_values = [14.5e-3, 8.2e-3, 5e-3, 2e-3]; % Corresponding RMS values
```

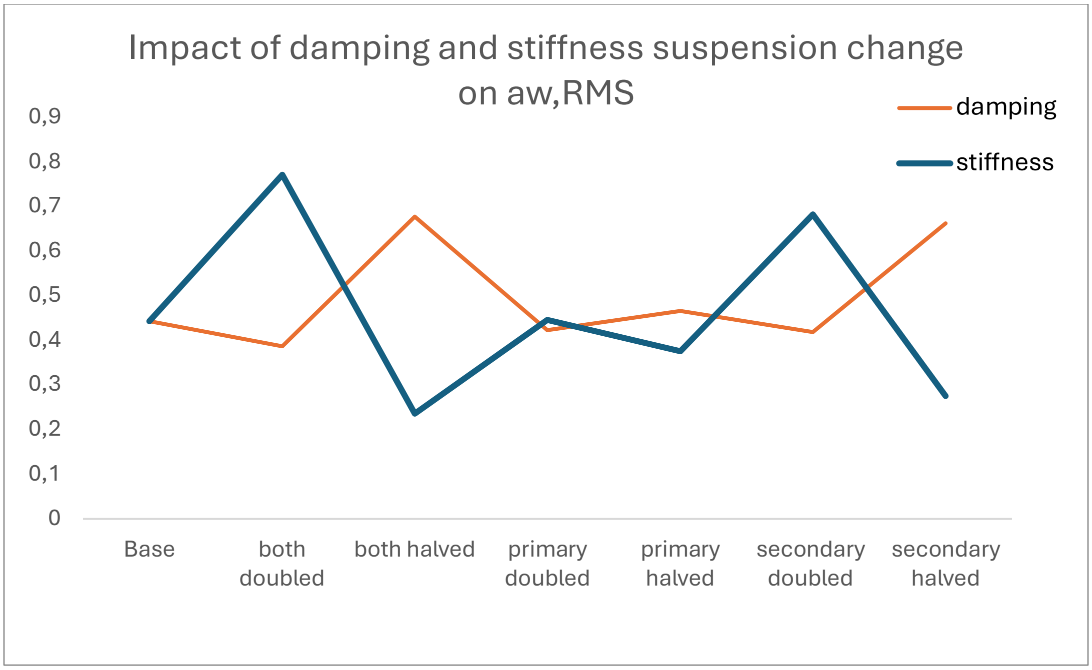
4.3 Sensitivity analysis and Mitigation solution

To have a deeper analysis of the comfort vibration, we changed the suspension stiffness and damping to see their effects on comfort.

$a_{W,RMS}$





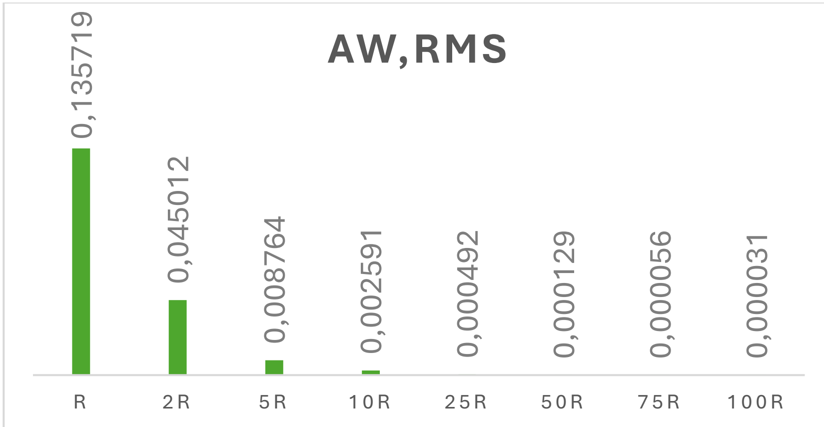


The comfort level is significantly more sensitive to stiffness adjustments compared to damping adjustments. Moreover, tuning the secondary suspensions has a much greater effect on comfort than tuning the primary suspensions because, the secondary suspensions are located under the carbody, directly influencing its vibrations.

To respect the standard ISO 2631 for aw_rms parameter, we can reduce the secondary suspension stiffness by 30 percent.

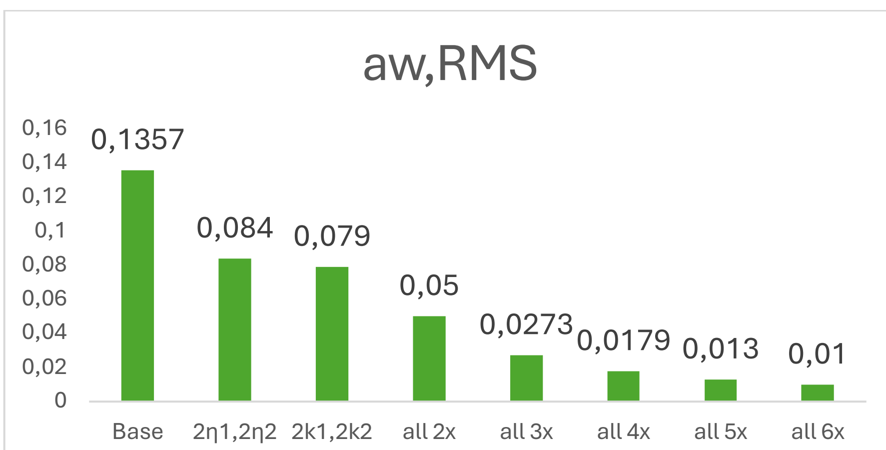
Ground borne

As the basis of our analysis, we tried to run the code considering the distance between the nearest house and the track is more than 11 meters. This suggests the optimum distance for the project. Meanwhile, it's not possible to move more than 11 meters due to the land situation in our worst-case scenario, so we tried to modify the rail pad stiffness, slab stiffness, rail pad loss factor (structural damping), and slab support loss factor (structural damping). This analysis helps us choose the most convenient factors in our project.

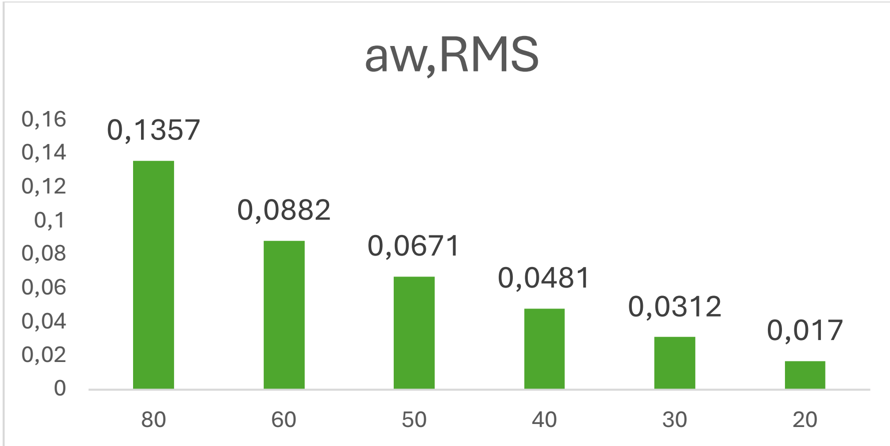


The first thing we perceive from the chart is that if we increase the distance from the path to the nearest house from 11 meters to almost 55, or 60 meters, we face no problem. But as it's not possible, we are trying to find an alternative way to enhance the situation. As a result, we change the below parameters to understand their effects on the weighted RMS acceleration.

- k_1= 3 × 10^8 N/m^2 – rail pad stiffness
- k_2= 6 × 10^7 N/m^2 – slab stiffness
- η_1= 0.35 – rail pad loss factor (structural damping)
- η_2= 0.35 – slab support loss factor (structural damping)



By increasing rail pad and slab stiffness, rail pad loss factor, and slab support loss factor (structural damping) by 6 times, we almost reached the desired result for aw, RMS.



Another potential factor we can take into consideration is speed of the train near the house which show the lower the speed the better the aw, RMS.

To meet the constraints on the aw_rms parameter, it is proposed to improve the infrastructure by enhancing the constituent materials:

k1=3*2*3e8; railpad stiffness [N/m2]

k2=3*2*6e7; ballast stiffness [N/m2]

η1 =3*2*0.35; railpad loss factor (structural damping) [-]

η2 =3*2*0.35; ballast loss factor (structural damping) [-]

Additionally, it is proposed to impose a speed limit of 40 km/h.

5- SIGNALING SYSTEM

The current signaling system in the Sardegna railway network (from the Olbia to Cagliari), utilizes traditional block signaling. Although effective, this system poses challenges such as delays, limited speed monitoring, and inefficiencies on single-track sections. For our new train line, we want to introduce the Sistema di Controllo della Marcia del Treno (SCMT) and the European Rail Traffic Management System (ERTMS) to enhance safety, efficiency, and reliability.

5.1 Current Signaling System in Sardinia

Analyzing the current signaling infrastructure on the Olbia to Cagliari line which uses Traditional Block Signaling helps us choose the most suitable system for the project.

- Main Components: Manual and automatic blocks, track circuits, and interlocking systems.
- Cost Estimate: Approximately €30.5 million for the Olbia to Cagliari line.
- Limits:
  - Delays due to single-track constraints and passing loop requirements.
  - Limited automated speed monitoring capabilities.
  - Noticeable reliance on manual interventions and visual signals.
  - Reduced operational efficiency, especially during high-traffic periods.

5.2 Proposed Signaling Systems

Two advanced signaling systems are among our options to enhance the railway infrastructure. We take a look at each one and decide the most convenient option.

1. SCMT (Sistema di Controllo della Marcia del Treno) [11]

- Components:
  - Sottosistema di Bordo (SSB): Onboard subsystem for receiving and processing track information.
  - Sottosistema di Terra (SST): Ground subsystem comprising transponders (Punto informativo) installed along the tracks.
- Performance:
  - Provides continuous monitoring and control of train movements.
  - Automatically calculates and enforces braking curves.
  - Integrates with existing Ripetizione Segnali (RS) system for enhanced signal monitoring.
- Cost Estimate: Approximately €10 million.
- Pros:

    - Significantly enhances safety through continuous speed monitoring and automatic braking interventions.
    - Improves operational efficiency, reducing delays.
    - Increases overall system reliability and enables smoother operations.
- Cons:
    - Initial operational delays due to increased emergency braking incidents.
    - Potential for increased wear and tear on train components, which makes it compulsory to adjust maintenance schedules.

2. ERTMS (European Rail Traffic Management System) [12]

- Components:
    - ETCS (European Train Control System) which consists of two Levels.
- Performance:
    - ETCS Level 1: Utilizes trackside equipment to transmit data to trains, enhancing signal monitoring capabilities.
    - ETCS Level 2: Enables continuous communication between trains and control centers, real-time speed, and signal information.
- Cost Estimate:
    - ETCS Level 1: Approximately €30 million.
    - ETCS Level 2: Approximately €72 million.
- Pros:
    - Ensures standardization with European rail systems, facilitating future interoperability.
    - Offers scalability for increased capacity and efficiency in the long term.
    - Enhanced safety features through continuous, real-time monitoring.
- Cons:
    - Requires substantial initial implementation costs.
    - Present challenges in integration with existing railway systems.

Below you can find the cost comparison of each signaling method. [12] [14] [15]

System	Initial Cost	Safety Improvements	Operational Efficiency	Scalability and Future-Proofing
Traditional Block	€30.5 million	Basic	Moderate	Low

SCMT	€10 million	High (continuous speed monitoring)	High (automated braking, fewer delays)	Moderate
ERTMS Level 1	€30 million	Very High (standardized, real-time)	Very High (continuous communication)	High (upgradable to Level 2)
ERTMS Level 2	€72 million	Extremely High	Extremely High	Very High

To address these issues of traditional block signaling, we propose the implementation of the Sistema di Controllo della Marcia del Treno (SCMT). SCMT offers enhanced safety through continuous speed monitoring and automated responses to signal changes, ensuring smoother and more reliable rail operations. With an estimated cost of €10 million, SCMT serves as a strong foundation for immediate improvements. Furthermore, the infrastructure of SCMT is compatible with future upgrades to the European Rail Traffic Management System (ERTMS) Level 1. By planning for this upgrade, which is estimated to cost an additional €20 million, we can align Sardinia's railway with European standards, providing long-term scalability and enhanced operational capabilities. [13]

Implementation Plan

Phase 1: SCMT Implementation (0-18 months)

- Install SCMT components (SSB and SST) along the Olbia to Cagliari line
- Train personnel and crew on the new system operations and maintenance
- Conduct comprehensive testing of the SCMT system

Phase 2: ERTMS Level 1 Upgrade (18-36 months)

- Install Eurobalises along the railway line
- Update onboard equipment to ensure ERTMS compatibility
- Ensure smooth integration between SCMT and ERTMS systems
- Provide extensive training to staff on ERTMS operations and maintenance

5.3 Conclusion

The proposed implementation strategy offers a balanced approach to upgrading Sardinia's railway signaling system:

1. Immediate Benefits: Implementing SCMT as an initial solution provides significant safety and efficiency improvements at a lower upfront cost.
2. Future-Proofing: Planning for a subsequent upgrade to ERTMS Level 1 ensures the Sardinia railway network aligns with broader European standards.
3. Scalability: This phased approach leaves room for future enhancements and potential upgrades to more advanced ERTMS levels.
4. Cost-Effectiveness: The estimated cost for transitioning from SCMT to ERTMS Level 1 is approximately €20 million, bringing the total investment to around €30 million.
5. This represents a more manageable financial commitment compared to an immediate full ERTMS implementation.
6. Sustainable Development: By balancing immediate needs with long-term goals, this strategy represents a sustainable and forward-thinking solution for Sardinia's rail infrastructure.

Also, the opportunity to Seek EU funding and other financial support to offset the high initial costs of ERTMS implementation and the Smoother and more efficient operations benefit daily commuters and tourists, assure us to apply the mentioned signaling system.

6-DIAGNOSTIC AND MAINTENANCE

6.1 General overview

Railway systems diagnostics involves inspection, monitoring, and maintenance of infrastructure and rolling stock. Railway networks are complex, integrating multiple systems for safety and operational efficiency. Techniques such as condition-based maintenance and predictive maintenance enhance reliability and safety by detecting and addressing issues. Maintenance is crucial for extending the operational phase of components, preventing failures, and ensuring the economic sustainability of the railway system.

Maintenance in railway systems is divided into ordinary and extraordinary categories. **Ordinary maintenance** includes routine, scheduled or unscheduled activities aimed at replacing parts subject to wear and tear. Associated costs are generally included in the regular budget. **Extraordinary maintenance** involves major parts of the system, often for improvements that enhance capital value.

Ordinary maintenance further divides into reactive and proactive maintenance. **Reactive** maintenance responds to issues and includes corrective actions. **Proactive** maintenance is preventive, aiming to prevent failures through three main approaches: ameliorative (design modifications), programmable/cyclic (periodic replacement), and condition-based (scheduled replacement based on specific measurements). Predictive maintenance utilizes data and models to predict and schedule future replacements.

In the railway sector, maintenance represents approximately 25% of infrastructure costs, with 70-90% of these costs related to corrective maintenance. Adoption of advanced approaches can reduce maintenance costs by up to 30%. Effective maintenance is crucial for ensuring the safety, reliability, and economic sustainability of railway operations.

Railway maintenance is complex, involving various elements and subsystems across the network, necessitating different types of inspections and measurements, from visual inspections to geometric measurements and specific parameters.

6.2 Maintenance of Trains in Sardinia

The maintenance of trains in Sardinia faces several unique challenges related to the island's geographical and infrastructural specifics. In Sardinia, Trenitalia is responsible for the management and maintenance of railway services, including both regional and long-distance trains.

The railway lines in Sardinia are predominantly single-track and non-electrified, which means that trains primarily operate with diesel engines. Regular maintenance of facilities includes the replacement of tracks and sleepers, checking signaling systems, and inspecting the condition of bridges and tunnels.

The creation of a new double-track and fully electrified railway line in Sardinia would bring significant changes and improvements to the maintenance of the railway system. Firstly, a double-track line would allow traffic to be more evenly distributed, reducing wear on existing infrastructure and decreasing the need for frequent maintenance interventions. This would lead to a longer lifespan for the tracks and more efficient resource management.

Many railway routes are subject to degradation and require periodic interventions to ensure safety and operability. Despite improvements, some areas of the island still suffer from limited railway services, with few daily runs making mobility difficult for residents.
Often, funding for maintenance and infrastructure improvements is limited, which can delay necessary interventions and affect the quality of service.

Trenitalia and the Sardinia Region are collaborating to improve the conditions of railway infrastructure and increase the frequency and reliability of services. Investments to renew existing lines, aiming to reduce travel times and increase safety. Introduction of more modern and comfortable trains, which are also more energy-efficient.

Some specific issues faced in Sardinia include the fact that railway routes are subject to degradation and require periodic interventions to ensure safety and operability. Despite improvements, some areas of the island still suffer from limited railway services, with few daily runs making mobility difficult for residents. Often, funding for maintenance and infrastructure improvements is limited, which can delay necessary interventions and affect the quality of service.

Predictive maintenance, which uses data and models to anticipate and prevent failures, is becoming an increasingly common practice. This methodology allows for interventions before serious problems occur, improving service reliability and reducing long-term costs.

Despite progress, challenges remain, particularly regarding continuous funding and modernization of existing infrastructure. However, the opportunities to improve the Sardinian railway system through advanced technologies and more efficient management are significant.

Electrified lines can be equipped with sensors for real-time monitoring of track and rolling stock conditions, facilitating predictive and condition-based maintenance. With continuous monitoring and data analysis, it would be possible to predict and prevent failures, reducing the need for corrective maintenance, which currently represents a significant portion of maintenance costs.

6.3 Depot

Depot		
lenght	86,08	m
windth	2,8	m
n° vehicle	10	
vehicle area	241,024	m^2
access area	964,096	m^2
visual inspection	1928,192	m^2
parking area	4820,48	m^2
maintenance area	964,096	m^2
total area	8676,864	m^2

From the equation $N_v = \frac{tf}{3600}$; $t = 7049\ s$; $f = 2\frac{trains}{h}$

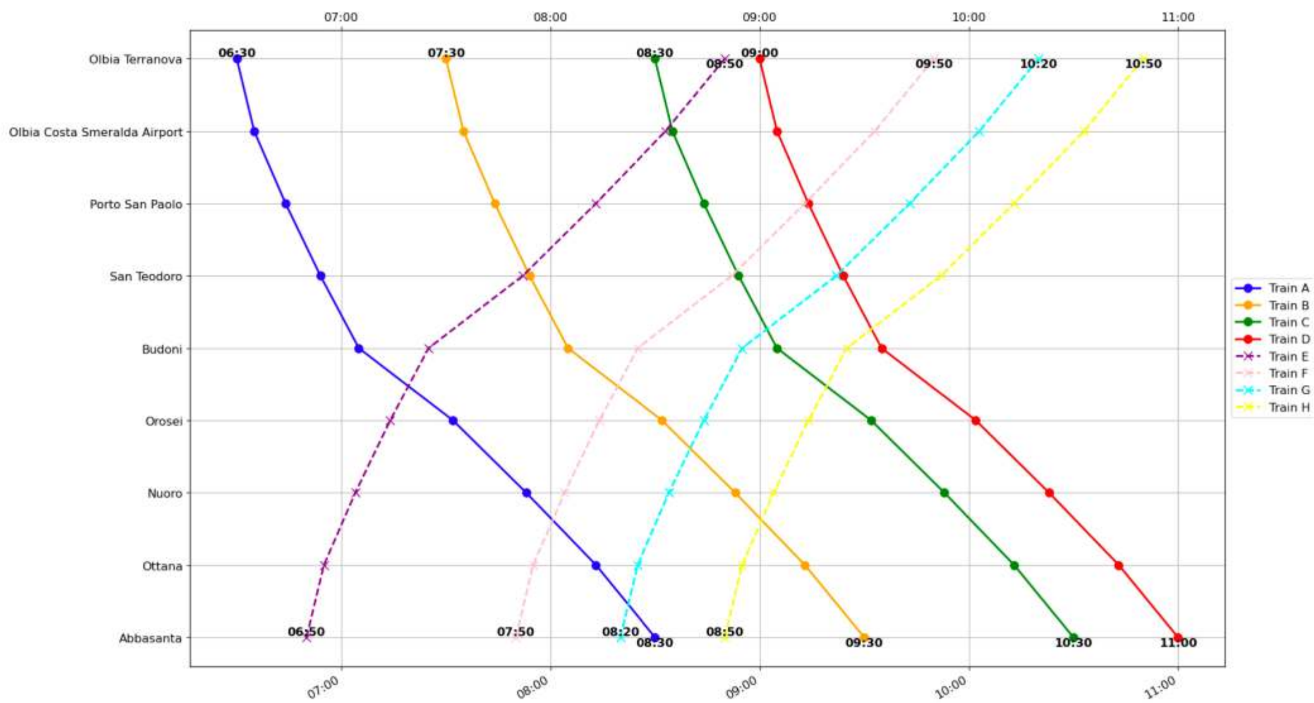
and from the mileage data obtained from the model, we derive the number of vehicles required to reach the chosen frequency, to which 2 vehicles are added as a buffer for maintenance, bringing the total to 10.

It was decided to locate the depot in Olbia at the terminus.

6.4 Service Schedule

The service schedule is divided into 30 time slots, indicating the departure times for each train from Olbia Terranova to the respective destinations, and vice versa.

In total there are 60 daily journeys conducted by these trains.



Train time table – example with first four trains

Here is the specific schedule briefly described:
-Olbia Terranova: The first train departs at 06:30 and the last at 00:00.
-Olbia Airport: The first train departs at 06:35 and the last at 00:05.
-Porto San Paolo: The first train departs at 06:44 and the last at 00:14.
-San Teodoro: The first train departs at 06:54 and the last at 00:24.
-Budoni: The first train departs at 07:05 and the last at 00:35.
-Orosei: The first train departs at 07:32 and the last at 01:02.
-Nuoro: The first train departs at 07:52 and the last at 01:22.
-Ottana: The first train departs at 08:10 and the last at 01:40.
-Abbasanta: The first train arrive at 08:30 and the last at 02:00.
And for return journey
- **Abbasanta**: The first train departs at 06:50 and the last at 21:20.
- **Ottana**: The first train departs at 07:11 and the last at 21:41.
- **Nuoro**: The first train departs at 07:28 and the last at 21:58.
- **Orosei**: The first train departs at 07:50 and the last at 22:20.
- **Budoni**: The first train departs at 08:16 and the last at 22:46.
- **San Teodoro**: The first train departs at 08:26 and the last at 22:56.
- **Porto San Paolo**: The first train departs at 08:36 and the last at 23:06.
- **Olbia Airport**: The first train departs at 08:45 and the last at 23:15.
- **Olbia Terranova**: The first train arrive at 08:50 and the last at 23:20.

This schedule is thought to serve the Airport in the hour needed, above all when last flies land in Olbia. We can also suppose that first train from Abbasanta starts at 5:00 to be fitted with first departures from Olbia Airport.

7-ECONOMIC ANALYSIS

7.1 Introduction to Economic analysis

To get an idea of the economic aspect of the project, costs and revenues have been analyzed. Revenues come from the sale of train tickets and subscriptions. Operational and capital costs are considered.

The construction of a rail project accounts for the largest share of a project cost.

7.2 Revenues

Starting with a maximum train seating capacity of 300, it was decided to have a weighted number of occupied seats based on the month of the year. The weights used refer to the arrival data for Sardinia [2]. To calculate the percentages of occupied seats, we computed a train occupancy coefficient, assuming that during peak periods, the train would be fully occupied at 100%, while in other periods, the load factor would be a percentage weighted by the number of arrivals in the month relative to the maximum (August). From there, the average capacity is obtained by multiplying the load factor by the maximum number of seats available.

	LOW DEMAND				HIGH DEMAND					LOW DEMAND		
								49996				
Olbia 2022	January	February	March	April	May	June	July	August	September	October	November	December
Turists	1586	2603	4186	11515	20016	35647	45579	45784	35664	16650	2982	2106
Residents	1667	1903	2395	2863	2738	3077	2384	4212	2610	2429	1801	2279
Load Factor	6,51%	9,01%	13,16%	28,76%	45,51%	77,45%	95,93%	100,00%	76,55%	38,16%	9,57%	8,77%
Passenger/Jouney	20	27	39	86	137	232	288	300	230	114	29	26

These data were aggregated from a dataset taken from the website mentioned earlier, which was processed using R Studio.

	anno	provincia	comune	mese	provenienza	arrivi	presenze
61754	2022	Provincia di Sassari	OLBIA	1	Francia	10	18
61755	2022	Provincia di Sassari	OLBIA	1	Francia	102	195
61756	2022	Provincia di Sassari	OLBIA	1	Paesi Bassi	5	5
61757	2022	Provincia di Sassari	OLBIA	1	Paesi Bassi	1	1
61758	2022	Provincia di Sassari	OLBIA	1	Paesi Bassi	15	22
61759	2022	Provincia di Sassari	OLBIA	1	Germania	30	75
61760	2022	Provincia di Sassari	OLBIA	1	Germania	12	15
61761	2022	Provincia di Sassari	OLBIA	1	Regno Unito	15	29
61762	2022	Provincia di Sassari	OLBIA	1	Irlanda	3	5
61763	2022	Provincia di Sassari	OLBIA	1	Irlanda	1	9
61764	2022	Provincia di Sassari	OLBIA	1	Danimarca	2	4
61765	2022	Provincia di Sassari	OLBIA	1	Grecia	2	9
61766	2022	Provincia di Sassari	OLBIA	1	Portogallo	3	5
61767	2022	Provincia di Sassari	OLBIA	1	Spagna	1	1
61768	2022	Provincia di Sassari	OLBIA	1	Spagna	7	8
61769	2022	Provincia di Sassari	OLBIA	1	Spagna	19	44
61770	2022	Provincia di Sassari	OLBIA	1	Belgio	2	4
61771	2022	Provincia di Sassari	OLBIA	1	Belgio	11	16

The analysis was conducted along the entire route, and fares were calculated from terminal to terminal. In this way, we calculate the maximum revenues that can be obtained. The fares were taken from the official tables of Trenitalia.

TARIFFA N.39/15/SARDEGNA

La presente tariffa è valida per la determinazione dei prezzi di trasporto per viaggi singoli nell'area regionale della Sardegna

TARIFFA N.39/15/1 ORDINARIA	
SCAGL KM	PREZZI ADULTI 2°CLASSE
0-10	1,30
11-20	1,90
21-30	2,50
31-40	3,10
41-50	3,70
51-60	4,30
61-70	4,90
71-80	5,50
81-90	6,10
91-100	6,70
101-125	8,10
126-150	9,50
151-175	11,00
176-200	12,50
201-225	14,00
226-250	15,50
251-275	16,50
276-300	18,00
301-325	19,50
326-350	21,00

TARIFFA N.39/15/BG BIGLIETTO GIORNALIERO	
SCAGL KM	PREZZI ADULTI 2°CLASSE
0-10	3,30
11-20	5,30
21-30	6,30
31-40	6,90
41-50	7,40
51-60	7,80
61-70	8,90
71-80	9,90
81-90	11,00
91-100	12,50
101-125	15,00
126-150	17,50
151-175	20,00
176-200	22,50
201-225	25,00
226-250	27,50
251-275	30,00
276-300	32,50
301-325	35,00
326-350	37,50

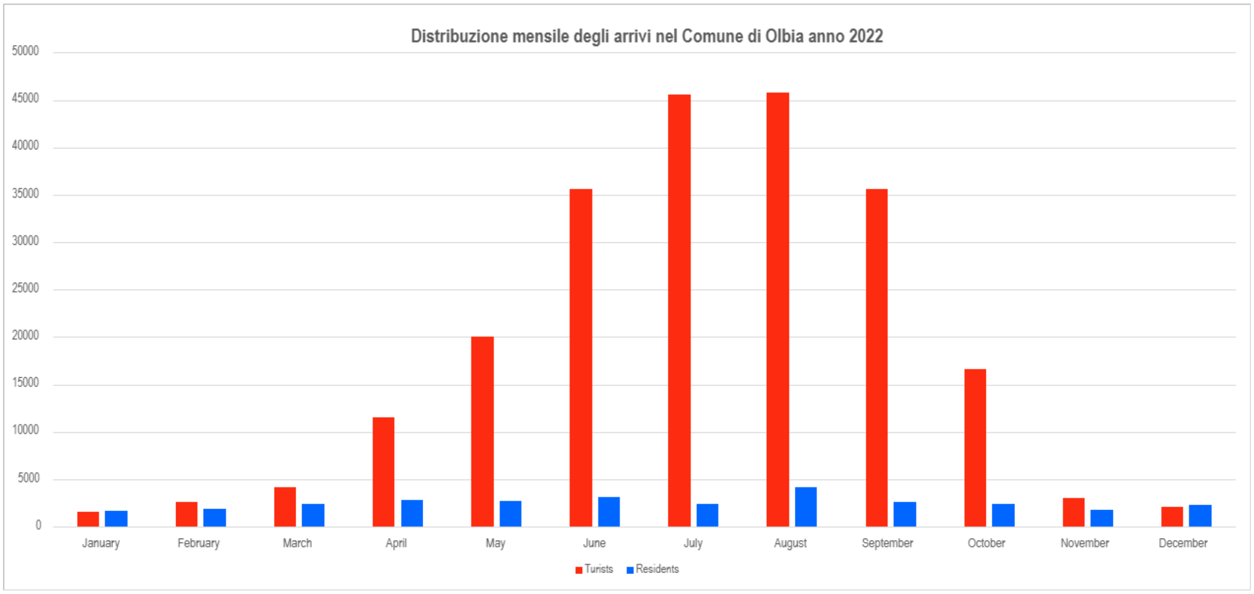
Tariffa 40/15/C ABBONAMENTO SETTIMANALE IMPERSONALE (ASI)	
SCAGL KM	PREZZI
0-10	8,30
11-20	11,50
21-30	14,00
31-40	17,00
41-50	19,50
51-60	22,50
61-70	25,50
71-80	28,00
81-90	31,00
91-100	33,50
101-125	36,50
126-150	39,50
151-175	42,50
176-200	45,50
201-225	48,50
226-250	52,00
251-275	55,00
276-300	58,00
301-325	61,00
326-350	64,00

Tariffa 40/15/A ABBONAMENTO MENSILE IMPERSONALE (AMI)	
SCAGL KM	PREZZI
0-10	26,00
11-20	34,50
21-30	43,00
31-40	52,00
41-50	61,00
51-60	69,00
61-70	78,00
71-80	87,00
81-90	95,00
91-100	104,00
101-125	113,00
126-150	123,00
151-175	132,00
176-200	141,00
201-225	151,00
226-250	160,00
251-275	169,00
276-300	179,00
301-325	188,00
326-350	197,00

Tariffa 40/15/B ABBONAMENTO PER 12 MESI IMPERSONALE (AAI)	
SCAGL. KM	PREZZI
0-10	239,00
11-20	320,00
21-30	401,00
31-40	482,00
41-50	563,00
51-60	644,00
61-70	725,00
71-80	806,00
81-90	888,00
91-100	969,00
101-125	1.056,00
126-150	1.142,00
151-175	1.229,00
176-200	1.316,00
201-225	1.403,00
226-250	1.490,00
251-275	1.577,00
276-300	1.664,00
301-325	1.751,00
326-350	1.837,00

To calculate how the number of people is divided according to the type of subscription, we hypothesized the percentage based on the monthly arrivals graph in Sardinia.

The alternative would have been to consider that all passengers would opt for the regular fare, but we preferred to weigh the regular fares, daily tickets, weekly, monthly, and annual subscriptions with reasonable coefficients to avoid assuming that all passengers would choose single tickets.



Monthly distribution of total arrivals in Olbia city – year 2022

Arrivals of residents in Sardinia, which we can consider as systematic, are shown in blue, while tourist arrivals from the mainland are shown in red.

The percentages we hypothesized, based on the arrivals graph, are as follows:

	% Fares	Single ticket	Daily ticket	Weekly ticket	Monthly ticket	Annual ticket
0<arrivals<20k	**LOW Demand**	0,2	0,15	0,05	0,2	0,4
arrivals>20k	**HIGH Demand**	0,4	0,2	0,25	0,1	0,05

The goal is to consider the number of trips for single tickets and subscriptions. Subscriptions will be considered as discounted single tickets. Each occupied seat will be associated with either a single ticket or a subscription.

Once the various trips for each category are hypothesized, it is possible to calculate the price per single trip.

Assumptions			Journeys						€/Journeys					
#	Range Km		Single ticket	Daily Ticket	Weekly ticket	Monthly ticket	Annual ticket		Single ticket	Daily Ticket	Weekly ticket	Monthly ticket	Annual ticket	
1	-	**10**	1	1	12	48	576		1,30	3,30	0,69	0,54	0,41	
2	**11**	**20**	1	1	12	48	576		1,90	5,30	0,96	0,72	0,56	
3	**21**	**30**	1	1	12	48	576		2,50	6,30	1,17	0,90	0,70	
4	**31**	**40**	1	1	12	48	576		3,10	6,90	1,42	1,08	0,84	
5	**41**	**50**	1	1	12	48	576		3,70	7,40	1,63	1,27	0,98	
6	**51**	**60**	1	1	12	48	576		4,30	7,80	1,88	1,44	1,12	
7	**61**	**70**	1	1	12	48	576		4,90	8,90	2,13	1,63	1,26	
8	**71**	**80**	1	1	12	48	576		5,50	9,90	2,33	1,81	1,40	
9	**81**	**90**	1	1	12	48	576		6,10	11,00	2,58	1,98	1,54	
10	**91**	**100**	1	1	12	48	576		6,70	12,50	2,79	2,17	1,68	
11	**101**	**125**	1	1	12	48	576		8,10	15,00	3,04	2,35	1,83	
12	**126**	**150**	1	1	12	48	576		9,50	17,50	3,29	2,56	1,98	
13	**151**	**175**	1	1	12	48	576		11,00	20,00	3,54	2,75	2,13	
14	**176**	**200**	1	1	12	48	576		12,50	22,50	3,79	2,94	2,28	
15	**201**	**225**	1	1	12	48	576		14,00	25,00	4,04	3,15	2,44	
								LOW	2,20	3,00	0,18	0,55	0,85	**6,78**
								HIGH	5,00	4,50	0,95	0,29	0,11	**10,86**

Finally, the annual revenue from the sale of travel tickets is as follows:

	January	February	March	April	May	June
MAX Revenues (one way ride)	132.3534716	183.3337667	267.7584373	584.991766	1482.209848	2522.505675
(operation day)	7808.854825	10816.69224	15797.7478	34514.51419	87450.38101	148827.8349
(total month)	234265.6448	324500.7671	473932.4341	1035435.426	2623511.43	4464835.046
	July	August	September	October	November	December
	3124.339937	3256.770833	2493.192393	776.2594174	194.6039516	178.4106895
	184336.0563	192149.4792	147098.3512	45799.30563	11481.63315	10526.23068
	5530081.688	5764484.375	4412950.535	1373979.169	344448.9944	315786.9205
Total Annual Revenues	26898212.43					

7.3 Operating expenditures

The following operating costs are considered: personnel, energy consumption, maintenance, administration, and vehicle depreciation. The costs in the table pertain to a single trip from terminal to terminal.

				one-way ride
Cost item	***Units***	***Value***	***Unitary cost***	***Cost***
Train Driver	2	1.95 h	17 €/h	66 €
Station Staff	5	1.95 h	12 €/h	117 €
Energy Cost	4.69 MWh		0.075 €/kWh	352 €
Maintenance	1	1.95 h	14 €/h	27 €
Overheads				210 €
Administrative costs				70 €
Other				30 €
Amortization				139 €
			Total	**1,012 €**

Travel time	117.5	min
#journeys per day	59	
#journeys per year	**21535**	
TOT OPEX	**21,788,564 €**	

7.4 Capital expenditures

For the calculation of CAPEX, estimates were made based on articles referenced from [16] to [20]. Therefore, a unit cost was calculated from the capital expenditure to refer to the case in question. The costs related to the construction of the line, both on flat ground and on viaducts and tunnels, as well as the costs of stations, electrification systems, signaling, and vehicle purchase are illustrated:

	units	specific cost			Cost
Doble-track rail ("Piano Campagna")	65%	2300000	€/km	€	263.350.000,00
Viaducts	29%	1E+07	€/km	€	500.000.000,00
Tunnels	6%	3E+07	€/km	€	315.000.000,00
New Stations	6	1,2E+07	€/station	€	69.000.000,00
Renewal stations and depots	2	5E+07	€/each	€	100.000.000,00
ERTMS equipment				€	154.578.096,95
Electrification (including TPSSs)	1	884057	€/km	€	154.709.975,00
Vehicles	10	6090909	€/train	€	60.909.090,91
			Total CAPEX	**€**	**1.617.547.162,86**

We assume that the initial investment cost would be covered by PNRR found and “Regione Autonoma della Sardegna” in accordance with RFI and MIT.

8-CONCLUSIONS

8.1 Social impact

The proposed railway infrastructure would complement the region's main road artery and open up opportunities for integration with public bus services, such as those provided by the "Deplano" company. This development would have a significant social impact by offering easy access to an area currently lacking adequate public transportation. Not only local residents but also regional, national, and international tourists would benefit from this service. For locals, it would facilitate regular commuting, while for tourists, it would provide a flexible solution to meet varying demands.

Moreover, this new railway line would expand the Sardinian network by connecting the province of Nuoro, which is currently isolated from the standard gauge railway. This connection would enable linkage from the town of Abbasanta to the rest of the regional railway system, which includes routes from the capital, Cagliari, to the northern cities of Olbia and Sassari.

8.2 Economic Considerations

The economic analysis highlights that, despite a significant initial investment in infrastructure and vehicles, the revenues from the sale of travel tickets and subscriptions fully cover and exceed operating costs. The initial investment costs cannot be covered solely by ticket sales, but, in the opinion of the presenters, the economic advantage for the territory is significant. In fact, it would improve the quality of life for residents by simplifying the systematic travel of commuters, easing traffic on the main road, and increasing the region's attractiveness by making the coast more accessible. Therefore, a significant public service is offered to the community. The economic analysis highlights that, despite a significant initial investment in infrastructure and vehicles, the revenues from the sale of travel tickets and subscriptions fully cover and exceed operating costs. The initial investment costs cannot be covered solely by ticket sales, but, in the opinion of the presenters, the economic advantage for the territory is significant. In fact, it would improve the quality of life for residents by simplifying the systematic travel of commuters, easing traffic on the main road, and increasing the region's attractiveness by making the coast more accessible. Therefore, a significant public service is offered to the community.

8.3 Technical Conclusions

The construction of a new double-track and fully electrified railway line in Sardinia would bring substantial improvements to the railway system's maintenance and operations. A double-track line would balance the distribution of traffic, reducing the wear on individual tracks and the frequency of maintenance interventions. This would prolong the tracks' lifespan and optimize resource allocation.

For vibration comfort, various solutions have been developed to meet regulated standards by adjusting suspension stiffness and damping parameters for different types of track defects.

The new railway lines would feature advanced signaling and control systems, enhancing the safety and reliability of the service. By incorporating cutting-edge technologies, the system would enable continuous monitoring of track conditions and rolling stock. This approach supports predictive and condition-based maintenance, where sensors and constant data analysis help anticipate and prevent failures, thereby minimizing corrective maintenance interventions, which currently comprise a significant portion of the maintenance budget.

A dynamic model based on power balance has been used to estimate the impact of resisting forces and the consequent power and energy requirements for operating the line. From the energy consumption data, we can gauge the environmental impact of the project.

8.4 Environmental Impact

While the train might not significantly reduce travel times compared to private transportation, it offers considerable benefits in reducing greenhouse gas emissions per passenger per kilometer. The new line, designed with catenary electrification, could spearhead the electrification of the entire regional network. This transition is crucial as it involves the integration of renewable energy sources. Given their intermittent nature, renewable sources necessitate energy storage systems to align production peaks with demand peaks. Concurrently, this move would contribute to reducing the reliance on coal, natural gas, and other fossil fuels.

In conclusion, the implementation of a new double-track and electrified railway line in Sardinia would represent a major technological and infrastructural advancement, yielding benefits that range from improved energy efficiency to enhanced environmental sustainability.

9- References

[1] OpenRailwayMap

[2] Dati 2022 | Osservatorio del Turismo, Artigianato e Commercio (sardegnaturismo.it)

[3] HIGIS 3/ﾌﾟﾚｾﾞﾝﾃｰｼｮﾝ資料/J_GrayA.ppt (cifi.it)

[4] https://www.regione.fvg.it/tav/194_L34400R18ROSE0000002A.pdf

[5] https://medias.sncf.com/sncfcom/pdf/DESTE/General-Method_InfoGHG_2022_Eng.pdf

[6] https://natural-resources.canada.ca/sites/www.nrcan.gc.ca/files/oee/pdf/transportation/fuel-efficient-technologies/autosmart_factsheet_6_e.pdf

[7] https://www.terna.it/it/sistema-elettrico/statistiche/evoluzione-mercato-elettrico/produzione-energia-elettrica-fonte

[8] https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche#:~:text=La%20potenza%20efficiente%20lorda%20di,2021%20del%205%2C3%25.

[9] https://www.sardegnaimpresa.eu/it/news/energia-elettrica-sardegna-si-produce-il-40-piu-di-quanto-si-consuma-intanto-si-discute-di

[10] Passenger Stability Within Moving Railway Vehicles: Limits on Maximum Longitudinal Acceleration (J. P. Powell, R. Palacin)

[11] RFI (Rete Ferroviaria Italiana). (2020). Sistema di Controllo della Marcia del Treno (SCMT). (https://www.rfi.it/en/Safety/Safety-Systems/SCMT.html)

[12] European Union Agency for Railways. (2020). ERTMS Deployment. (https://www.era.europa.eu/activities/european-rail-traffic-management-system-ertms_en)

[13] European Railway Agency (ERA). (2021). European Railway Signaling Systems. (https://www.era.europa.eu/)

[14] Railway Gazette International. (2019). *Cost Analysis of ERTMS Projects*. (https://www.railwaygazette.com/infrastructure/cost-analysis-of-ertms-projects/)

[15] National Railway Safety Agency of Italy (ANSF). (2018). *SCMT Technical Documentation*. (https://www.ansf.it/)

[16]Elettrificazione facciamo un rapporto in base ai km RFI – Al via i lavori di elettrificazione della tratta Rocchetta-Potenza

[17]ERTMS https://www.italiadomani.gov.it/it/Interventi/investimenti/sviluppo-del-sistema-europeo-di-gestione-del-trasporto-ferroviario-ERTMS.html

[18]Stazioni piccole RFI – Lombardia: attivo il nuovo assetto della stazione di Dubino

[19]Treni https://www.sardegnamobilita.it/trasporto-pubblico-ferroviario

[20]Doppio binario https://compassinternational.net/railroad-engineering-construction-cost-benchmarks/