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Bonum Histria Mobility Group

Nova Istra

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Dynamics, Control and Diagnostics of Ground Transportation Systems

Contents

Abstract

Environmentally neutral mobility and interregional connections are two of the main challenges of the European Union. As many funds were invested in the last thirty years, the latest eastern enlargement of the Union shown how many improvements can be implemented in those regions. As Croatia joined Schengen Area at the beginning of 2023, the eastern border of the European Union moved forward from Slovenia.

Istrian region, which is part of the Historical Venetian Region, has been always connected to the rest of Central and Southern Europe. During the Yugoslavian years, these connections were discontinued, as the country was located "on the other side" of the Iron Curtain. As the Yugoslavian era ended and independent countries were restored, connections with the European Continent restarted. However, no recent investments were implemented in order to create green and sustainable transportation networks.

As of April 2023, Croatian Parliament financed researches having the goal to connect the Istrian region to the rest of the country, as its border location and its geographical conformation always divided the peninsula from the rest of the Balkan country.

Not only a geographical but also a cultural and social divide exists between Istria and other regions, as many people identify themselves as "Istriots" instead of "Croats", speak a very different dialect (and also a different Croatian from the innermost regions) and have a different culture.

It's interesting how the Istrian region, once a part of the bigger region named "Venezia Giulia" and now divided between three countries, became almost a standalone region in the Croatian scenario.

Our analysis has the goal of "restarting" an old existing railway, which still has paths, tracks and stations. A renewal of this almost abandoned railway line can be considered as an intervention needed in order to give a different transportation alternative to those people (workers, students, tourists) who need to travel between the main cities of the historical region, now connected only by unreliable services.

Chapter 1

Context Presentation

1.1 General Overview

1.1.1 Introduction to Istrian Railway

Istria is a peninsula located in Southeastern Europe. Due to its location on the border between Italy, Slovenia and Croatia, the region has been involved in many conflicts between contending countries. During the last 150 years, the country underwent four different administrations. As in first three governments the peninsula was included in one single country (Austro-Hungarian Empire, Kingdom of Italy and Republic of Yugoslavia), the latter administrating countries split the historical region mainly between Slovenia and Croatia, as Italy only administrates one town.

Its strategical position needed a connection with the rest of the countries: Austro-Hungarian government was the first institution which built a railroad connecting the southernmost city of Pula/Pola to the whole national network through a freight and military line, which still exists nowadays. However, due to many events this line is almost no more used.

Istrian Railway was a project developed in order to connect the stations of Divača/-Divaccia and Pula/Pola, crossing the whole Istrian Region. Intermediate stops were built close to main towns. The network then is connected from Divača to the Trieste – Vienna railway.

Last country which had the possibility to fully use the line without having to cross an international border was Republic of Yugoslavia. Dissolution of the socialist republic lead and the consequent establishment of Slovenian and Croatian republics put the line in a difficult situation: crossing the border became a problem and the passenger line was deprecated. As Croatia entered Schengen in January 2023, there are no more borders between the three countries and implementing a passenger network is a challenge.

Figure 1.1: Istrian Railway route.

Northernmost part of the Istrian Railway is now part of the Slovenian railway, which is still connected to the Austrian and the Italian railway networks. Slovenian standard uses electrical traction in direct current at 3 kV.

Southernmost part of the same network, which is running from the border to Pula, is controlled by the Croatian Railway Company but it's isolated from the rest of the Croatian Railway Network, as the whole network was engineered having the peninsula under the same administration. As a consequence, all of the trains must transit from Slovenia in order to reach Continental Croatia. This section of the line is still using diesel traction motors, which is way more antiquate than the 25 kV AC network developed in the rest of the Croatian network. The Croatian part of the network is running on a single-track railway, a signaling system is missing on the track which lead to a low maximum speed. Croatian Railways bought hybrid diesel – electric traction trains which are used on the line only limited as there is no available contact line on the network.

The only technical specification which is shared between the three parts of the considered network is the track gauge, as they're all built using the 1435 mm standard gauge.

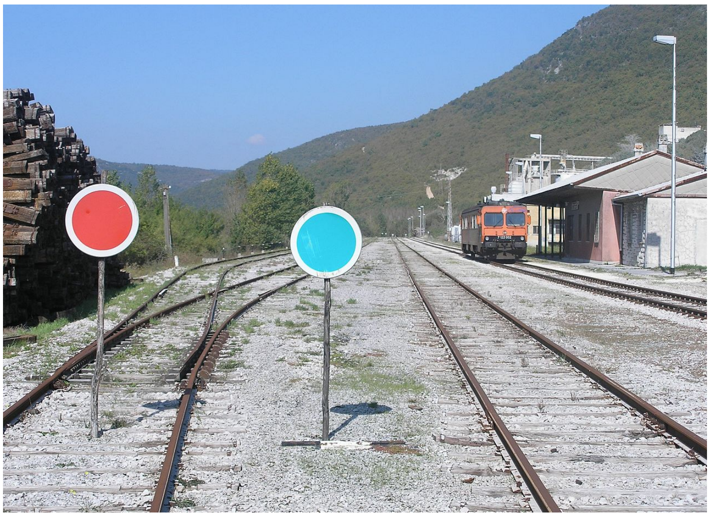

Figure 1.2: Raša abandoned branch line. Picture of 1997 where are displayed all of the characteristics of the network: old rolling stock, lack of electrification, old but still available stations.

1.2 Demographical and Economic data

As Slovenia is already well connected with the rest of the European railway network, the following analysis will be related only to the Croatian Istria, which is the Westernmost region (zupanija) of the Croatian Republic.

1.2.1 Population

As an administrative region in the Croatian Republic, Istria Region has a population of 190,000 inhabitants (2021 census). Majority of the population is Croatian, having small communities made of Italians, Serbs, Slovenian and "Istriots".

Municipality	**Population**
Pula	52200
Poreč	16607
Rovinj	12968
Umag	12699
Labin	10424
Pazin	8279
Medulin	6004
Buzet	5999
Vodnjan	5838
Buje	4441

Largest and most important cities in the peninsula are Pula/Pola, Pazin/Pisino, Rovinj/Rovigno and Poreč/Parenzo. Population is distributed between these cities and the inland, which is characterized by small rural towns and some Medieval burgs. Most of the population lives on the coastal line of the peninsula, having some exceptions as seen in the map.

Population growth is negative, following national trend, and the most of the population in the small towns consists in over 65 years old people.

Istria is mostly composed of a limestone plateau surrounded by the Adriatic Sea. The coastline encompasses beaches, steep cliffs, and small islands. The region is also home to numerous medieval towns, vineyards, and olive groves. The climate in Istria is Mediterranean, with mild winters and hot, dry summers. The interior of the peninsula is also very mountainous, with several peaks reaching over 1,500 meters in elevation.

1.2.2 Public transport, highways and motorways, airports

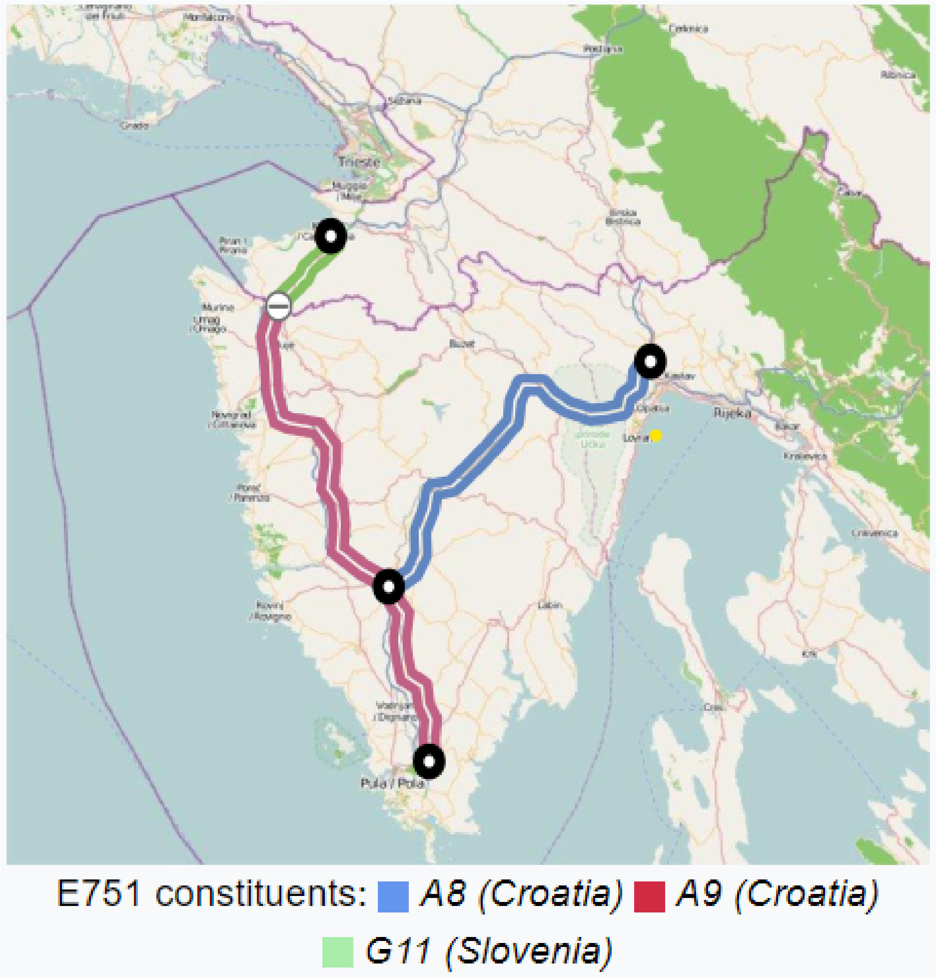

Figure 1.3: Motorway roads in Istria.

Cities in Istria are connected mainly through coaches. A very important connection is running from Lupoglav to Rijeka. This line, which crosses the Učka Tunnel, is necessary in order to reach the rest of Croatia.

Current railway line connects Pula to Buzet running six rides a day, having a long path and running almost all the stops on the route. As many people request the stop of the train, the line is further slowed down (line performs a “taxi” service for people on the train).

Connection between Pula and Trieste is guaranteed using private bus companies. Brioni Pula (Flixbus) and Fils are the main companies.

Main highways in the region connect the North of the region (A9) (Umag and the border with Slovenia) with Kanfanar, and Pula with Učka tunnel (A8) (and the rest of Croatia through Rijeka). These two highways are managed by Bina Istra and are called “Istarski Ipsilon” due to the shape that resemble the Y letter. Učka tunnel allows vehicles to reach Rijeka. However, the gallery is a bottleneck to the whole highway system due to its reduced width. The two Istrian motorways are part of the E751 European corridor.

City of Pula is provided with the main airport and the main port of the region. The port connects the city to many locations in the whole Dalmatian coast.

1.2.3 Economic Activities

According to 2019 data, Istrian Region had a GDP per capita of 15.776,00 EUR (4th in Croatia), which was 17% higher than the rest of Croatia, and an unemployment rate of 3.2%, 58% lower than the Croatian average.

Istrian economy is very diverse. Istria is traditionally the most visited tourist region, so that it realized 27 % of all arrivals and 35 % of all nights in the Republic of Croatia in 2003. It has a well-developed processing industry, construction industry, trade, sea fishing and fish growing, agriculture, and transportation. According to the number of economic subjects and according to financial indicators, the leading activities are processing industry, tourism, and trade.

In the field of industry, the most developed branches are shipbuilding, production of construction material (lime, cement, brick, stone), tobacco products, furniture, electric machines and appliances, parts for the automobile industry, glass, processing metals, plastic, wood, textile, and the production of food.

Great attention has been given to the revitalization of agriculture in the previous few years, which marked a big improvement in wine- and olive- growing, and in the system of ecologic food production.

Istria is a region moving upwards on the scale of development cycle. Strategic geographic position and good traffic connections between Europe and the Mediterranean, preservation of natural resources, stability of regional politics and the collaboration with numerous regions abroad make Istria an attractive destination for foreign investments.

1.3 The Bura wind phenomenon

Istrian region is subject to high wind effects, both primary and secondary. Among all of them, the most known sweeping wind of Istria (and bordering regions) is Bura. Bura is a wind that occurs in the whole Adriatic coastal regions, which has always been a problem to transportation and infrastructures there. Bura gusts can reach 200 km/h. However, the average speed of Bura is typically lower, around 50-80 kilometers per hour, but it can still have a significant impact on the region. The speed of Bura can vary depending on the local topography and weather conditions.

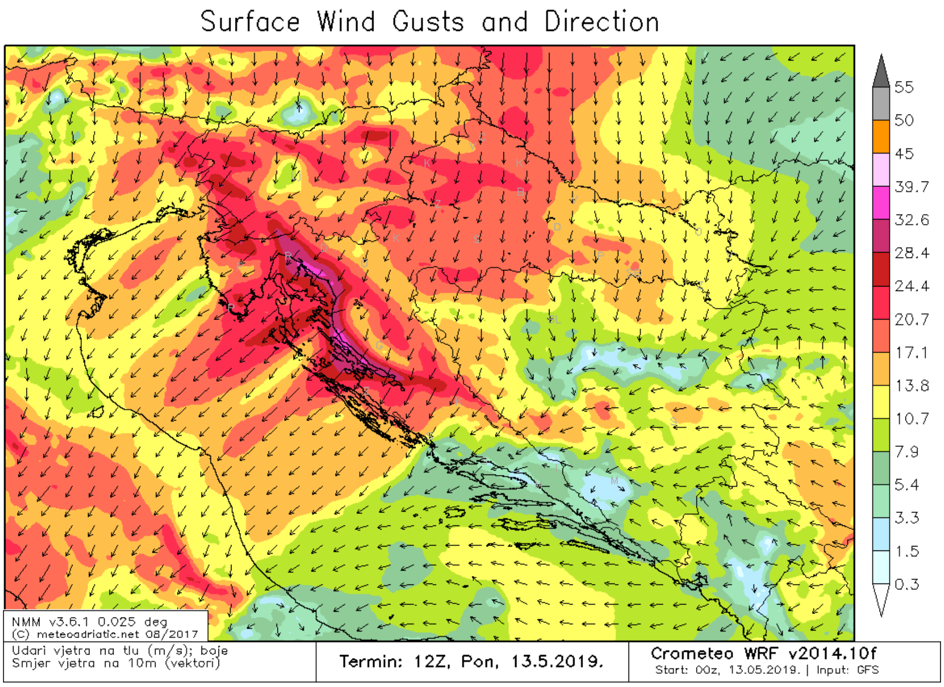

Figure 1.4: Wind direction and strength on the study area.

The speed of wind that would affect a train's movement on rail depends on various factors such as type of train, weight, and wind direction. Generally speaking, wind speeds starting from 80 kilometers per hour can affect the movement of trains, especially if the wind is blowing perpendicular to the direction of travel.

Strong winds can cause the train to sway, which can affect the stability of the train and potentially cause it to derail.

The potential impact of Bura winds on a railway line connecting Pula and Trieste would depend on a variety of factors, including the design of the railway infrastructure, the type of trains used, and the frequency and severity of Bura winds in the region. Although wind effects on rail vehicles are usually analyzed for high speed lines, the above average speed of Bura wind requires further analysis.

Considering a dynamics point of view, wind effect can be summarized on both lateral and longitudinal dynamics.

- Cross rail wind (orthogonal or anyways diagonal) is generally considered as one of the derailment contributing factors.
- Longitudinal winds can be considered as resistante forces if opposed to the vehicle's motion or give a positive contribution if following the same direction. They

must be considered anyway because of their impact on speed and, as a direct consequence, on the required breaking distance.

Railway infrastructure can be designed to withstand high wind speeds. For example, railway tracks can be built with specific designs to reduce the impact of strong winds, such as using windbreaks or building tunnels and bridges that are less susceptible to wind loads.

Trains used on the railway line would also need to be able to withstand high wind speeds and remain stable on the tracks. Train operators may need to adjust their speed or operations during periods of high wind activity to ensure passenger safety and comfort.

In order to avoid disruptive effects, as a standard protocol for wind effects prevention doesn't exist, most of the interventions are usually implemented:

- Along exposed sections of the railway line where the wind is likely to hit the tracks directly. These sections could be protected by building wind barriers parallel to the tracks, on the side of the tracks facing the wind;

- At the entrances and exits of tunnels and bridges, where wind speeds can increase due to the wind being funneled through a confined space. Wind barriers can be built at these locations to reduce the impact of the wind on the trains as they enter and exit the tunnels and bridges;

- Near areas where the railway line crosses over valleys or other areas with significant changes in topography. These locations can create localized wind effects that may require wind barriers to protect against gusts or other disruptions to train operations;

1.3.1 Croatia's National Recovery and Resilience Plan

Croatia's National Recovery and Resilience Plan (NRRP) is an ambitious outline of reforms and investment designed to mitigate the pandemic's socio-economic fallout. Compared with the size of its economy, Croatia is the largest recipient of Recovery and Resilience Facility (RRF) funds, with a total financial allocation of €6 295 million, or 11.6% of the country's gross domestic product (GDP).

The allocation corresponds to 0.9% of the total RRF volume and is entirely grant-based. In June 2022, the grant allocation was revised downwards to €5 512 million (-12.5%) The use of the loan component under the facility is currently not envisaged but may be requested by 31 August 2023 at the latest.

The measures in the plan aim to help Croatia overcome the socio-economic ramifications of both the pandemic and the two devastating earthquakes from 2020, while fostering the green and digital transition. The post-earthquake recovery measures in particular are among the NRRP's major objectives, and contribute to smart, sustainable and inclusive growth.

Croatia has so far received 35.2% of the resources in the form of pre-financing and the first two grant installments, above the current EU average which stands at roughly 28%. Implementation of the plan must be concluded by 2026.

RRF funds, combined with others3 from the Next Generation EU instrument and the EU's multiannual financial frameworks (2014-2020 and 2021-2027), will put at Croatia's disposal roughly €30 000 million by the end of the decade, an unprecedented chance to boost socio-economic development. The European Parliament continues to ensure transparency and accountability through interinstitutional dialogues on RRF implementation, and scrutiny of the Commission's work.

The plan allocates a significant part of reforms and investments to the objective of addressing the challenges of the green transition. Planned measures are aligned with the National Energy and Climate Plan and aim at being complementary with the future Territorial Just Transition Plans. As such, they are expected to directly contribute to the EU's 2030 climate targets and 2050 climate neutrality objective. Specific measures are expected to contribute to meeting national and EU targets for environmental policy, directly focusing on waste management, water supply and wastewater treatment, flood protection, sustainable mobility, sustainable food systems and biodiversity protection.

The plan addresses the main challenges of sustainable mobility transition, supporting infrastructure development of low-carbon transportation modes. In the rail sector, major investments are targeted towards modernization and electrification of the TEN-T rail network, in order to accelerate the modal shift from road to rail. For example, the plan entails the reconstruction and electrification of the 22 km railway section Dugo Selo - Novska, sub-section Kutina - Novska (EUR 140.7 million), along the TEN-T rail network and the Alpine-Western Balkans rail-freight corridor.

Chapter 2

Scenario Analysis

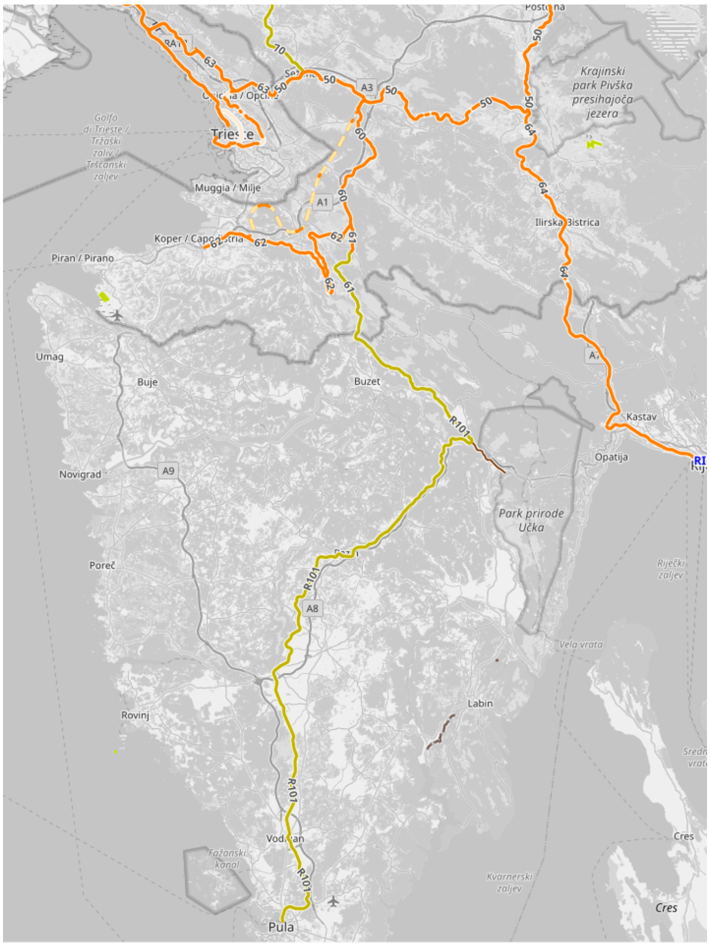

Figure 2.1: Lines officially available on the network. On official records, Istrian Railway is a branch line (displayed in yellow), the Slovenian section is a regional line and the Italian too. On the map are also shown former tracks which are now abandoned due to different reasons (Rovinj branch line due to disuse, Raša due to rock slide on the track.

2.1 Current scenario

State of art doesn't perform an express railway line from Pula to Trieste. However, it is possible to connect the two cities through different means of transport. Assuming that the railway network is working properly, the connection between the two cities is split between three companies. From Pula to the Slovenian Border there is a regional line owned by Croatian Railways. From the border to the city of Divača there is a Slovenian line and then from Divača to Trieste Centrale there is an Italian regional line. Due to different formation, we must divide this route further. The only common attribute on the whole line is the standard gauge (1435 mm), as electrification is only available in the Slovenian and Italian parts of the network.

The only train which is today passing through the Croatian – Slovenian border is a Ljubljana – Pula connection which is scheduled only during summer.

- Pula – Buzet
  The first part of the railroad runs in Croatian territory, crossing the whole Istrian peninsula in its innermost part. The line has diesel traction and it's running on a single-track standard gauge rail. This railroad has many available interchanges with other abandoned branch railroads in the region, as this line is the only one still in service and available. In the city of Kanfanar, there once was a connection to the seaside location of Rovinj. However, the railway was abandoned during the 20th Century as Yugoslavian Government didn't invest further on that railway. Over 86 km of the line, 26 stops are performed. Some of them are located in small towns. Rolling stock includes Kalmar Verkstad/Fiat 7122 trains, manufactured between 1979 and 1981, operating on the whole Croatian railway line. As the line had no improvements since 1976, when it was engineered and built, a renewal is necessary on the track. Main stations in the cities are still working and in a good shape;

- Buzet (HR)– Border – Rakitovec (SI)
  This section is almost unused as this short single-track railroad is crossing the border and until 2022 there were border controls. Also, due to long maintenance schedules part of this section (and of the previous) are not operational today, replaced by busses which extend furthermore the trip duration;

- Rakitovec – Divača
  Entering Slovenia most of the issues are solved, as Slovenian network is properly working. From this point on, the line is double track, DC electrified and standard gauge;

- Divača – Trieste
  Last section has the same specifications of the previous, criticality on the line include the long road from Trieste Villa Opicina to Trieste Centrale which cannot be avoided, as the available gallery is used only for freight transport;

2.1.1 Current scenario analysis

Most of the station on the line, even though they're running on a single-track road, have double or more tracks available. This is necessary in order to avoid congestions between trains from different directions.
Route top speed is heavily limited due to different factors:

- Lack of signaling system;
- Lack of security implementations;
- Geographical conformation of the region;
- Low distance between stops;
- No prevention systems for wind effect on the railway;

As easily understandable from the provided information, using the existing railway is not an efficient solution. Most of the demand is supplied by private cars/vehicles and private bus companies. Bus companies have both express and intermediate stops bus. This situation led to further abandon of this railroad and no more investments in the last years.

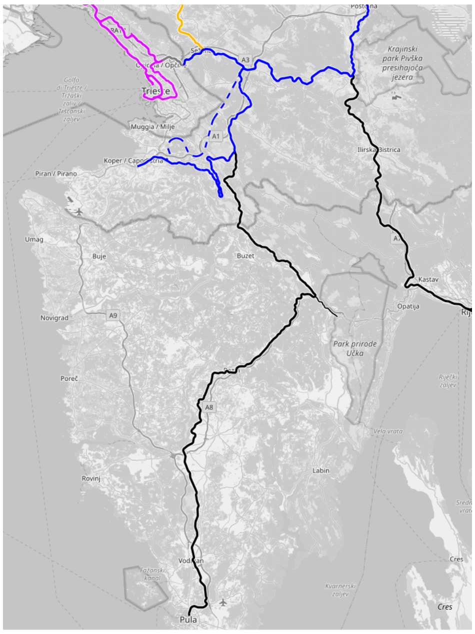

Figure 2.2: Current signaling systems in the study area. It can be noticed the complete lack of signaling after the border between Slovenia and Croatia. Solving this problem is one of the main goals of this analysis.

2.1.2 Rolling stock

Figure 2.3: Croatian Railways new rolling stock.

The current rolling stock includes two new trains which are suitable for the suggested route, as they are provided with electric traction motors and their specifications match the requirements. By the beginning of the service, the two units match the schedule of "one train every three hours", assuming they can work without interruption. Full schedule service requires four of these vehicles. Končar DEMU (Diesel Electric Multiple Unit) trains are a type of self-propelled, medium-capacity diesel multiple unit passenger train manufactured by Končar-Koprivnica, a Croatian manufacturer of railway rolling stock and railway electrification equipment. Končar DEMU trains are designed for regional railway transportation and are equipped with a range of features to ensure safe and comfortable travel for passengers. These features include air-conditioning, comfortable seating, CCTV surveillance, Wi-Fi, and power outlets for mobile devices. The trains are powered by a 1,000-kW diesel engine and are capable of reaching speeds of up to 120 km/h. The trains also have regenerative braking, which helps to reduce energy consumption and lower their environmental impact. The trains are equipped with advanced control systems and have maximum gradeability of 20%.

Bogie width	$1435\ mm$
Traction	$25kV Ac/3\ kV\ DC\ diesel$
Wheelset base	$Bo'2'2'2'Bo'$
Available seats	$20\ 1st,\ 192\ 2nd\ class$
Floor height	$600\ mm$
Door width	$1300\ mm$
Length	$75000\ mm$
Train width	$2885\ mm$
Height (down pantograph)	$4280\ mm$
Maximum weight	$172\ t$
Axis distance	$2700\ mm$
Reductor ratio	$1 : 4,831$
Traction power	$2000\ kW$
Maximum traction force	$200\ kN$
Starting acceleration at full load	$> 1\frac{m}{s^2}$
Maximum braking deceleration	$> 1,3\frac{m}{s^2}$
Maximum speed	$160\frac{km}{h}$

Some old vehicles are still available in the fleet. These vehicles, which are diesel traction units or even locomotives, are being slowly replaced by the new Končar diesel electric vehicles. If the current service, which is not always properly performed, is intended to be kept, at least two new vehicles may be necessary in order to have a full performing service.

2.2 New Service

2.2.1 Route definition

It has been decided to implement a 3 kV DC system as it would have been meaningless installing a high capacity or high-speed line. High speed line requires curvature radius, which are not available on the track, and the top speed on the line won't reach speeds higher than 150 km/h anyways. Also, Slovenian and Italian networks in the line were developed using DC systems, so it would be an unnecessary expense the implementation of a more expensive solution. This solution is contrasting the recent Croatian railway network development which is replacing direct current with alternate current systems.

In order to allow full service of the desired line, and also in order to allow further investments and extensions towards different significant locations in the bordering regions, structural investments must be performed in order to improve the tracks conditions and install the contact line traction system.

Rail crossing are mandatory and necessary as current crossings are not connected with the signaling system.

The track improvement, combined with the electrification of the network, allows to increase the top average speed from less than 80 km/h to 110 km/h. The analysis was run subject to the curve radius constrains on the whole track. The top speed was set to 110 km/h as the selected train has a nominal top speed of 120 km/h. Main effects of the suggested solutions are:

1. Pollutant reduction as electric traction is by default less pollutant than diesel traction;

2. Time reduction as electric traction is over performing the current diesel traction vehicles;

3. Time reduction due to reduced number of stops;

Side effects which can be attributed to the project development include:

1. General interventions on the distribution line: installing the contact line requires external interventions on the electricity distribution line, which is generally a side benefit;

2. Improvements on galleries due to wind effect avoidance and other infrastructural renewals required in order to run a new line;

3. Some of the current trains are not using electric traction despite having a proper pantograph: this improvement can lead to a better use of the network;

4. Both work and tourism usage as naturalistic as sightseeing available from train: during the working days the line is used in order to reach the working spot, during the rest of the year the connection is faster than the bus and can avoid the use of the private car;

5. Rescheduling of private transport: coaches used for long distance lines can be used for shorted distance routes;

2.2.2 Stations choice

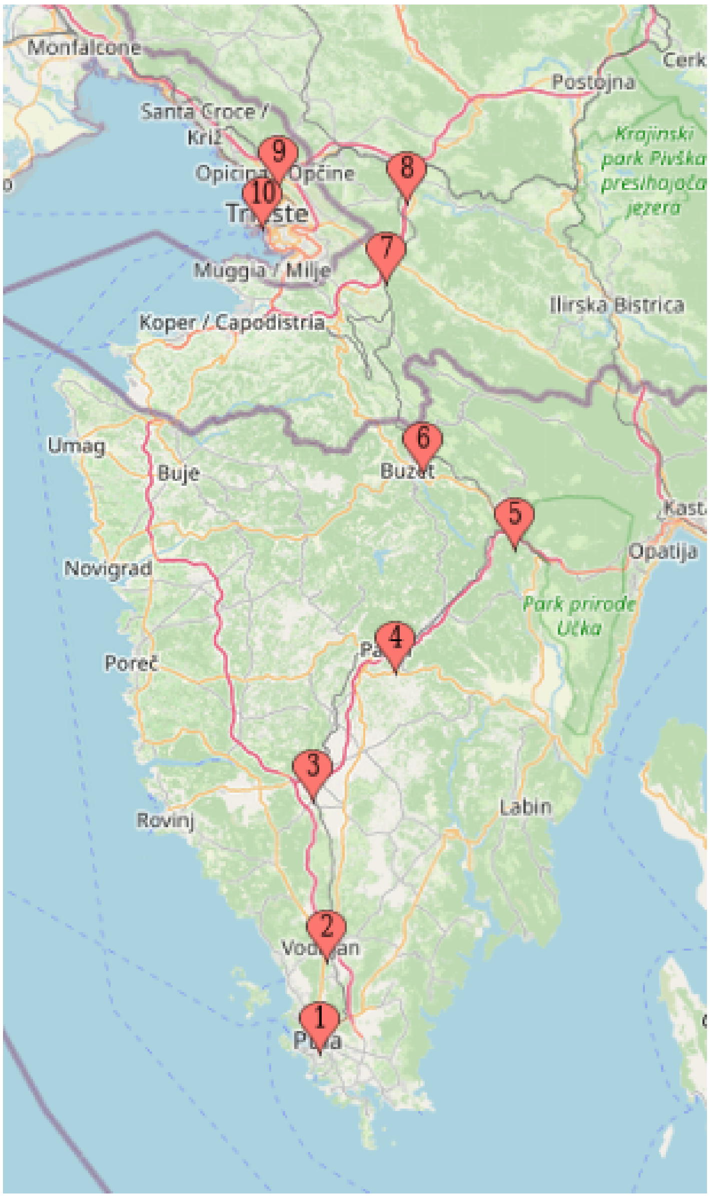

Figure 2.4: Chosen stops among the available on the network.

Stations have been chosen doing an analysis based on both geographical and demographical factors. The previous line had a high number of stops in many small towns, of which some are now almost uninhabited.

1. Pula/Pola station has been chosen as southernmost terminus as the main station is still working now and the city has a high population;

2. Vodnjan/Dignano station has been included in the analysis as the municipality itself is in the center of many smaller towns. The city had two available stations, the bigger one had more intermodal connections (buses and coaches);

3. Kanfanar/Canfanaro stations was once the terminus for the branch line heading to Rovinj/Rovigno. The position of the town in the Istrian context (in the

middle of the motorway connections) is very important in order to allow the implementation of the renewal on the track;

4. Pazin/Pisino is hosting part of the administrative employees of Istria. The city connection is very important as the station is still used today, despite the low level of service;

5. Lupoglav/Lupogliano station, due to its position, has a geographical predisposition to the implementation of a branch line heading to the rest of the Croatian Railway Network. A tunnel connecting the line to the city of Rijeka/Fiume through the Učka/Monte Maggiore has always been planned but never implemented;

6. Buzet/Pinguente is the last station before the border between Slovenia and Croatia;

7. Hrpelje-Kozina/Erpelle-Cosina is a transit station where already now most of the trains connecting Italy to Slovenia stop.

8. Divača/Divaccia station is where now the almost abandoned branch line to Pula/Pola is connected to the Slovenian Network. It can be bypassed in order to create a faster line;

9. Villa Opicina is located in Trieste and has good intermodal connections to the northern part of the city. The stations should be in charge of those passengers which are not going to the downtown of Trieste;

10. Trieste Centrale is the desired terminus for the network, also connected to the rest of Italy both using HS/HC line and regional lines;

2.2.3 Traction system

As Traction Power Substations are necessary in order to allow the current flow on the network, seven locations have been found, computing the required distance between them.

1. Pula/Pola as the start of the line;

2. Vodnjan/Dignano as available space outside the inhabited center. This location is close to the first TPSS but necessary as the first part of the track undergoes easily gusts of wine;

3. Kanfanar/Canfanaro as the central location allows the installation also of the central signaling control station;

4. Heki Tovariste/Checchi as required due to its intermediate position;

5. Lupoglav/Lupogliano as might be studied a connection to the rest of Croatian Network;

6. Buzet/Pinguente as it is necessary full traction in order to climb higher slopes;

7. Podgorje/Piedimonte d'Istria: this location in the middle of the hills is close to Golic plateau, where onshore wind turbines are planned to be installed;

The remaining part of the network is already electrified using 3 kV DC system, which shouldn't need further investments.

2.2.4 Signaling

Chosen signaling standard is ETCS Level 2, as necessary in order to achieve European standards for new railways and renewal projects. Further analysis is attached in the dedicated section.

2.2.5 Objective Analysis

During the analysis some objectives were set in order to follow guidelines.

- minimize generalized cost of transport: the trip's cost using the suggested railway line is lower than the cost of a private car trip or a bus trip. As train's schedule should be constant during the year and can serve workers and students, season tickets can be proposed.

- minimize pollution: as the train is not fossil fuel powered but an electric traction vehicle, pollution due to fuel emissions is reduced.

- minimize unemployment: as the railway requires many new employee, the workforce can be hired in the region (or in close locations). Hiring local people won't have a direct impact on unemployment (which is already relatively low) but can have an impact on population reduction due to emigration.

- maximize accessibility: not directly mentioned, but having low floor vehicles gives a more suitable vehicle for reduced mobility people.

- maximize passengers' comfort: a brand new and ipothetically well maintained rail track gives a better comfort performance than both a old track and a bus service.

2.2.6 Impact Analysis

The To Be scenario has important impact on many different fields of study.

- Economic impact: having a entering investment stream from European Union (and further possible investors) raises the appeal of the location and gives the possibility to increase the region's global cash flows.

- Territorial impact: land use is reduced as many of the land consuming infrastructures are already available (stations, track). On construction sites must be considered the impact on the territory. Land use must be computed where suggesting creation of wind turbines park.

- Social impact: the infrastructure gives both a positive impact on employment rate and demographical reduction phenomenom.

- Environmental impact: apart from pollution reduction, having a unused material disposing already planned reduces the impact on the environment.

2.2.7 Further notable interventions

Figure 2.5: Old rolling stock crossing the border between Croatia and Slovenia. It is evident that the double consecutive turn can be easily replaced by a less stressful for the train, having as a result a better passengers' comfort.

Apart from main infrastructural and service interventions, it is necessary to mention some architectural and civil engineering requirements in order to allow the network to work.

The whole selected route runs on an open air rail, excluding one gallery between Lupoglav and Buzet. It is necessary to renew this gallery as it was built more than one century ago and it doesn't fit 21st Century's security standards. The gallery renewal is necessary also in order to allow the contact line to pass through the gallery: the current gallery's height is not defined and it could be lower than the reported open-pantograph height of the vehicle. Some curves may need further analysis as following the current route (engineered earlier than 1900) is not performing the current best path.

In order to avoid lateral effects of the wind, the first section of the track must implement wind barriers (between Pula and Vodnjan) as the path is running in a flat ground windswept by gusts. Irregular wind effect will affect both lateral and longitudinal dynamics of the vehicle.

It is necessary to mention that in order to avoid accidents between road cars and the rail vehicles must be considered installing railway crossings on the whole line in many locations. The cost of this intervention is already included in the infrastructural section of the Capital Expenses as already considered in the estimation criteria.

2.3 As Is - To Be comparison

In order to compute the required comparisons, three scenarios have been considered, having only two of them actually performed by a train. The bus connection has been reported as a benchmark.

1. As Is performing at its best: train from Pula to Buzet diesel traction, Buzet to Rakitovec diesel traction, Rakitovec to Divača 3 kV DC, Divača to Trieste 3 kV DC, running all the current stops. As the line between the Croatian station of Buzet and Trieste doesn't exist, the model has been run having not detailed information on intermediate stops;

2. As Is using Coaches: the bus is following a different route from the train, but it's the only existing and working alternative connecting the two terminuses chosen for this model;

3. To Be: completely electrified line using 3 kV DC traction, running only the chosen intermediate stops;

Must be mentioned that the bus express line trip duration is reported from the company's schedule, and it's not always strictly followed. It is reported only as a benchmark as a precise comparison with the To Be scenario can be performed.

The Buzet – Rakitovec section of the route is limited at the moment. Calculations were computed assuming the track as working and no time on the border crossing is lost. As is solution has been computed using the latest available train and best performing schedule, no intermediate stops between Buzet and Trieste on the As Is standard solution.

	Duration	Consumption	Available seats	Operative costs
AS IS	3h20min	330 L	212	462.00 €
AS IS Bus	2h45min	33 L	46	46.20 €
TO BE	2h32min	2389 kWh	212	238.90€

Cost of a journey has been computed having:

1. 1.4 €/L for diesel cost

2. 33 L/100 km for coach diesel engine

3. 200 L/100 km for train diesel engine

4. 0.10 €/kWh for electric engine

2.4 Track choice

Ballasted track using prestressed concrete has been chosen for the track interventions. As different options were available (and already installed in some of the track parts) they were discarded as not economically and/or environmentally sustainable. Replacing the whole Croatian section of the track has been chosen among all the alternatives (including refurbishing the previous track) as the current infrastructure's reliability is not possible to be estimated as no maintenance has been executed in the last 30 years at least. Also, replacing those damaged sections with compatible track (based on wooden sleepers) would have been an unnecessary bigger expense.

Chosen standard is (UNI) UIC-60 having mass of 60.340 kg/m

2.4.1 Sleepers material

Wooden sleepers were way more expensive than concrete ones, and maintenance would have been way more expensive. As the whole track would have been replaced, it was computed as less expensive to use the prestressed concrete sleepers.

2.4.2 Track type

Above the available options, ballasted track has been chosen. Slab track was discarded as external environmental phenomenon may have disruptive effects on the track. Clear example of this is the effect of the soil on a branch line in Istria, close to the main line here analyzed. The branch line is now nicknamed "Drunk Railway" as soil subsidence caused the track to move from its original bed. Having a solid ballastless track would be a problem in case of maintainance, as non ordinary interventions on ballastless tracks are way more expensive than on simple ballast track.

Figure 2.6: "Drunk railway" shows the effect of the Istrian unstable soil on the railway. A ballastless track would have overperformed the chosen track but unpredictable effects would make ordinary some extraordinary and expensive maintenance interventions.

Chapter 3

Longitudinal Dynamics

3.1 Model presentation

3.1.1 Longitudinal dynamics model

In order to gather numerical results on the selected route, a model of the longitudinal behavior has been developed. Model is based on simple input, including vehicle's specifications (top speed, maximum acceleration, mass) and track limits (maximum speed, curvature radius, slope). The computed output includes significant information on accelerations, engine power, speed and energy consumption.

The algorithm used by the model can be briefly summarized as follows:

1. Starting conditions are set: as the vehicle is not moving, main attributes are set to starting values.

2. Time index is increased and resistant forces are computed, together with torque values and acceleration.

3. Speed and space values are computed for the time value.

4. Power is computed for the time value.

The time index is then used to execute the algorithm on the whole route. At the end of the route, energy consumption is computed.

3.1.2 Input values

Input values are divided between route and vehicle attributes.

Parameter	**Description**	**Unit of measure**
Vmax	Maximum speed available on the track	km/h (m/s)
max_acc_comfort	Maximum acceleration	m/s^2
alpha	Road slope value	Rad

Table 3.1: Route parameters

Parameter	**Description**	**Unit of measure**
Rated torque	Maximum engine torque	Nm
Rated power	Maximum engine power	kW
fr	Rolling resistance coefficient	-
A	Frontal area of the vehicle	m^2
rho	Air density	kg/m^3
Cx	Drag coefficient	-
m	Vehicle curve mass	kg
tau	Transmission ratio	-
eta_d	Direct flow transmission efficiency	-
eta_r	Reverse flow transmission efficiency	-
R	Wheel radius	m

Table 3.2: Vehicle parameters

3.1.3 Control Logic

When creating the simulation model, the following logic has been used in order to compute the values for acceleration, speed, distance covered and energy consumption.

```
if (distance from next stop > breaking distance)
        if (speed < speed limit)
                 vehicle is accelerating (acceleration > 0)
        else
                 vehicle speed is constant (acceleration = 0)
else
        vehicle is decelerating (acceleration < 0)
```

Subject to
$speed \leq speed\ limit$
$power \leq nominal\ power\ of\ the\ engine$
$comfort\ deceleration \leq acceleration \leq comfort\ acceleration$
$curvature\ radius > 0$
$Having$
$Resistance\ Forces = P_{weight} + P_{roll} + P_{aero} + P_{curvature}$
$Direct\ Torque = f(comfort\ acceleration, Resistance\ Forces)$
$Reverse\ Torque = f(comfort\ deceleration, Resistance\ Forces)$
$Direct\ Acceleration = ((eta_d * T_m)/(r_w * tau_g) - F_{r,tot} - T_{b,tot}/r_w)/(m * +(eta_d * J_m)/(r_w * tau_g)^2)$
$Reverse\ Acceleration = ((T_m)/(r_w * tau_g) - eta_r * F_{r,tot})/(eta_r * m * +(J_m)/(r_w * tau_g)^2)$
$Power = f(Direct\ Torque, speed)$
$Energy\ consumption = \int_{start}^{end} Power\, dt$
$speed\ limit = \min(f(curvature\ radius), top\ speed)$

3.1.4 Model output

The simulation produced the following output, computed processing the input data. It is easy to understand the correlation between high acceleration values and increasing speed values, whereas acceleration is zero (or very low value, due to slope changes) where the speed reached the speed limit.

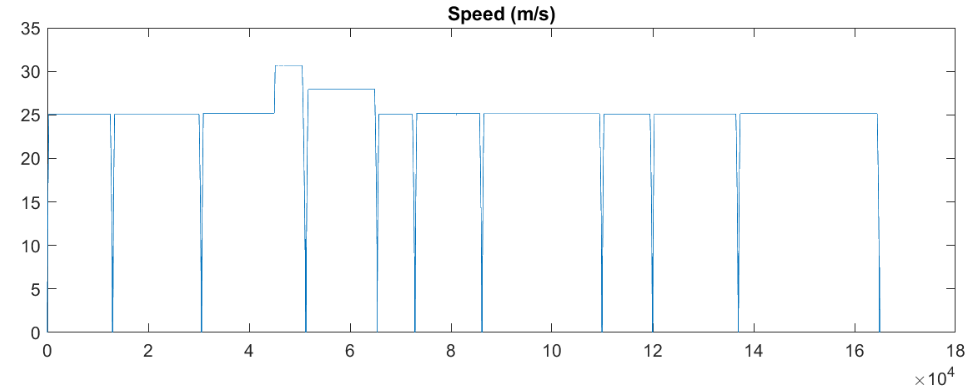

Figure 3.1: The speed is generally reaching the speed limit set for the section of the path. Speed limit has to follow guidelines set by both track conditions and curvature radius. Most of the track's curves are wide enough to not reduce significantly the maximum allowed speed. The displayed minimum points, as in all the plots, represent the intermediate stops on the line, which are computed as 0 km/h sections of 100 meters length.

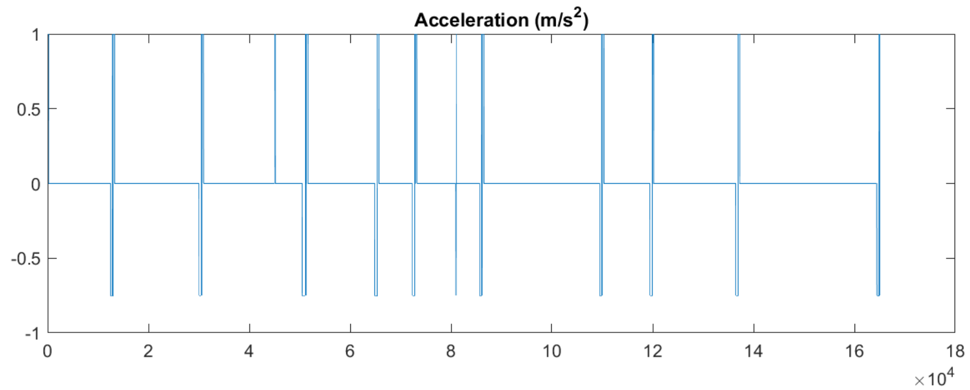

Figure 3.2: Acceleration is reaching the top value as the model tries to reach the maximum speed in the lowest time required. Power on time plot is not displayed as doesn't show further notable information. In the track conditions, the top acceleration is easily reached as there are not critical sections on the path. Maximum acceleration is then equal to maximum comfort acceleration.

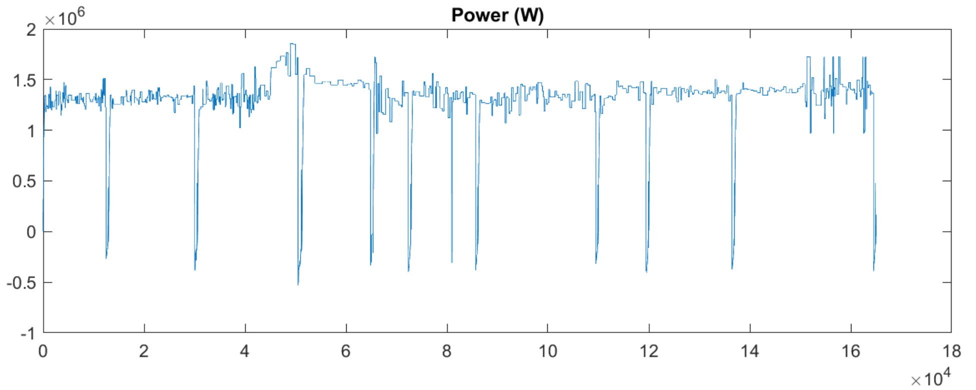

Figure 3.3: Power output is not homogeneous as keeping the speed constant having a changing slope requires higher power in some points. The power output of the engine is always under the limit set to 1.9 MW, which is 5% lower than the maximum power output of the vehicle's engine assuming this value drop necessary for computing auxiliary services. In the calculation is also included regenerative braking.

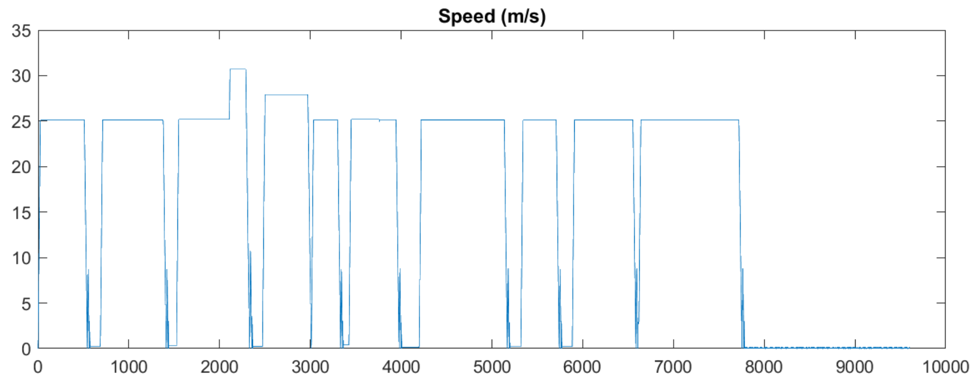

Figure 3.4: Speed is increasing in the time and it is possible to check where the stops are located: points with zero speed are those where there is a stop. Stop time is shown in this plot, which wasn't displayed in the space/speed plot.

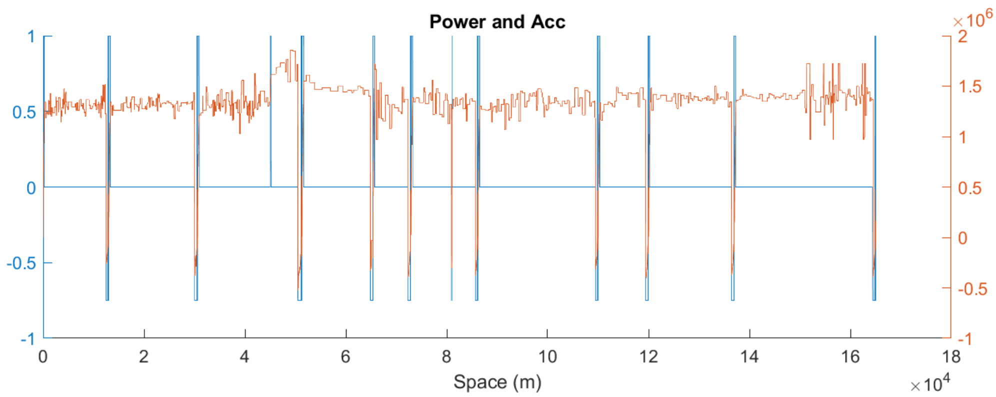

Figure 3.5: The relationship between power and acceleration is displayed as the higher power output is necessary where increases the acceleration.

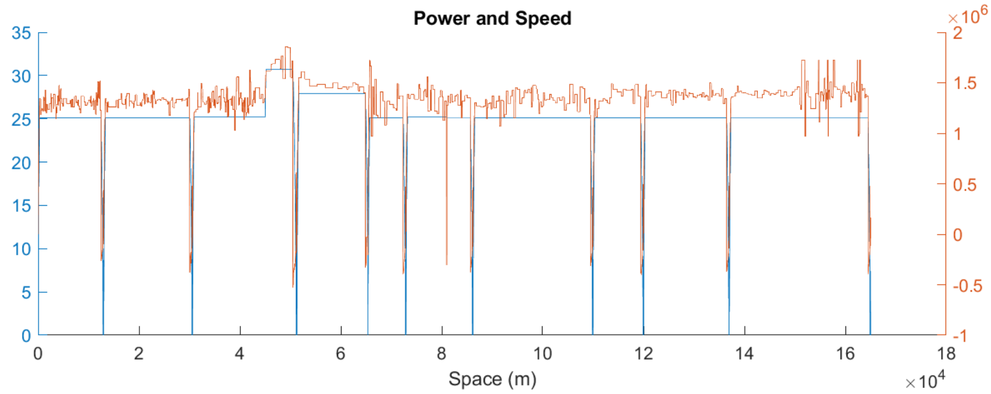

Figure 3.6: Power output is not constant (even when the desired speed is reached) as keeping the value costant having different slope requires more power. This happens as the displayed plot is showing the whole 165 km path: on a lower scale, there would be different power output variations.

Chapter 4

Vibrations Analysis

4.1 Vertical dynamics

4.1.1 Rail irregularity

A quarter-car model has been used in order to evaluate and analyze the behavior of the train to the rail irregularity.

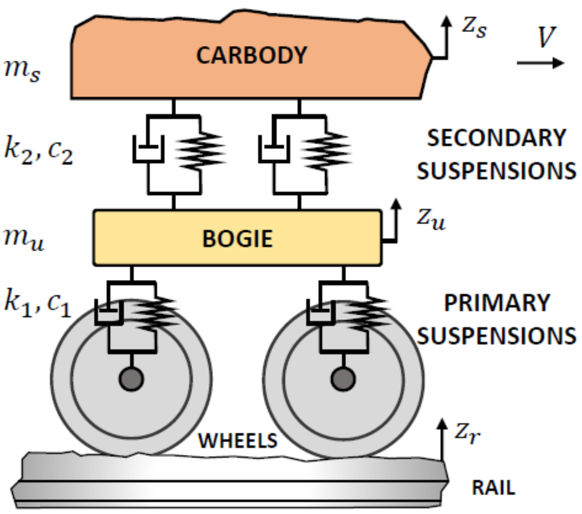

Figure 4.1: Quarter-car model.

m_s = *Sprung Mass* $[kg]$

m_u = *Unsprung Mass* $[kg]$

$k_{1,2}$ = *Suspension/Tyre Stiffness* $[N/m]$

$c_{1,2}$ = *Suspension/Tyre Damping* $[Ns/m]$

Figure 4.2: Quarter-car model parameters.

Track irregularity for rail vehicles is defined starting from the Power Spectral Density (PSD)

$$G_d(\Omega) = \frac{A_v \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} \tag{4.1}$$

Where Ω is the angular spatial frequency, defined as $\Omega = 2\pi n$, in which n is an array of spatial frequencies. A_v is a parameter which refers to the defects of the track. Considering the actual scenario, characterized by the bad condition of the rails, it's possible to use $A_v = 1.0800 * 10^{-6}$ $[m/rad]$ representing big defects on the rail; instead, for the new solution, with new rails, the parameter used is $A_v = 4.0320 * 10^{-7}$ $[m/rad]$ representing small defects.

The analysis will be in the frequency domain, so the frequency array is defined as $f = \frac{v\Omega}{2\pi}$, where v is the speed of the train, constant for the section of path considered. For an analysis of vibrations is useful to put on the worst condition, so the highest speed of the train, in this case, 110 km/h.

Given the PSD and the vehicle parameters (sprung mass, unsprung mass, suspension stiffness, and suspension damping) it's possible to obtain the transfer function (TF) and then displacement, velocity, and acceleration of the road, the sprung mass (carbody) and unsprung mass (bogie).

Vehicle parameters:

m_s	Sprung Mass	9000 kg
m_u	Unsprung Mass	1400 kg
k_2	Secondary Suspension Stiffness	$3.4 * 10^5$ $[N/m]$
k_1	Primary Suspension Stiffness	$1.95 * 10^6$ $[N/m]$
c_2	Secondary Suspension Damping	13000 $[Ns/m]$
c_1	Primary Suspension Damping	16000 $[Ns/m]$

The following picture shows the transfer function for sprung and unsprung masses.

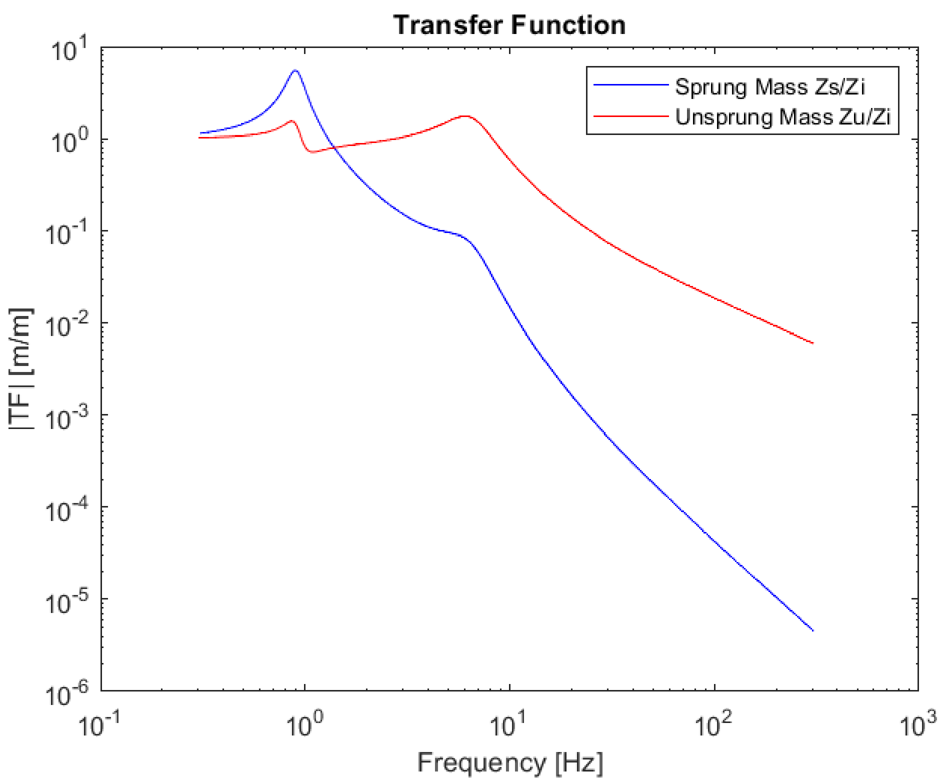

Figure 4.3: Transfer function (TF.)

The following pictures are the sprung/unsprung masses and the rail irregularity in the frequency domain.

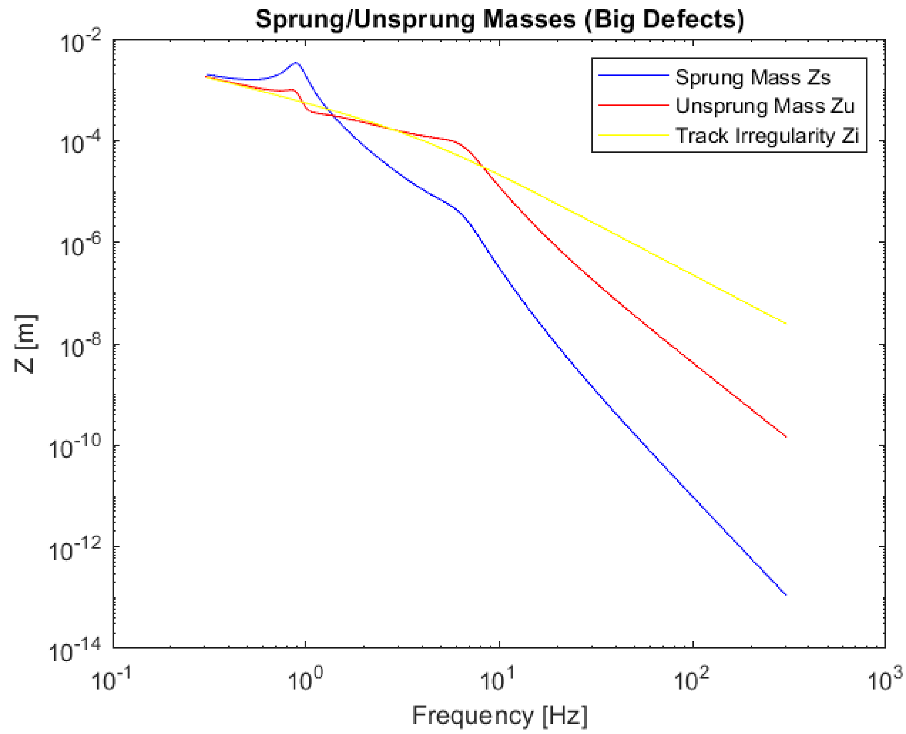

Figure 4.4: Sprung/unsprung masses and rail irregularity in case of big defects.

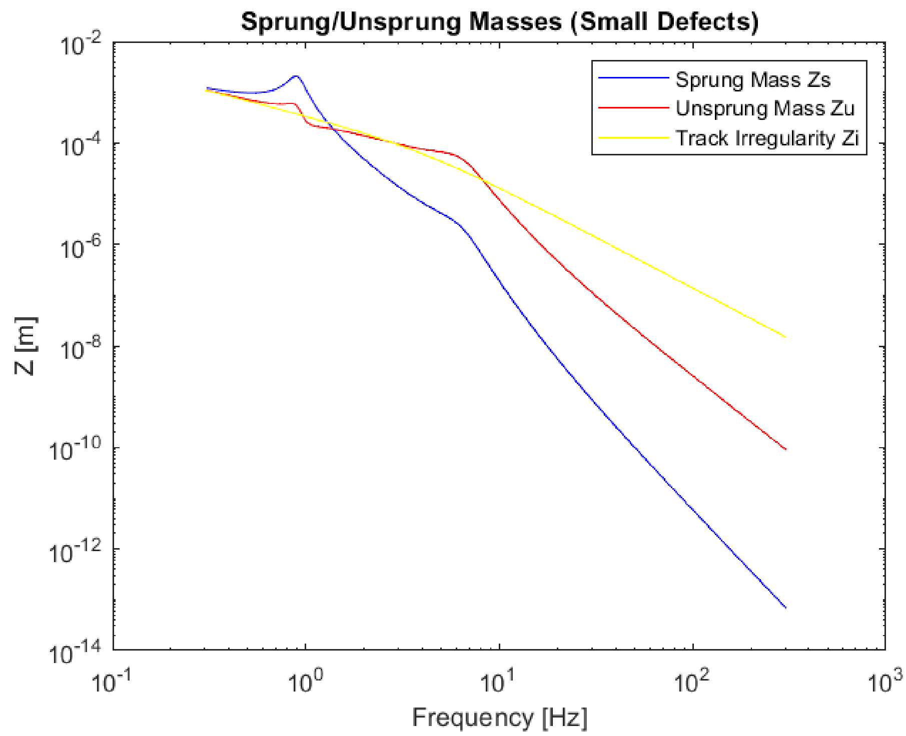

Figure 4.5: Sprung/unsprung masses and rail irregularity in case of small defects.

The following are the plots of displacement, speed and acceleration of sprung mass, unsprung mass and rail irregularity for a section of the path of $1km$.

Displacement

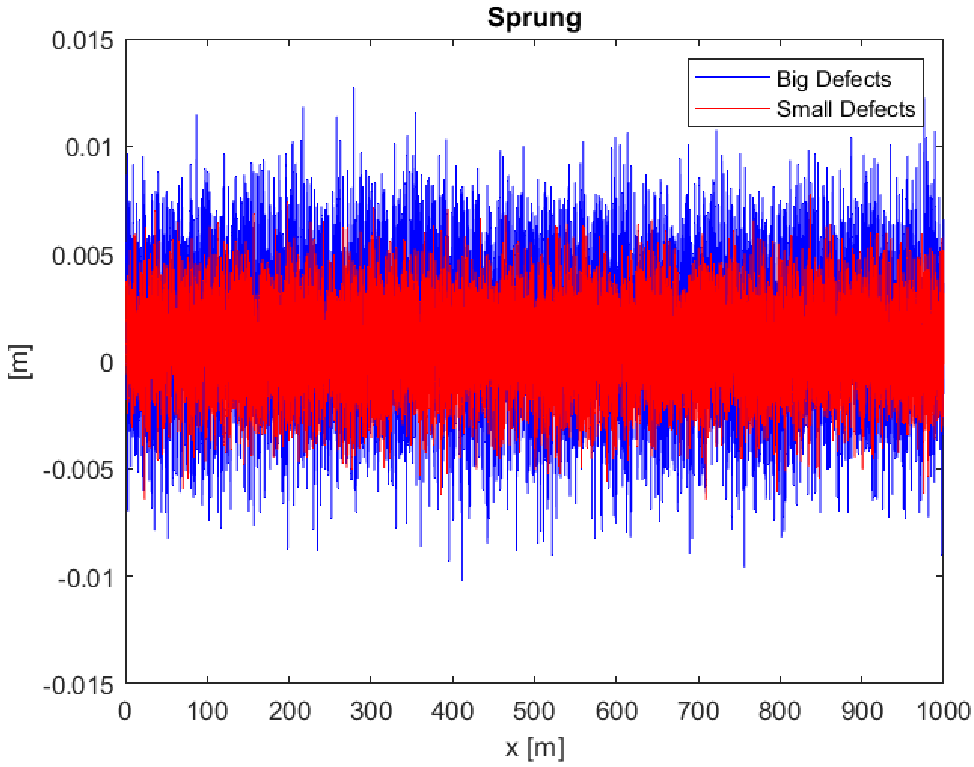

Figure 4.6: Sprung displacement for big and small defects.

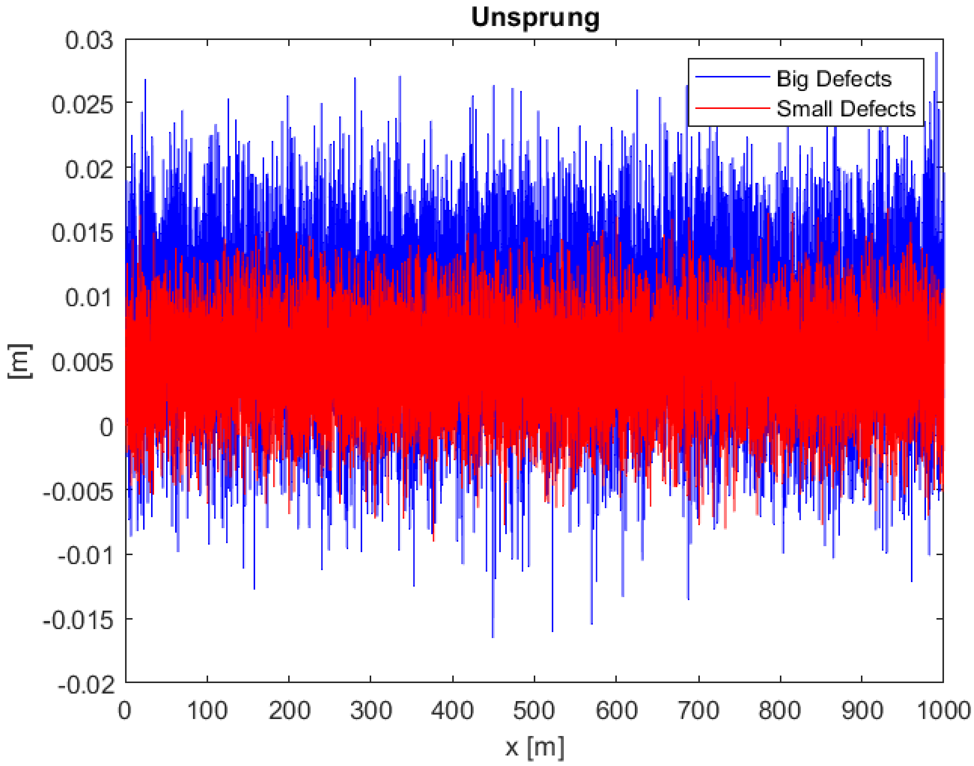

Figure 4.7: Unsprung displacement for big and small defects.

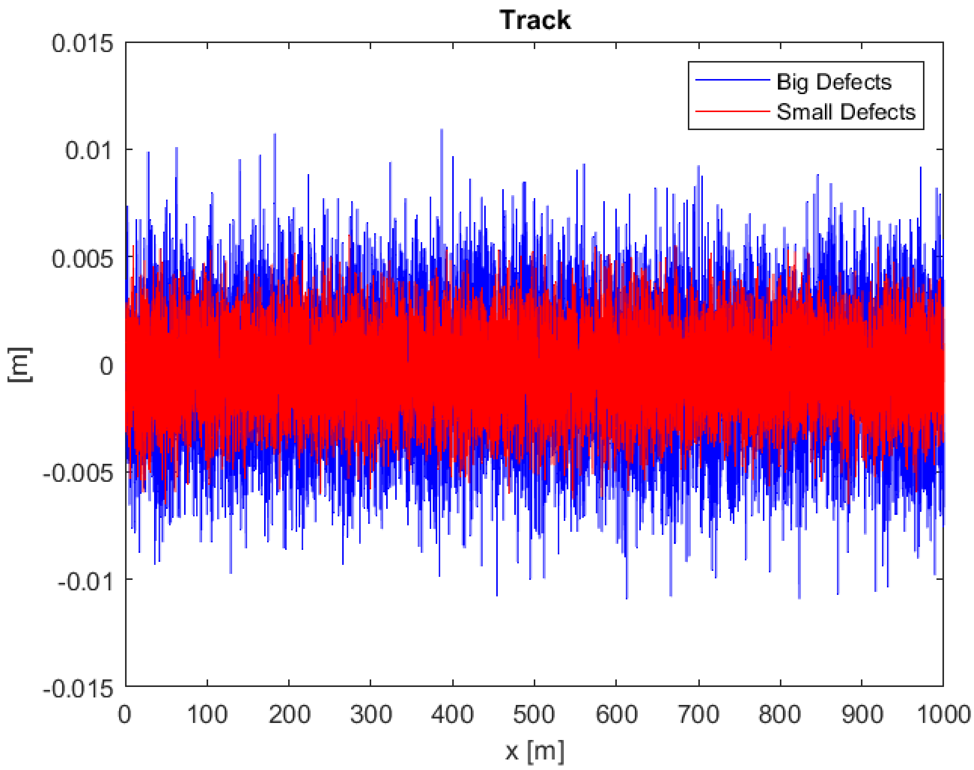

Figure 4.8: Track irregularity displacement for big and small defects.

Velocity

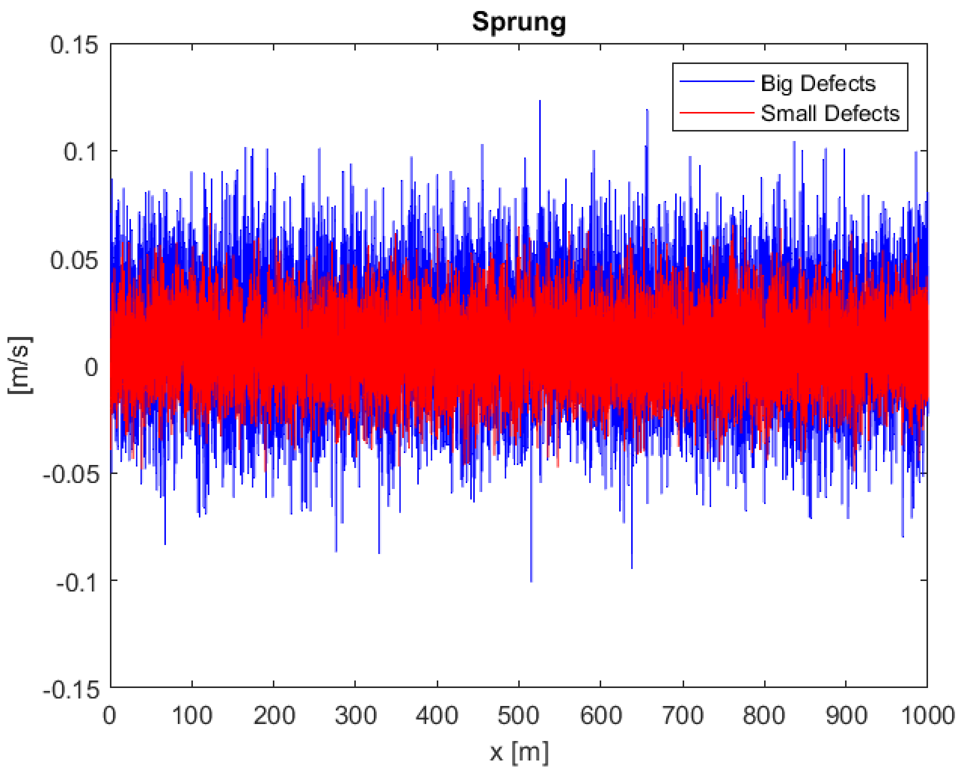

Figure 4.9: Sprung velocity for big and small defects.

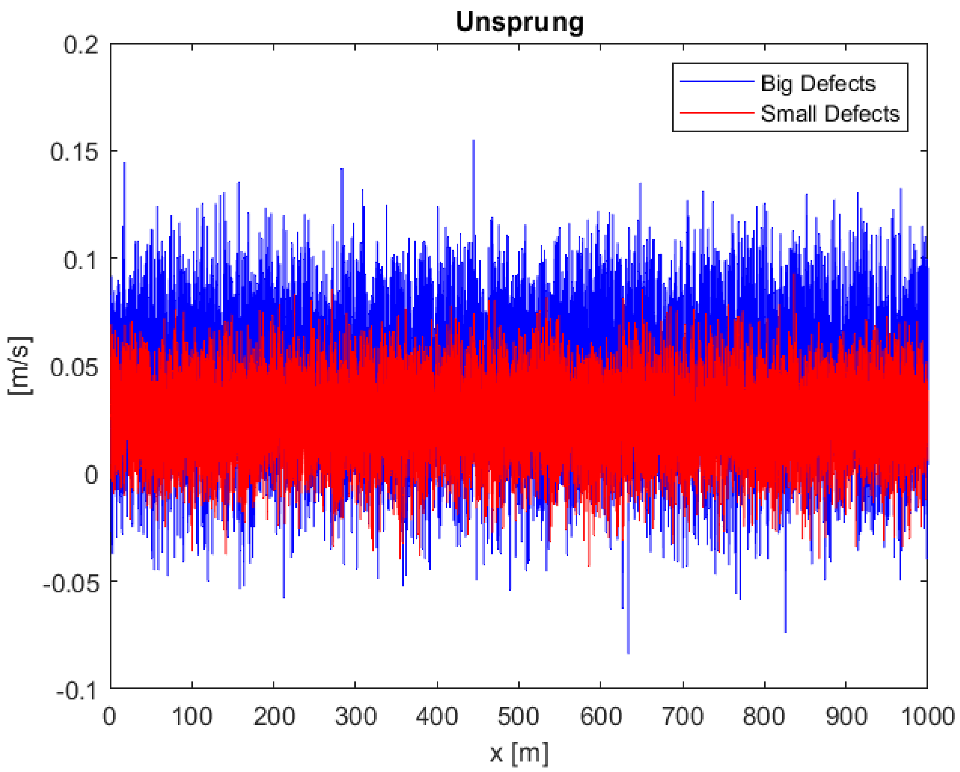

Figure 4.10: Unsprung velocity for big and small defects.

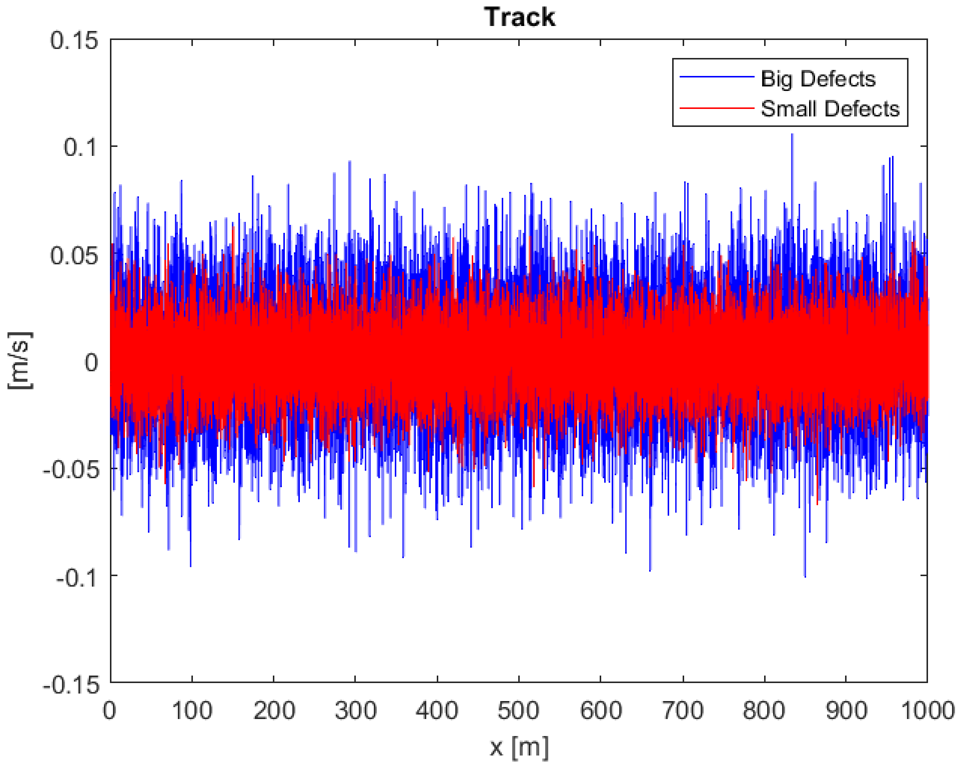

Figure 4.11: Track irregularity velocity for big and small defects.

Acceleration

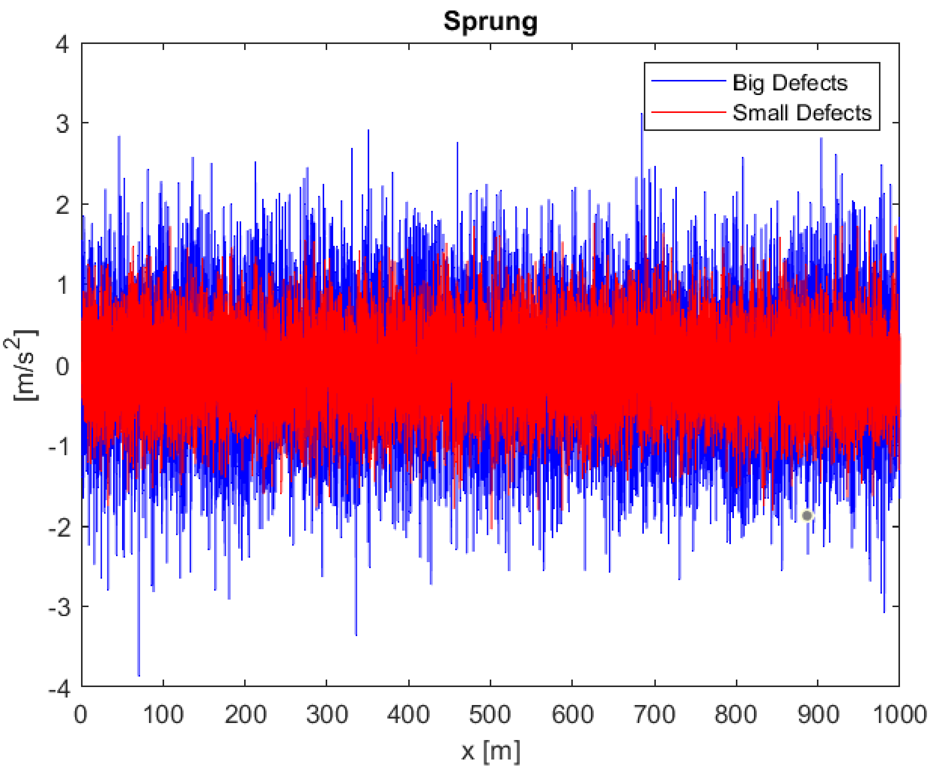

Figure 4.12: Sprung acceleration for big and small defects.

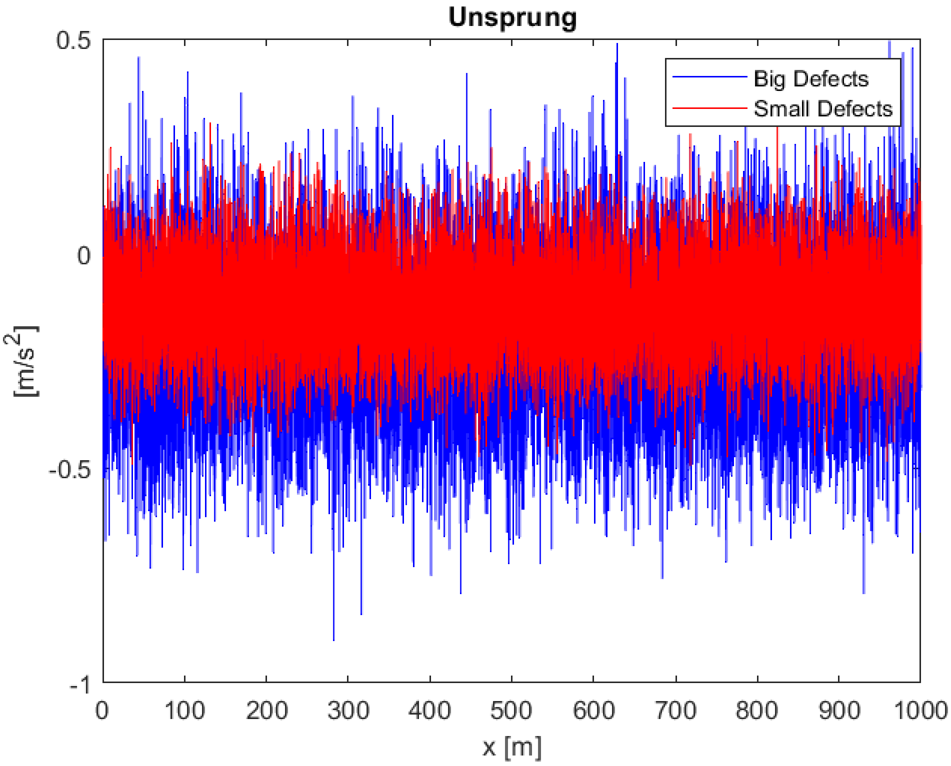

Figure 4.13: Unsprung acceleration for big and small defects.

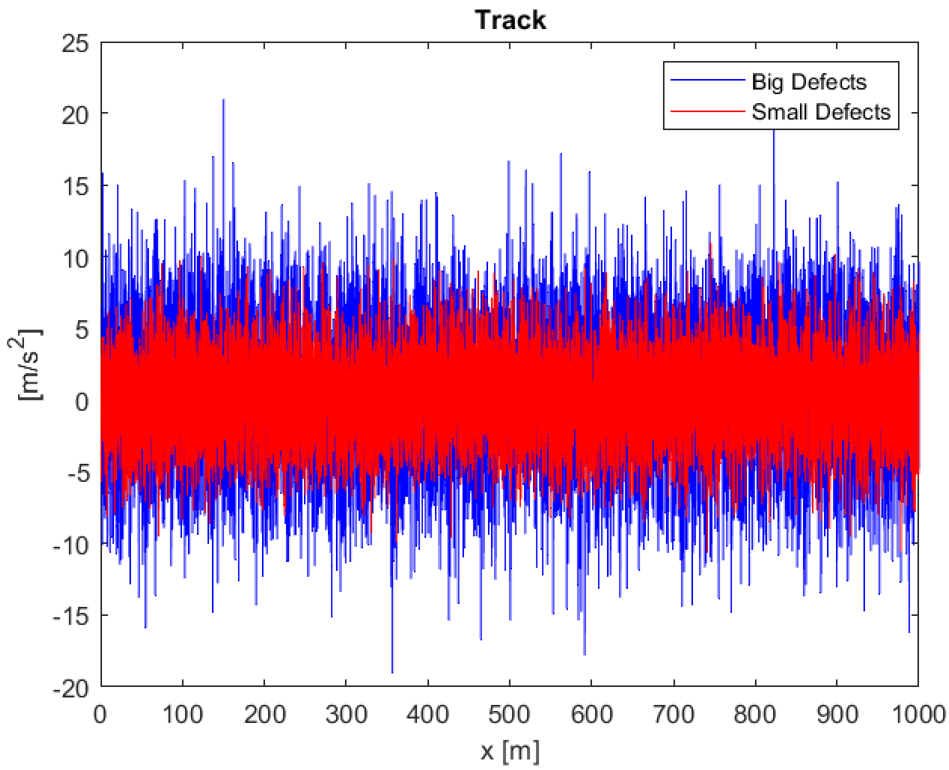

Figure 4.14: Track irregularity acceleration for big and small defects.

4.1.2 Comfort

Starting from the carbody acceleration $\ddot{Z}_s(f)$, the passenger comfort is evaluated through the following procedure:

1. Turn the narrow band signal power spectrum in third-octave bands:

$$\frac{\ddot{Z}_s(i)^2}{2} = \sum_{f\ mini,i}^{f\ maxi,i} \frac{\ddot{Z}_s(f)^2}{2} \qquad i = 1, 2, n_{bands} \tag{4.2}$$

2. Calculate the Root Mean Square value (RMS) of the third-octave bands carbody acceleration:

$$\ddot{Z}_{s,RMS}(i)^2 = \sqrt{\frac{\ddot{Z}_s(i)^2}{2}} \qquad i = 1, 2, n_{bands} \tag{4.3}$$

3. Apply the ponderation filter $W_k(i)$ and compute the weighted RMS acceleration $a_{w,RMS}$:

$$a_{w,RMS} = \sqrt{\sum_i (W_k(i)\ddot{Z}_{s,RMS}(i))^2} \tag{4.4}$$

The following pictures are the frequency weighting curve according to ISO 2631 for the z-axis (W_k) and the filter effect on $\ddot{Z}_{s,RMS}$.

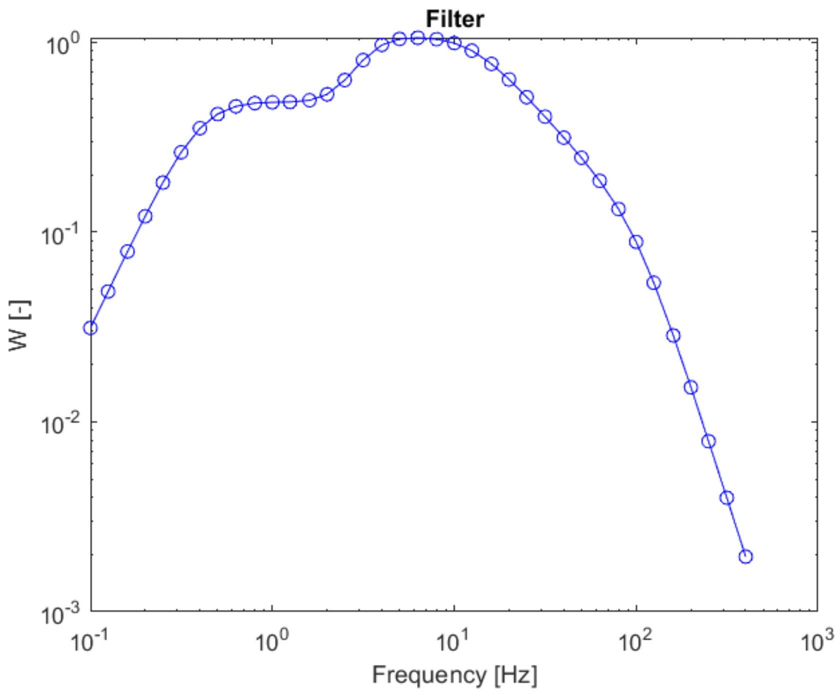

Figure 4.15: Filter W_k

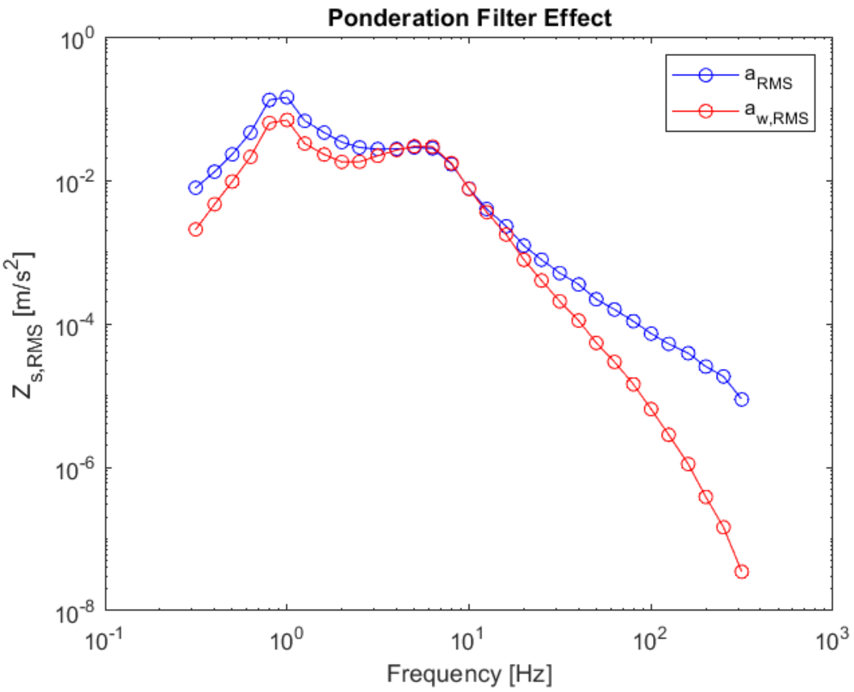

Figure 4.16: Filter effect

Considering the parameters in chapter 4.1.1 the value is $a_{w,RMS} = 0.1217\ m/s^2$. Taking into account the following standard values

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

Figure 4.17: Reference values for $a_{w,RMS}$.

it is possible to conclude that $a_{w,RMS}$ is good, being in the "not uncomfortable" zone.

Suspension Tuning

The tuning has the aim of evaluating how changes the $a_{w,RMS}$ changing the vehicle parameters in chapter 4.1.1. It is considered a variation of the 50% for stiffnesses and dampings and a variation of the 20% for the sprung mass.

Variation of stiffness k_2 (secondary suspension, between carbody and bogie).

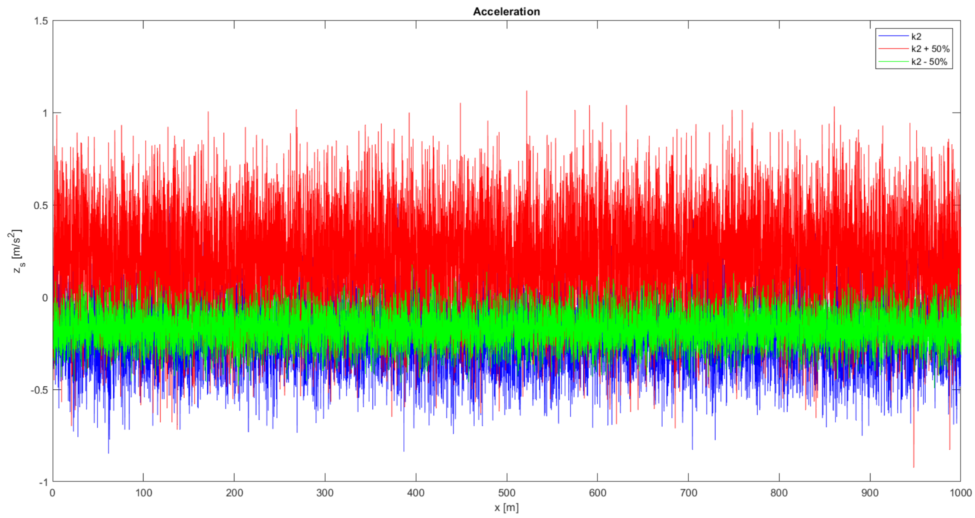

Figure 4.18: $k_2 \pm 50\%$.

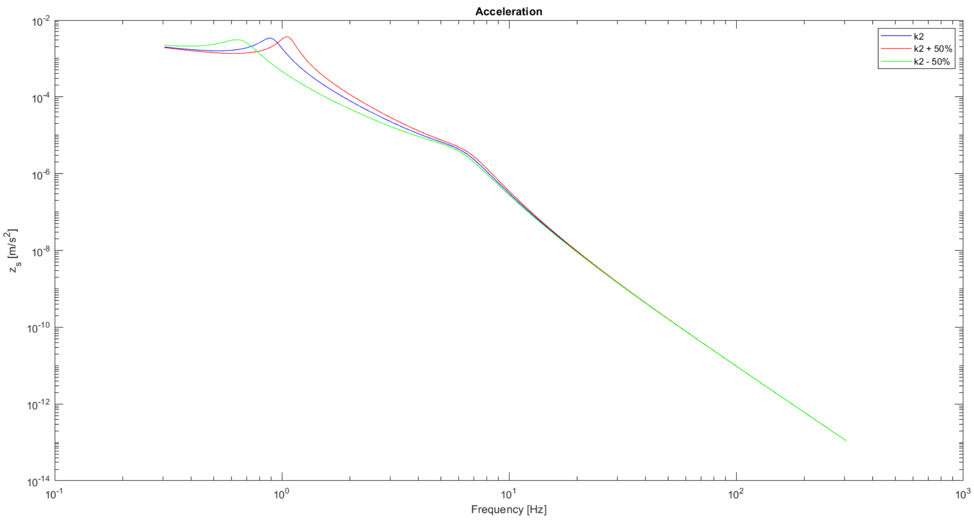

Figure 4.19: $k_2 \pm 50\%$ in f domain.

Variation of damping c_2 (secondary suspension, between carbody and bogie).

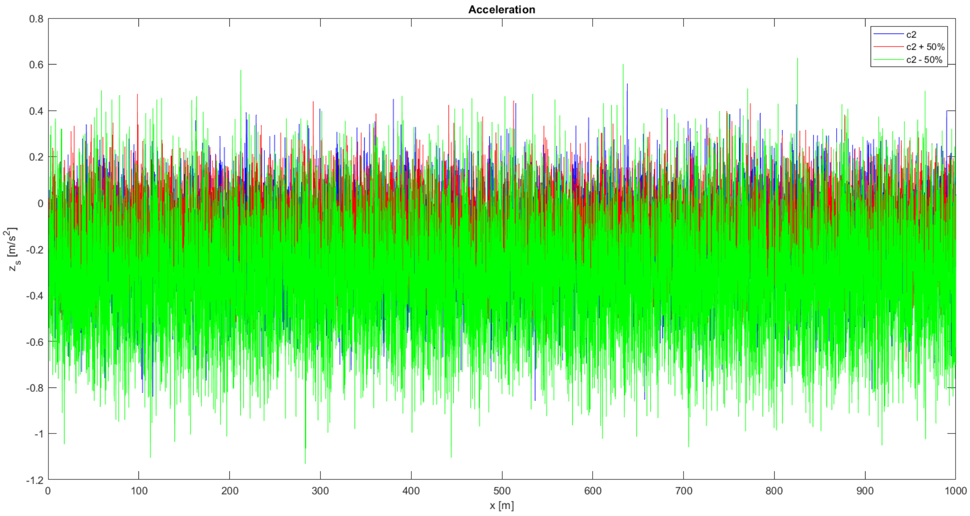

Figure 4.20: $c_2 \pm 50\%$.

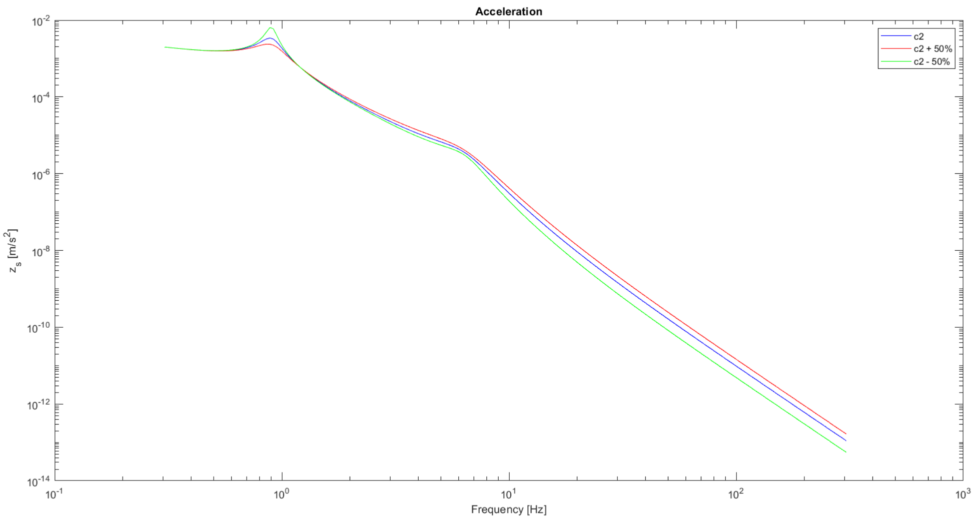

Figure 4.21: $c_2 \pm 50\%$ in f domain.

Variation of sprung mass ms (carbody).

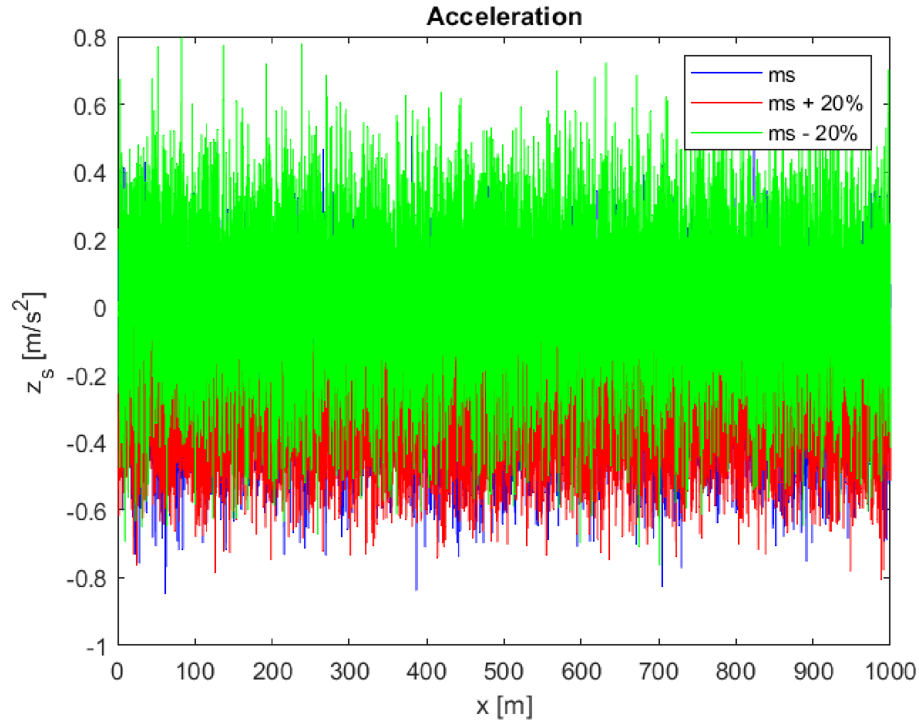

Figure 4.22: $ms \pm 20\%$.

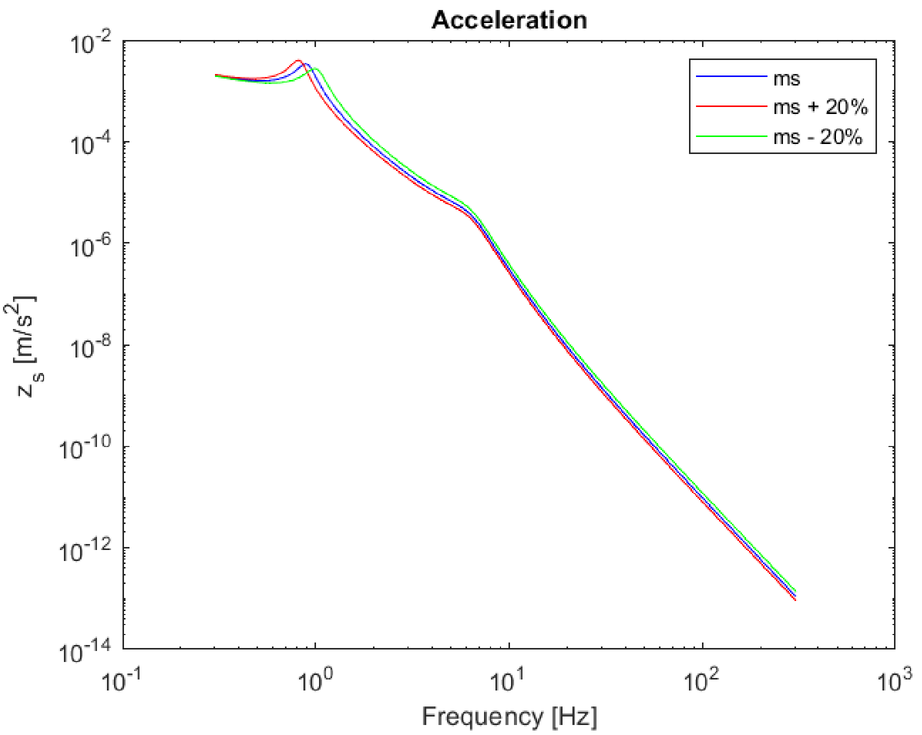

Figure 4.23: $ms \pm 20\%$ in f domain.

The following are the results in terms of $a_{w,RMS}$, the reference value is $a_{w,RMS} = 0.1217\ m/s^2$.

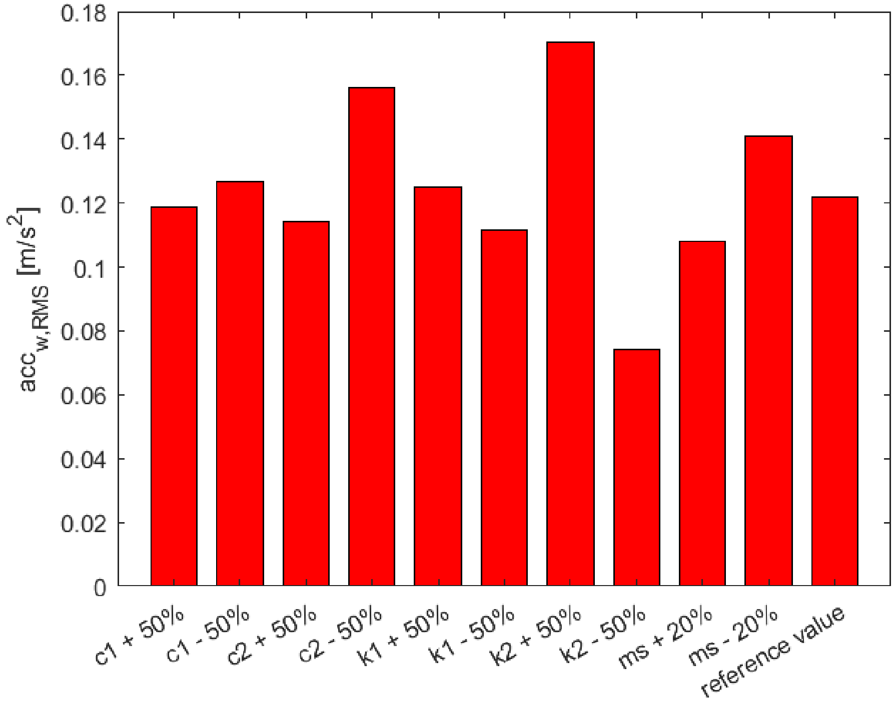

Figure 4.24: $a_{w,RMS}$ values.

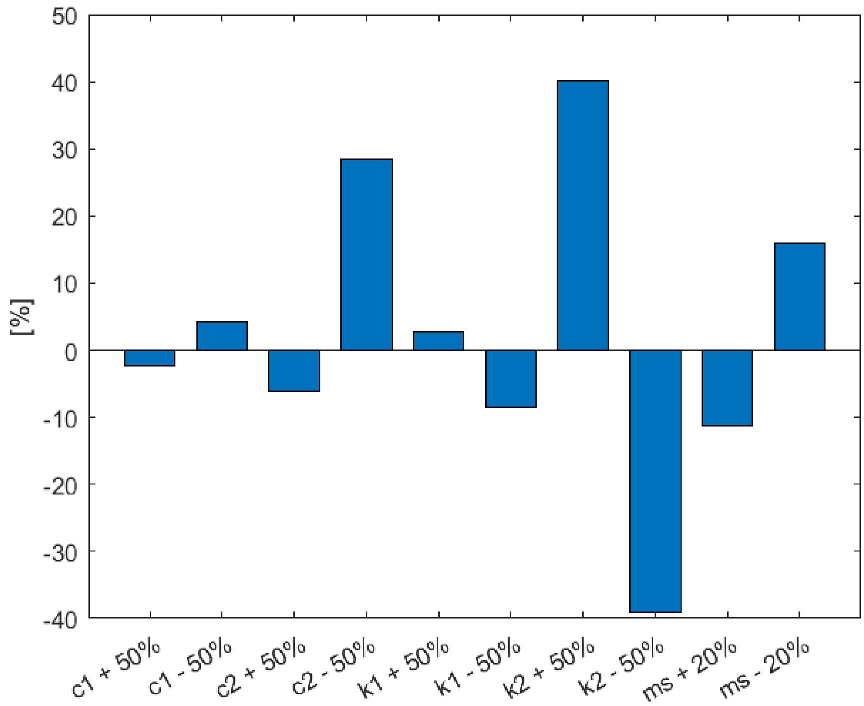

Figure 4.25: Variations in percentage from the reference value.

In conclusion, from the graphics above, it is possible to see how the primary suspension (k_1 and c_1) does not affect the $a_{w,RMS}$. Instead, it is interesting to note that halving the secondary damping and doubling the secondary stiffness increases the $a_{w,RMS}$ by 28% and 40%, correspondingly. Halving the secondary stiffness decreases $a_{w,RMS}$ by 39%, which corresponds to a value of 0.0742 m/s^2, the lowest value found. Working on the sprung mass, the modification is only of the 20%, considering the engineering difficulties in real applications, and the results are that increasing the mass decreases the $a_{w,RMS}$ about 11.2% and decreasing the mass increases the $a_{w,RMS}$ about 16%. Despite that, all the possible solutions maintain the model in the "not uncomfortable" zone.

4.2 Ground-borne vibrations

Vehicles running on the rails are responsible for the vibrations transmitted through the ground and then to the foundations and the buildings, as a consequence. For this reason, it is interesting to analyze the effect of the vibrations of the train on the nearby buildings and infrastructures. The track and the train are modeled according to a model simplified to a single wheel on the rail.

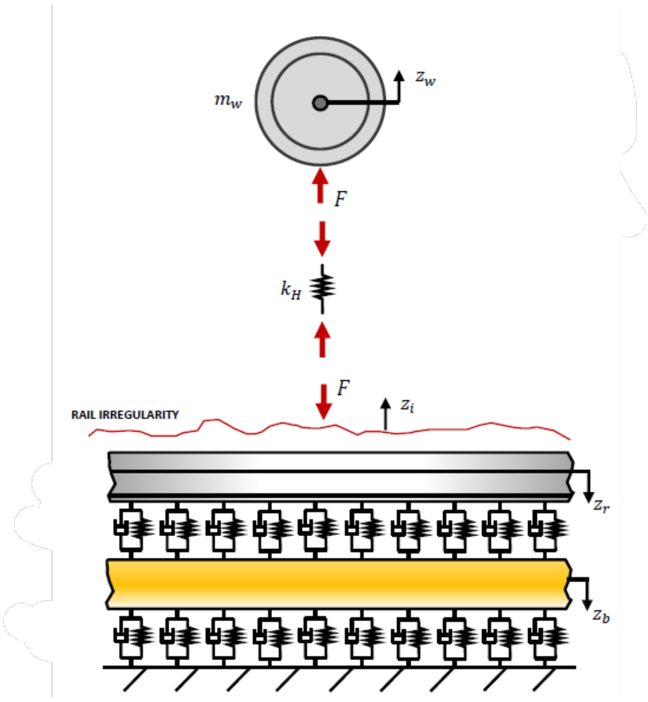

Figure 4.26: Simplified model.

First of all, it is important to analyze the most critical situation, that, in our case, is where the distance between the rail and the nearest house is 4.35 m and the train has a speed of 90 km/h.

Figure 4.27: Critical situation.

Considering a frequency range of $(0.25 - 625\ Hz)$, the procedure for the evaluation of the force transmitted to the ground (F_{soil}) is the following:

1. Compute the track vertical receptances (rail and ballast) according to the Timoshenko double-layer model (G_r and G_b);

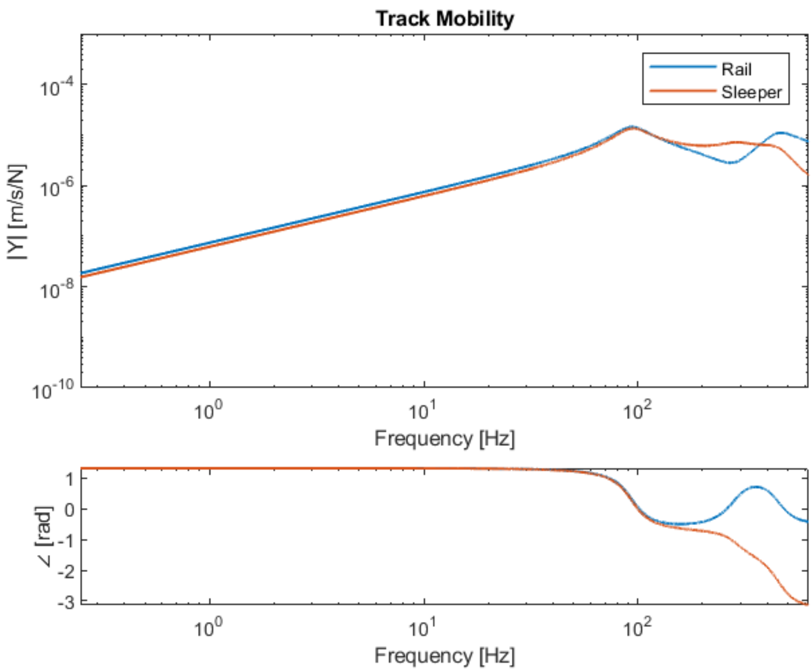

Figure 4.28: Track mobility.

2. Compute the ratio displacement/force for the wheel, function of the frequency;

$$G_w(f) = \frac{Z_w(f)}{F(f)} = -\frac{1}{m_w \omega^2} \tag{4.5}$$

3. Calculate the elastic force;

$$F = \frac{Z_i}{(\frac{1}{k_H} + G_r + G_w)} \tag{4.6}$$

where Z_i is the track irregularity.

4. Compute the displacements for wheel, rail and ballast;

$$Z_w = G_w F = \frac{G_w Z_i}{(\frac{1}{k_H} + G_r + G_w)} \tag{4.7}$$

$$Z_r = G_r F = \frac{G_r Z_i}{(\frac{1}{k_H} + G_r + G_w)} \tag{4.8}$$

$$Z_b = G_b F = \frac{G_b Z_i}{(\frac{1}{k_H} + G_r + G_w)} \tag{4.9}$$

5. Calculate the F_{soil};

$$F_{soil}(f) = k_2 Z_b(f) \Delta L \tag{4.10}$$

where $\Delta L = 2L$ and $L = 0.6\ m$; $k_2 = 7000\ N/m$ is the ballast stiffness.

Knowing the F_{soil} it is possible to evaluate the traffic-induce ground vibrations through the Hunt function. The first step is calculating the relative distances between the receiver and the wheelsets of the coaches. Considering that the train has two locomotives and two coaches, and four wheelsets for each coach/locomotive the four relative distances are 27.6 m from the locomotives and 9.55 m from the coaches.

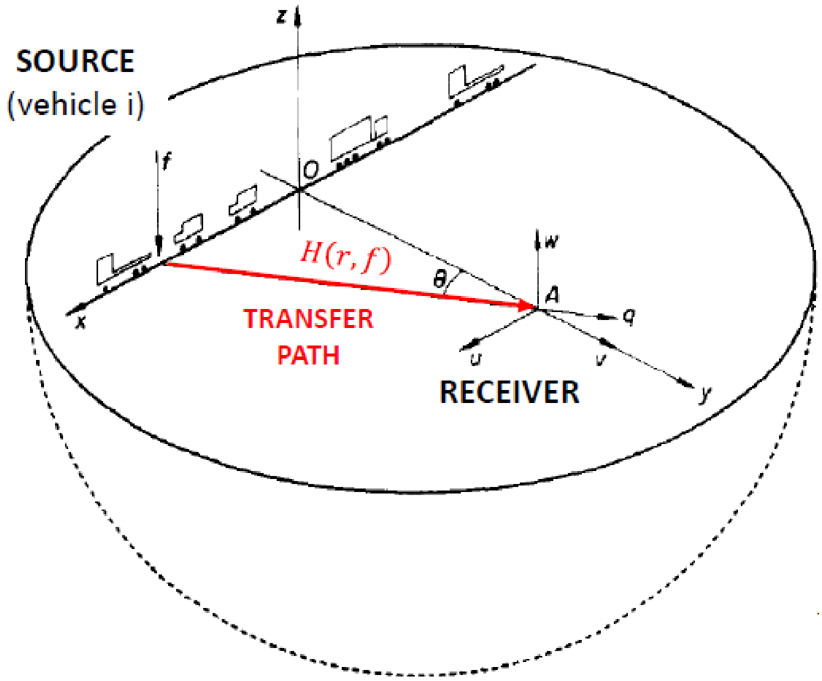

Figure 4.29: Vibration source model.

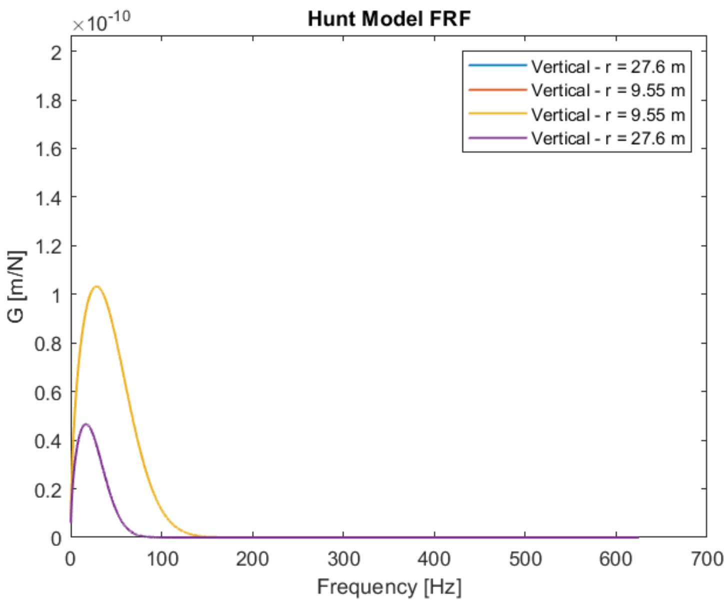

Figure 4.30: Hunt model.

After the evaluation of the distances, the steps are:

1. Calculate the Soil Transfer Function;

$$H^{(i)}(r,f) = \frac{Displacement}{Force} = \frac{d^(i)(f)}{F^{(i)}_{soil}(f)}\ [m/N] \tag{4.11}$$

   where r is the vector of the distances and f is the vector of the frequencies.

2. Calculate the Power Spectrum of the displacement for a single vehicle contribution ($PS_d^{(i)}(r,f)$) from the absolute value of the Hunt receptance ($H(r_i,f)$) and the Power Spectrum of the Soil Force ($PS_F^{(i)}(f)$), considering a force for each wheelset;

$$PS_d^{(i)}(r,f) = |H(r_i,f)|^2 PS_F^{(i)}(f) \tag{4.12}$$

3. Calculate the Power Spectrum of the displacement for the overall contribution;

$$PS_d^{(tot)}(r,f) = \sum_i |H(r_i,f)|^2 PS_F^{(i)}(f) \tag{4.13}$$

The final step is, from the vibration spectrum (receiver), passing through the Third-Octave Bands, applying the Ponderation Filter and computing the weighted RMS acceleration like in the chapter 4.1.2 and comparing the acceleration with the following standard values.

	$a\ [m/s^2]$
Critical areas	$5.0 * 10^{-3}$
Residential areas (night)	$7.0 * 10^{-3}$
Residential areas (day)	$10.0 * 10^{-3}$
Office	$20.0 * 10^{-3}$
Factories	$40.0 * 10^{-3}$

In conclusion, the comfort index is $32 * 10^{-3}\ m/s^2$. The value is too high for a residential area, but considering the very low distance between the house and the rail (4.35 m) and the speed of the train (90 km/h) the acceleration is acceptable.

Another possible configuration is with two wheelsets for each coach ad so two F_{soil}, considering two consecutive wheelsets of adjoining coaches as one. In this case, the relative distances between the source and the receiver are 4.35 m, 17.55 m and 27.6 m.

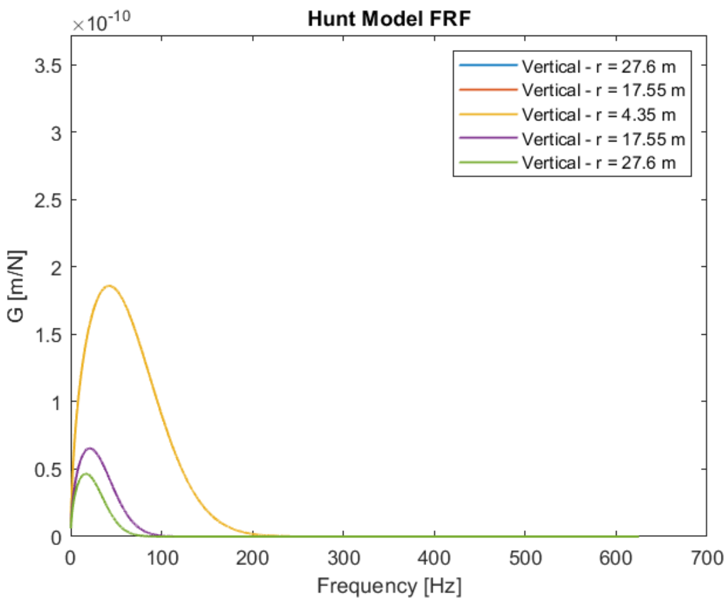

Figure 4.31: Hunt model.

With this configuration, the comfort index is $24.1 * 10^{-3}\ m/s^2$, lower than the above configuration, but still high.

In conclusion, in order to reduce the acceleration and the noise for the inhabitants near the rails there are different possible solutions:

1. Reduce the speed from 90 km/h to 35 km/h, in this case the RMS acceleration is $7.8 * 10^{-3}\ m/s^2$, good for a residential area according to the standard reference values;

2. Reduce the speed from 90 km/h to 60 km/h, in this case the RMS acceleration is $17.4 * 10^{-3}\ m/s^2$, still high but better, in particular during the day;

3. If the noise and the vibrations are too much bothering, a solution is buying the nearby houses and infrastructures and relocating the people far from the railway;

Chapter 5

Economic Analysis

5.1 Introduction to economic analysis

5.1.1 Captial Expenses (CAPEX)

Economic analysis has been computed using different methods based on the three following cathegories. Summary information on the investment is reported as follows.

Component	*Cost* (*Euro*)
Track interventions	10,096,334
Signaling System	82,500,000
Electrification (including TPSSs)	40,000,000
Uncertainty Adjustment	17,403,666
Total Costs	150,000,000

The reported capital expensed were performed without considering external interventions, delays, further necessary studies and sudden events. For these reasons, it is necessary to consider a uncertainty factor on the capital expenses. Externalities for infrastructural interventions were not computed as data on externalities for big infrastructure are not available in Croatia.

5.1.2 Operational Expenses (OPEX)

Operational Expenses are computed in order to show the average cost of the service, including workforce, mainteinance, drivers, energy supply and other accountable values. Values were computed using fixed values, reported on the study from Sapienza University of Rome.

It is necessary to consider that those expenses were computed using Italian values for workforce and drivers, then adjusted to Croatian values, as a consequence they will result more expensive than the real solution.

Assuming an average number of passengers equal to 100 per ride, a ticket price higher than 8.32 €/passenger is the break even point for the cost of the ride.

Cost	Units	Value	Unitary cost	Total
Train Driver	2	2 hours	17 €/hour	34 €
Station staff	5	2 hours	12 €/hour	120 €
Energy Cost	2.5 MWh		0.10 €/kWh	250 €
Maintenance	1	2 hours	12 €/hour	24 €
Parts & Materials	1		80 €	80 €
Insurance	1		130 €	130€
Administrative staff	1	2 hours	12 €/hour	24 €
Office & Administrative cost	1		40 €	40 €
Other expenses	1		30 €	30 €
Depreciation	0.1	1 day	1000 €	100
One-way ride	1	-	Total	832 €

5.2 Tracks, stations, intersections and other infrastructural investment

5.2.1 Interventions summary

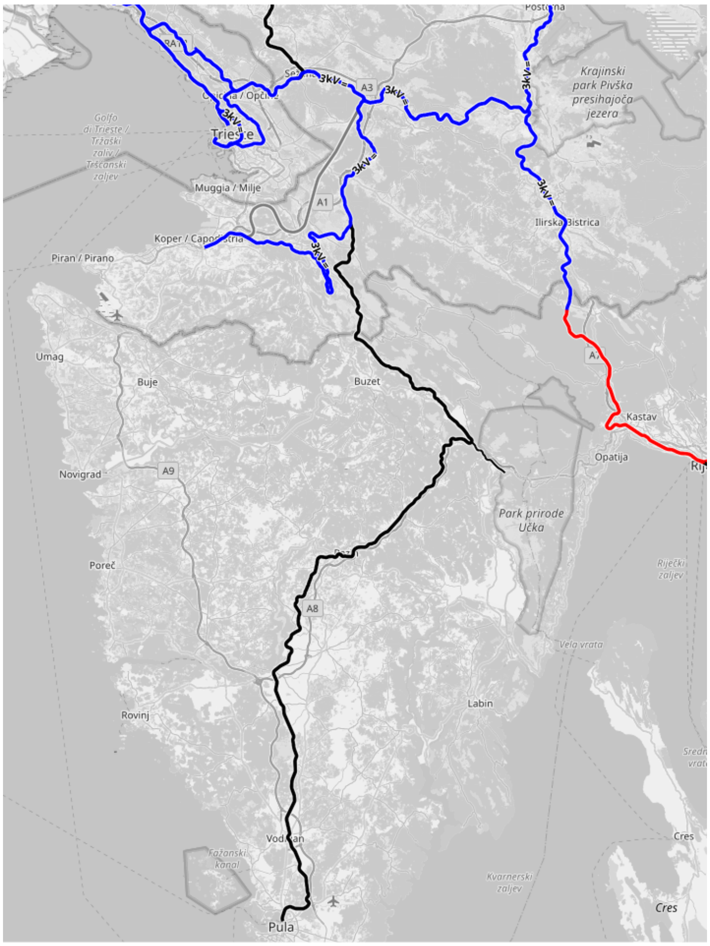

Figure 5.1: Current track electrification status. It can be noticed that the whole Croatian railway in Istria has a diesel traction system.

The following data displays the current scenario and the final state. Prestressed concrete sleepers were used instead of wooden sleepers as less expensive in both terms of maintenance and purchase.

Where interventions are performed in gallery or in other non-standard locations, it is necessary to implement a multiplying factor. F section is the only one which is running in some galleries. As a consequence, the cost of the intervention will be increased of 50%.

Infrastructure upgrade includes also the implementation of a signaling system, which is mandatory as reported by the European Union when a new railway network is created and/or improved.

The current scenario has the whole track from Pula to Hrpelje-Kozina running in single track, diesel traction.

ID	Route Segment	km	TO BE
A	Pula - Kanfanar	20.5	Double track, 3 kV DC traction
B	Kanfanar - Zminj	4.3	Single track, 3 kV DC traction
C	Zminj – Heki Tovariste	9.6	Double track, 3 kV DC traction
D	Heki Tovariste - Pazin	6.8	Single track, 3 kV DC traction
E	Pazin – Lupoglav	21.6	Double track, 3 kV DC traction
F	Lupoglav – Buzet	13.6	Single track, 3 kV DC traction

After passing the station of Hrpelje-Kozina (as already mentioned) the Slovenian Railway is already respecting modern standards for both track and electrification.

5.2.2 Track interventions

As track construction and renewal is a more complex and heterogenous process than the electrification, it has undergone a deeper analysis during the pricing cost. Pricing for the track renewal has been computed using analytical estimating method.

In order to have realistic costs, the pricing has been developed using the Rete Ferroviaria Italiana pricing list, updated to 2023.

As RFI's table is reporting costs including all of the overheads, it is necessary to adjust the workforce costs to the Croatian and Slovenian Parity of Purchase Power indexes, published by World Bank. As Croatian adjustment factor is slightly lower than Slovenian, we use the second one in order to not underestimate expenses. Italian raw material prices may also be overpriced.

$$Cost = unit*cost*(1-\%cost\ of\ workforce+\%cost\ of\ workforce*\frac{PPP_{Foreign}}{PPP_{ITA}}) \quad (5.1)$$

Having

PPP_{IT}	$0,65$
PPP_{SL}	$0,56$
PPP_{HR}	$\frac{3,26}{7,53}$

In order to follow RFI guidelines and avoid further charges, central construction site must be placed close to center of the whole region constructions site in order to have shorter distance to all of the tracks. The centermost location available for this use is Kanfanar. It must be noticed that in the same locations highway improvements are currently being performed, which can reduce the necessary space for construction sites.

Negative values are reported as are discounted if the contractor is allowed to recycle the old track for the required intervention on the line. Old materials disposal is included in the price if track renewal is chosen. Track ballast replacement is not necessary. However, we must consider a fresh installation including ballast where a doubling of the track is implemented.

Description	Code	Units	Cost
Track Installation using Prestressed Concrete Sleepers installing 35cm of ballast	AM.BN.A.2101.D	108 m	98.259
Cost reduction	AM.BN.A.2101.L	1 m	-2.16
Track Renewal using Prestressed Concrete Sleepers having 30cm of ballast, replacing ballast	AM.RN.A.2104.E	108 m	97.41
Cost reduction	AM.RN.A.2104.L	1 m	-2.17
Track Renewal using Prestressed Concrete Sleepers having 30cm of ballast, not replacing ballast	AM.RN.C.2101.F	108 m	57.06
Cost reduction	AM.RN.C.2101.U	1 m	-2.43
Track and service start	AM.BN.Q.2101.A	1 m	0.28

In order to create a double track railway, reported solution assumed that the existing track is replaced with a new one, and the new one (where built as the necessary width is not always available) will be installed as a brand new one.

Route ID	Units (rounded up)	Total per unit (€)	Cost (€)
A	190 AM.RN.A.2101.F 190 AM.RN.A.2104.L 190 AM.BN.A.2101.D	16541	3,142,663
B	40 AM.RN.A.2101.F 40 AM.RN.A.2104.L	5928	237,110
C	90 AM.RN.A.2101.F 90 AM.RN.A.2104.L 90 AM.BN.A.2101.D	16541	1,488,630
D	63 AM.RN.A.2101.F 63 AM.RN.A.2104.L	5928	373,448
E	208 AM.RN.A.2101.F 208 AM.RN.A.2104.L 208 AM.BN.A.2101.D	16541	3,440,390
F	13 AM.RN.A.2101.F 13 AM.RN.A.2104.L	5928	77,061
G	221 AM.RN.A.2101.F 221 AM.RN.A.2104.L	5928	1,310,032
Service	100 AM.BN.Q.2101.A	270	27,000
Total			10,096,334

5.2.3 Electrification process

Figure 5.2: Divaca Railway station, already electrified as part of the Slovenian section of the railway.

Electrification cost has been computed using analogous estimating process, gathering information on the most similar project developed in Croatia (and more generally in the former Yugoslavia) in the last years. Sampled project is renewal of the Križevci - Koprivnica railway, having similar track conditions but more complicated gallery and bridges infrastructural interventions. The cost of the sampled project was computed in about 400 billion euros, having 380 kilometers length of the track.

The total cost per kilometer has been computed reducing the total price per kilometer from the sampled process, discounting 20% of the cost of galleries and bridges, removing 20% of the cost which has been assumed as the cost for the track, and the total assumed for the signaling (which will be computed separately). The total cost of electrification includes the cost of the Traction Power Substations, as the construction cost was charged as overhead cost.

Cost per kilometer for electrification was estimated as 400 thousand euros, as the remaining costs are allocated for signaling and further infrastructural intervention costs.

Electrification on the Istrian Railway is necessary for 100 kilometers. The total cost of the electrification was then computed in 40 million euros.

5.2.4 Signaling system

Signaling system's cost has been computed using hybrid analytical and analogous estimanting processes. Gathered information on ETCS costs quantify the overall cost of the signaling infrastructure approximately in 1.5 million euros per kilometer of covered line. However, these calculation included the development of the technology and many overhead costs and delay fees and services. Adapting vehicles was also included in the cost, which is not needed in the case of the selected vehicle. If considered using older rolling stock, an adjustment may be necessary. However, the whole analysis was developed using the already mentioned vehicle, which doesn't require any retrofitting interventions.

The actual cost of the technology, apart from increments due to external causes, has been computed in the range of 400-500 thousand euros per kilometer, overheads costs included.

A good estimation can be in the order of 500 thousand euros per kilometer, implemented on 165 km of the complete line from Pula to Trieste. Total cost of the signaling system is computed as 82.5 million euros, not considering that some sections of the route may have already working signaling systems.

5.3 Signaling

5.3.1 Croatian scenario

The lack of signaling in the Croatian railway system is a serious safety concern. The signaling system is responsible for ensuring that trains can safely travel along the tracks without colliding with each other or encountering other hazards. Not having a signaling system impacts both on safety and speed limits on the track, as not implementing signaling significantly reduces maximum speed.

One of the main reasons for the lack of signaling on some Croatian railway lines is due to the age of the system. Many of the railway lines in Croatia were built over a century ago, and their signaling systems may not be up to modern safety standards. This can pose a significant risk to passengers and railway workers.

Additionally, the lack of investment in railway infrastructure in recent years has contributed to the problem: without proper funding, it is difficult to both upgrade and maintain the signaling.

However, it is important to note that Croatian Railways (Hrvatske željeznice) has been working on the improvement of its signaling system and overall safety record. The company has implemented new technologies and safety protocols in recent years and has been working with other European rail operators to share best practices and improve safety standards across the continent.

Nowadays in some of the lines of the country a German signalling system is used, named Punktförmige Zugbeeinflussung.

Punktförmige Zugbeeinflussung (PZB), or the intermittent train control system, is a signaling and train protection system used in many European countries, including Croatia.

In Croatia, PZB is used primarily on high-speed railway lines, where trains are traveling at speeds of over 160 km/h. The system works by using trackside magnets that communicate with a receiver on the train, which then sends information to the train's control system. This information can include speed limits, signals, and other important data that can help the driver operate the train safely.

The implementation of PZB in Croatia has significantly improved the safety of the railway system, particularly on high-speed lines where trains are traveling at high speeds. The system helps prevent accidents by automatically slowing down or stopping a train if it exceeds a speed limit or encounters a hazardous situation.

It is important to note that PZB is not a foolproof system, and accidents can still occur if the system is not functioning properly or if there is human error. Therefore, it is important to maintain the system and ensure that it is functioning correctly to ensure the safety of passengers and railway workers.

5.3.2 Interchangeability of signaling systems

Considering the fact that the line runs across three countries (Croatia, Slovenia and Italy), the chosen technology must match the safety criteria of the three countries.

In Italy, the adopted railway signaling system is the Train March Control System (SCMT), which is a distance signaling system based on wired technology. Unlike the Punktförmige Zugbeeinflussung (PZB), which uses magnets along the railway line, SCMT uses control signals, written indications, and lights to communicate with the train.

Since PZB and SCMT are different railway signaling systems, they are not directly compatible. This means that trains that use PZB in the Croatian railways cannot operate on the Italian railway lines that use the SCMT system, and vice versa.

Compatibility issues can be fixed using an interoperable signaling system known as the European Train Control System (ETCS) that could be a perfect solution for the selected line. ETCS is a standardized railway signaling system that uses advanced wireless and satellite communication technologies to communicate with moving trains. If implemented correctly, ETCS could gradually replace existing railway signaling systems and allow interoperability between railway signaling systems of different countries, including the PZB system used in some European countries.

In July 2009, the European Commission announced that ETCS is mandatory for all EU-funded projects that include new or upgraded signaling.

5.3.3 ETCS functioning mode

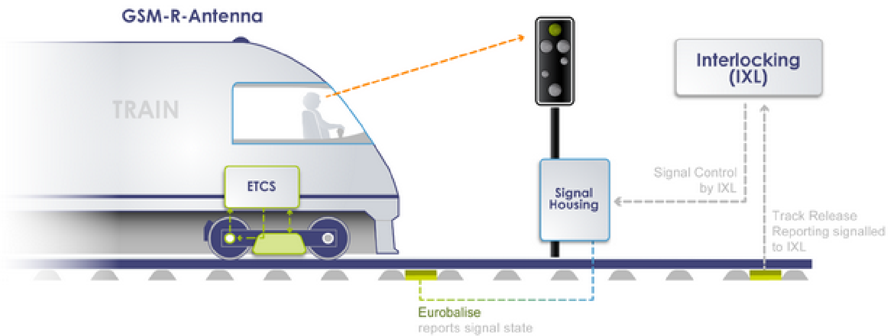

Figure 5.3: ETCS working scheme.

ETCS functions by communicating information between the train and the trackside equipment using radio signals. The system uses a combination of two main components: the European Vital Computer (EVC), which is installed on the train, and the Eurobalises and Euroradio, which are installed along the tracks.

The Eurobalises are physical markers placed on the track that send out a signal containing information about the track ahead. These signals are picked up by the train's onboard receiver, which relays the information to the EVC.

The Euroradio component of the system uses a wireless communication system to transmit information between the train and the trackside equipment. This allows for more frequent updates and real-time communication between the train and the control center.

The EVC processes the information received from the Eurobalises and Euroradio to determine the speed and position of the train, as well as any hazards or speed limits ahead. If necessary, the EVC will automatically apply the train's brakes to ensure it slows down or stops as needed.

5.3.4 Location and distances between eurobalises

Eurobalises are often placed at key locations such as:

- Entry/Exit of a signaling section: Eurobalises are positioned at the beginning and end of a signaling section to mark the boundaries.
- Junctions: Eurobalises are installed before and after junctions to provide information to the train control system about the upcoming branching or merging of tracks.
- Speed transitions: Eurobalises may be placed before and after speed transitions, such as when entering or exiting a reduced speed zone.
- Fixed landmarks: Eurobalises may be positioned at fixed points along the track, such as bridges, tunnels, or specific geographic locations.

In the European Train Control System (ETCS) Level 2, the distance between Eurobalises is typically determined based on the allowable movement authority (MA) given to a train. The MA defines the distance within which a train is allowed to operate. The formula to calculate the distance between Eurobalises in ETCS Level 2 is as follows:

$Distance = MA - TrainLength - SafetyMargin$

Where:

- MA is the allowable movement authority given to the train by the ETCS system.
- Train Length is the length of the train that is considered in the calculation.
- Safety Margin is an additional buffer distance added to ensure safe separation between trains.

The specific values for MA, Train Length, and Safety Margin will vary depending on the specific implementation and requirements of the ETCS system. These values are typically specified by the railway authorities and infrastructure managers.

It's important to note that the distance between Eurobalises is not solely determined by this formula. It is also influenced by other factors such as the track layout, speed restrictions, signaling system, and operational requirements. The ETCS system uses various algorithms and communication protocols to continuously update and adjust the train's position and movement authority based on the information received from Eurobalises and other trackside equipment.

Chapter 6

Maintenance and diagnostics

6.1 Track maintenance

During the route definition, some main possible track damages have been reported. These possible damages are most likely to happen as more compatible with the different characteristics of the route, in particular the sub-structure, the location and the curves profile.

6.1.1 Main track problems and potential causes

In order to keep the service on line, it is necessary to check the track damage frequently. Following possible track degradation have been reported, which must be considered as preventive maintenance. Non-ordinary maintenance must be considered as the region is exposed to unpredictable natural phenomenom.

- Rail cracks and fatigue: due to transit of both new vehicles and older vehicles with unknown maintenance state, including some freight vehicles, it can't be excluded that track will have a degradation due to stress.

- Unstable substructure: according to reported images from the region, the unpredictable substrate composition requires constant maintenance, in particular in the hills section. Non-homogeneus ballast lacks may occur on the route, must be mentioned that the single track section will have a double transit volume.

- Curve damage: curves must undergo more frequent maintenance as subject to higher level of transversal and logitudinal forces. Curve maintenance must be performed as curve damage combined with wind effect and other components can be a serious cause of derailment.

6.1.2 Maintenance systems

As the line is not scheduled to be working at night, the most of the interventions can be carried out during service suspension. However, service interruptions and delays must be considered for on fault maintenance.

Avoiding these interventions can be done scheduling the maintenance. Most of the monitoring (including the rail inspection) can be performed in one night as the route length is short. It must be mentioned that Italian and Slovenian sections are already maintened, so only the Buzet - Pula section of the path requires specific maintenance schedule. As costing was computed using the Italian pricelist, it must be considered that in Croatia Končar is not only the vehicles' manufacturer, but also the infrastructure, signaling and diagnostics leader. Known that, it can be assumed that the whole infrastructure will be realized using their products, including the diagnostics train.

For the suggested track renewal, ultrasonic rail inspection can be considered as a compatible rail check. Croatian railway company already owns inspection vehicles but it's not mentioned how to bring them in Istria. If a line further upgrade will be planned, a more efficient inspection system must be implemented, for example laser or AI-based inspection.

Chapter 7

Environmental sustainability Analysis

7.1 Croatian energy supply

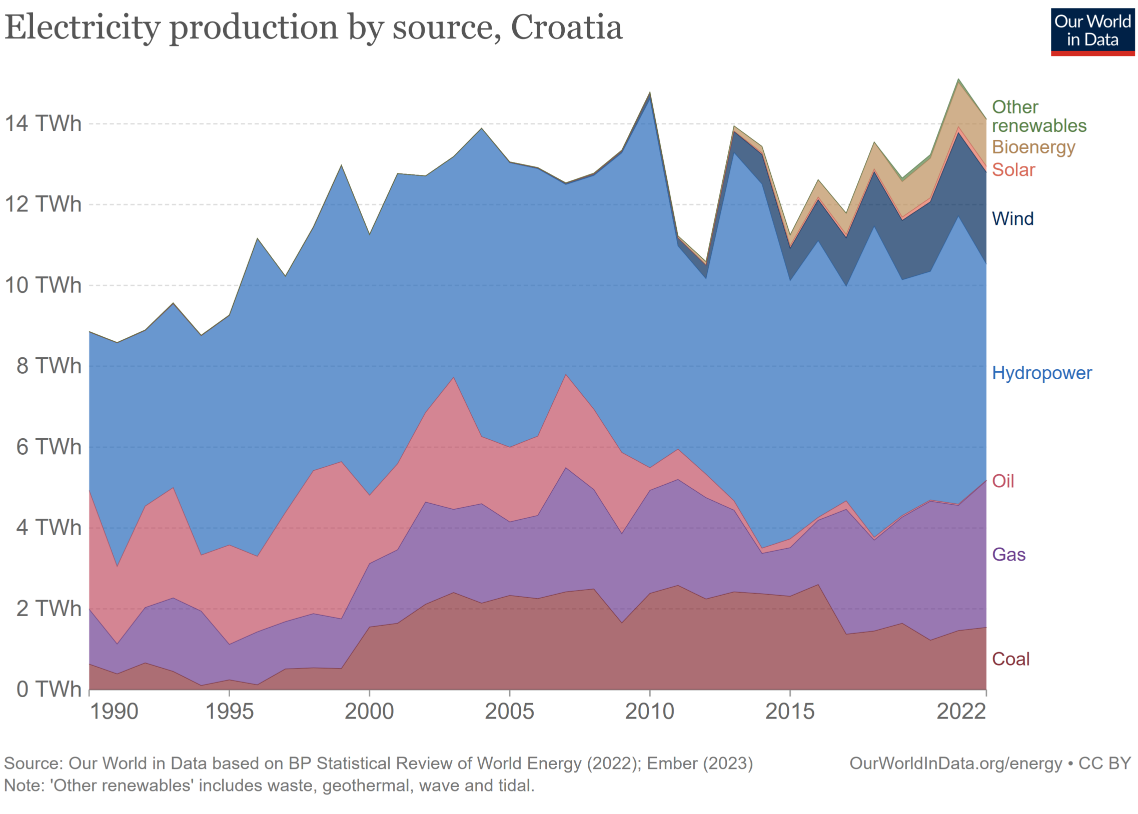

Figure 7.1: Croatian energy sources shares.

Electricity production in Croatia relies on different sources, including low impact sources such as hydroelectric, solar and wind energy. Most of the domestic production comes from hydroelectric power plants, even though that share has reported a decreasing trend in the last few years. This decrease is partially balanced by the development of the wind turbines in the Country. The Country is importing 100% of the consumed coal and 80% of the oil, having a high dependence from foreign countries. Must be mentioned that part of the imported electricity comes from the Krško nuclear power plant, located on the border between Croatia and Slovenia, and managed by both countries as former Yugoslavian agreements. The power plant has one reactor and a second one should be implemented by 2030. The increased production may change the shares on the electricity sources.

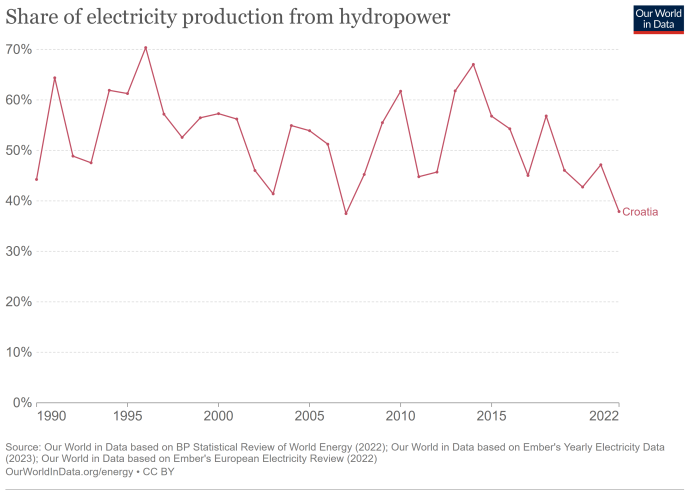

Figure 7.2: Croatian hydroelectric sources share trend.

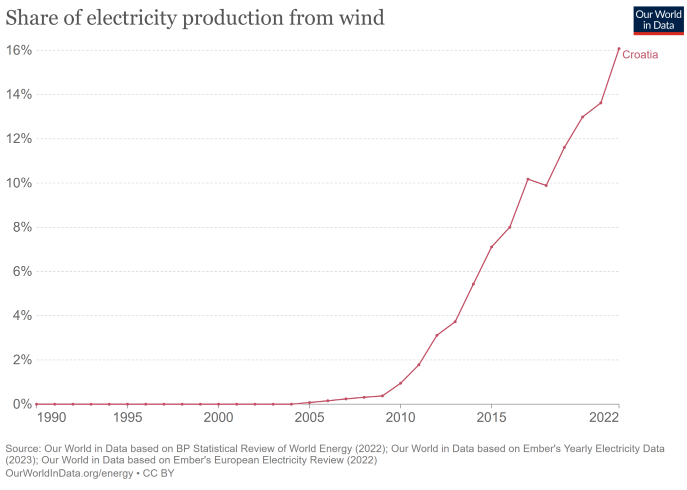

Figure 7.3: Croatian wind sources share trend.

By creating a new infrastructure which needs a high power in order to work, it is necessary to raise the available power in the region. In order to use clean sources for energy, increasing the available wind turbines energy is a solution which can allow to have a low-emissions and environmentally sustainable infrastructure. As Is energy supply scenario, without increased available clean power supply, may lead to the necessity of non-neutral energy supply, as the electricity demand increase would be crowded out by the "dirty electricity" supply. Analyzing this scenario by a Well to Wheel point of view, improvements won't be acceptable.

7.1.1 Wind turbines in the Slovenian section

Known that the region is easily under the effect of the wind, it is necessary to consider clean energy production using wind turbines. Investments were already made in the research of locations available for production of energy from wind in order to reduce the fossil fuels share in the energy mix. Golic plateau was chosen as one of the best performing locations, as in the plateau can be installed up to 25 turbines.

Golic plateau is located along the railway, as a consequence it can be used to supply power to the line. Podgorje traction power substation was chosen in order to use this power supply. Golic project has an estimated power output of 80 MW.

Wind turbines can be installed simultaneously with the renewal of the railway. Depending on the power and of the investment for the wind turbines, two alternatives will be available:

- Wind turbine of 60 kW, height 30 m, for medium-high winds;
- Wind turbine of 200 kW, height 40 m, for medium-high winds;

Figure 7.4: Top view of Golic plateau, on the border between Croatia and Slovenia. Its border location is very important as both countries can access the produced energy, as already many power plants are shared between the two countries.

7.2 Sustainability comparison

Implementing a electric traction line which replaces a diesel traction one allows the contractor to reduce the necessity of imported raw and/or refined oil. Reducing this imported oil has a positive impact on emissions.

7.3 Different sustainable alternatives

Electrification of the Istrian Railway was not the only available impact reducing solution. Having many bus companies running rides everyday around the Region, a electric coach line was also assumed as a generally compatible solution. However, replacing the existing coaches with electric vehicles would have had a smaller impact on the network. Energy consumption would have been different but one of the goals of the network renewal was reducing wheel transit on the roads and motorways. Railway advantages compared to road service can be summarized in:

- The railway would perform a better origin/destination ride duration as running on an almost reserved track, the coach would find itself in the city traffic. The duration was computed on shorter time despite having a longer distance.
- The railway requires smaller reserved locations in the cities, as train stations already exist in the study area and are located on the chosen route. Electric bus stations require a dedicated infrastructure for charging.
- The vehicle investment is lower as the units are already available to the Croatian railway company. Also, useful life of rail vehicles is longer than road vehicles, and the residual value is higher even after 30 years.
- Trains' capacity is much higher than coaches and can have a stricter schedule, demand forecasting can be easier.
- A secondary goal includes removing vehicles from highways and city traffic: having electric coaches implies having them entering and exiting the highway at every stop.
- Further vehicles may be removed from the roads as a train trip can provide a higher comfort than a private car. Having a first class section available on the train may attract different customers.
- Electric buses are still under development and their range is not always predictable: if their development wasn't so bounded to batteries duration and charging time, it would have been easier to choose that alternative. As the technology is not 100% ready by now, it is harder to choose this solution for a express service.
- During the summer season, having a connection between Trieste and the main cities of Istria can lead to many advantages: roads are overcrowded during that season and a rail line can be used in order to avoid the traffic.

Figure 7.5: Pula Railway Station, currently used as a terminus and as freight transport center, connecting the Pula port to the city. Passengers transport has decreased. However, the station building is still perfectly available for higher volumes. As Pula port is reducing its goods usage, terminal can be converted to passenger transit.