Deliverable D7.3:

Performance of a cost-benefit analysis on the use cases selected

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1 Executive Summary

The purpose of this deliverable is to conduct a Cost-Benefit Analysis (CBA) for the three identified use cases selected in **[D7.1]** to assess their economic impact.

A detailed description of the methodology is provided, including the guidelines and key CBA concepts used. Each use case is analysed by comparing a Reference Scenario with a Project Scenario. Key performance indicators, along with CBA data and parameters, are highlighted to offer operational elements and specific values referred to the exact application context for the analysis. Specific growth rates and Value of Time (VOT) are defined, and financial costs are converted into economic costs to create a comprehensive data system for the analysis.

Afterwards, the different scenarios considered for the CBA are described, starting with the reference scenarios and then moving to the new use case scenarios. For each use case, two scenarios are considered: one without significant technological or infrastructural upgrades and one with major upgrades to maximise MDS potential (except for the "Hybrid MDS based on air levitation" use case, which has only one scenario due to negligible differences between scenarios). Based on the simulation analysis results from **[D7.2]**, an operational model is provided for each use case scenario to define and assess various cost components.

The CBA is then performed, addressing all investment costs such as Capital Expenditures (CAPEX), including contingencies and other costs, Operational Expenditure (OPEX) and maintenance costs, and direct benefits and externalities to calculate the main economic performance indicators, namely Net Present Value (NPV), Benefit/Cost (B/C) ratio, and Internal Rate of Return (IRR). A sensitivity analysis is conducted on key variables such as investment costs, routine and extraordinary maintenance costs, operating costs, and kilometres of road and rail travel saved, to evaluate their impact on the overall results.

The analysis results indicate that one of the promising applications is the incline pusher, specifically in Scenario A, which shows a significant reduction in investment costs and travel time savings for freight trains, leading to a B/C ratio greater than 1. For Scenario B, the benefits do not outweigh the higher investment costs, suggesting that a different geographical context might be more suitable. The air levitation (airlev) configuration does not offer distinctive benefits due to high energy consumption costs. The Hybrid MDS based on magnetic levitation configuration shows positive results for Scenario A, with the highest B/C ratio within all the use cases, with benefits related to time savings and low operational costs, while Scenario B might require a different context to achieve a positive B/C ratio.

An additional business case for an intermodal terminal and pull-in service operations is considered. The MDS implementation aims to enhance sustainability and increase operational efficiency by optimising rail operations up to Grade of Automation (GoA) 3/4 and minimizing the use of diesel locomotive operations. An NPV analysis shows that the automation and electrification project is feasible and highly advantageous, promising significant returns and improved operational efficiencies in terminal operations.

Finally, an high-level comparison between Cost-Benefit consideration, in a qualitative perspective, of MDS with those of pure maglev and hyperloop has been conducted, to provide a broader perspective on cost, benefits, and feasibility. By evaluating key cost components and expected advantages, the study assesses MDS's viability as a competitive guided transportation solution.

Keywords: Cost Benefit Analysis, Economic Analysis, Economic Impact

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
Airlev	Air Levitation
ART	Autorità di Regolazione dei Trasporti
B/C	Cost-Benefit Ratio
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CCS	Command & Control System
CO2	Carbon Dioxide
DAC	Digital Automated Coupling
EC	European Commission
EDW	Electro Dynamic Wheel
EMU	Electric Multiple Unit
ENPV	Economic Net Present Value
ERTMS	European Rail Traffic Management System
ES*	Eurostar
ETCS	European Train Control System
ETR	Elettro Treno Rapido (Fast Electric Train)
EU	European Union
GDP	Gross Domestic Product
GoA	Grade of Automation

HS	High-Speed
HSR	High-Speed Railway
IC	Intercity
IM	Infrastructure Manager
IRR	Internal Rate of Return
ISFORT	Istituto Superiore di Formazione e Ricerca per i Trasporti
ISTAT	Istituto Nazionale di Statistica
LSM	Linear Synchronous Motors
M	Merci (Freight)
MaDe4Rail	Maglev-Derived Systems for Rail
MCA	Multi-Criteria Analysis
MDS	Maglev-Derived System
MIT	Ministero delle Infrastrutture e dei Trasporti
NMVOC	Non Methane Volatile Organic Compounds
NOx	Nitrogen Oxide
NPV	Net Present Value
O/D	Origin/Destination
OPEX	Operational Expenditure
PM	Particulate Matter
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations

REG	Regionale (Regional/Metropolitan)
RFI	Rete Ferroviaria Italiana
RV	Regionale Veloce (Fast Regional)
SJ	Statens Järnvägar
SO2	Sulphur Dioxide
TDS	Train Detection System
TMS	Traffic Management System
TRL	Technology Readiness Level
UIC	Union Internationale des Chemins de Fer
UVAL	Public Investment Evaluation Unit
VAT	Value Added Tax
VC	Virtual Coupling
VOC	Vehicle Operating Costs
VOT	Value Of Time

3 Background

The present document constitutes the Deliverable D7.3 “Performance of a cost-benefit analysis on the use cases selected” in the framework of the MaDe4Rail project from EU-Rail’s Innovation Pillar Flagship Area (FA) 7 - Innovation on new approaches for guided transport modes as described in the EU-Rail Multi Annual Work Programme (MAWP).

4 Objective/Aim

This chapter outlines the main objectives and aims of the CBA for the three use cases identified in Task 7.1 **[D7.1]**.

The study focuses on analysing the specific economic impact of implementation projects for each use case across different MDS configurations. To achieve this, a comparative analysis between a Reference Scenario and a Project Scenarios (see Chapter 6.1) is conducted for each use case. Various economic performance indicators are defined for each scenario:

- ENPV: Economic Net Present Value;
- B/C: Benefit-Cost Ratio;
- IRR: Internal Rate of Return.

The results are further analysed for sensitivity to specific variables, including:

- Investment costs;
- Routine and extraordinary maintenance costs;
- Operating costs;
- Kilometres of road travel saved (vehicles*km) and kilometres of rail travel (trains*km).

Additionally, an optional study related to a terminal use case is included to perform a business case analysis, highlighting potential benefits in terms of sustainability and performance.

5 Overview of results from previous tasks

For a better understanding of this document, a summary of the results obtained from WP6 and WP7 (**[D7.1]** and **[D7.2]**) is presented below.

First, WP6 aimed to provide a Technological Readiness Assessment (TRA) on the technical maturity of the technologies involved and the overall system and propose the most appropriate technologies for the different subsystems that best fit the maglev-derived systems (MDS) identified.

WP6 also had the objective of identifying the spectrum of possible use cases and operational context based on their performance, and technical and commercial characteristics to quantify the criteria for MDS selection for further analyses (technical-economic feasibility study), providing the technical characteristics of the MDS that best fit each selected type of service.

In this way, the final goal of this section was to provide a set of possible use cases to be analysed, based on a comprehensive technology readiness assessment on the technical maturity of the technologies involved in MDS.

Deliverable 6.1: Technology Readiness Assessment of Maglev-derived systems **[D6.1]** developed a complete evaluation of the technological maturity of the technologies and components involved in the MDS, based on a TRA that is a formal and metrics-based process. This TRA has been used to propose which of them best fits the different MDS, as well as to evaluate the overall Technology Readiness Level (TRL) of each MDS.

The TRA concluded with the findings and comparison of the different systems, considering the four main subsystems of an MDS: vehicle, infrastructure, energy system and Traffic Management System (TMS). As a result, this TRA has completed a technology analysis by comparing the different systems and identifying and exploring significant development gaps.

Based on the results of the TRA **[D6.1]**, an analysis of the state of development of each MDS and the pipeline of future work has been carried out to outline the possible expected evolution for the sector.

The second step was to analyse different use cases for the different technologies and to identify and propose a set of use cases to be evaluated in the next work packages.

For this purpose, a Multi-Criteria Analysis (MCA) was carried out to select the different MDS use cases that would be most appropriate to consider in the next tasks for the possible use on existing railway lines **[D6.1]**. Several criteria were used, considering aspects such as TRA, scalability, adaptability, type of vehicle, system configuration, impact on existing infrastructure and the possibility of installation on existing railways.

With the selected criteria and their weights, the results presented in Figure 1 and Table 1were obtained.

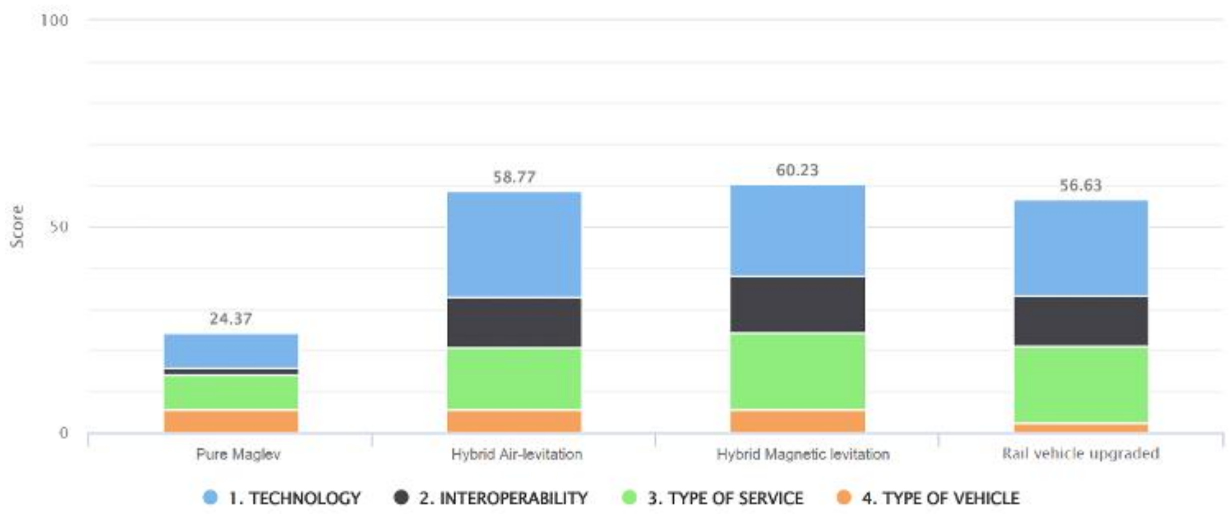

Figure 1: Criteria contribution in the MCA

Table 1: Criteria for selection of possible use cases

System Configuration						
Definition	**Definition**		**Pure Maglev**	**Hybrid Air Levitation**	**Hybrid Magnetic Levitation**	**Upgraded traditional railway MDS**
3. TYPE OF SERVICE	3.1	Passengers: Urban services	Yes[1]	Yes[1]	Yes	Yes
	3.2	Passengers: Conventional services	Yes	Yes	Yes	Yes
	3.3	Passengers: High speed services	Yes	Yes	Yes	Yes
	3.4	Freight:	No	No	Yes	Yes

		Conventional services				
	3.5	Freight: Local applications	No	Yes[1]	Yes[1]	Yes
	3.6	Both passengers and freight traffic	No	Yes	Yes	Yes
4. TYPE OF VEHICLE	4.1	Fixed trainsets	Yes	Yes	Yes	Yes
	4.2	Pods	Yes	Yes	Yes	No

From this analysis, it appeared that the MDS configurations with the greatest potential for use in today's rail infrastructure are the hybrid magnetic levitation and the air levitation MDS, closely followed by the rail upgraded vehicles. In contrast, the systems that are the most challenging to implement on the current infrastructure are pure maglev systems since they require the substitution of the existing railway infrastructure with (potential) loss of interoperability and network effect.

After the selection of the three MDS configurations through the MCA and the analysis of the possible use cases where they could be applied, an early selection of the most interesting use cases was made in terms of applicability of the MDS technology to the specific use case, considering the actual existing needs for transport infrastructures or services across Europe.

This primary selection was composed of six use cases, where, in order to cover a wide range of possibilities, it was considered the inclusion of the three MDS configurations that emerged from MCA analysis and the three different time horizons defined for the analysis (short, medium and long term). These possible use cases are shown in Table 2.

Table 2: Selection of possible use cases for MDS applications

	Freight application	Passenger application
Hybrid MDS based on air levitation	Local freight applications *(Medium-term)*	Conventional passenger services *(Long-term)*
Hybrid MDS based on magnetic levitation	Conventional freight services *(Long-term)*	High speed passenger services *(Long-term)*
Upgraded traditional railway MDS	Local freight application *(Short-term)*	Conventional passenger services *(Medium-term)*

The complete results of this TRA can be found in previous deliverable **[D6.1]**.

On the other hand, Deliverable D7.1 – Use Case Analysis **[D7.1]** presented an overview of the different generic use cases identified within WP6 and as well as the results of the use case workshops organised within WP7, which involved various experts and stakeholders in the field of transportation, both from passenger and freight sectors such as transport operators, infrastructure managers, and railway undertakings. From these outputs, three use cases have been selected, located, and thoroughly defined for passenger and freight applications, which should also present the different benefits that each use case may bring.

The use cases identified were the following:

1. Upgraded traditional railway MDS configuration – Incline pusher;
2. Hybrid MDS based on air levitation configuration;
3. Hybrid MDS based on magnetic levitation configuration.

Several workshops were performed for the identification of MDS applications in Europe. The workshops involved over 40 participants from 8 countries, representing relevant stakeholders for rail transportation in Europe between Infrastructure Managers (IM), Railway Undertakings (RU), terminal operators, end customers (freight), technology companies, research and development institutions and regional transport administrators.

Applying the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) method, the selection of the three use cases was carried out by means of MCA, which takes into account criteria related to the aspects of operations and traffic control, technology, interoperability, environmental sustainability, and implementation and economics.

Finally, **[D7.2]** presented the analysis conducted for the development of the technical feasibility study for the three identified use cases and the results of the assessment of the identified risks associated with the implementation of the MDS systems in two identified railway lines in Sweden and Italy.

The deliverable contains the description of the operational scenarios, detailing the context, expected demand, and a high-level architecture of the system functions and elements considered in the study and identified in previous tasks.

Following this, the document described the impact on the current alignment for the identified use cases. It should be noted that not all scenarios may impact the alignment. In fact, for those scenarios where an increase in capacity is expected without an increase in the maximum speed on the line, no major modifications have been foreseen. This does not mean that the analysed MDS technologies do not allow running at higher speeds.

The document also presented general aspects that are common to all scenarios, such as the signalling systems and the methodology for the magnetic analysis.

Finally, the document detailed the feasibility study for the three use cases and related scenarios.

The results of the feasibility study and operational scenarios were the main input for Task 7.3, where a cost-benefit analysis will be performed to evaluate the economic impact of the projects, and WP8, which focuses on the design of the prototype of a sample vehicle for one use case identified as per the economical evaluation study.

6 Methodology

The references used for developing this Cost-Benefit Analysis (CBA) include:

- European Commission, Guide to Cost-Benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014-2020, (2014) **[1];**
- European Commission, Guida all'Analisi Costi-Benefici dei progetti di investimento - Strumento di valutazione per la politica di coesione 2014-2020, Italian version, (2014) **[2]**;
- Ministry of Infrastructure and Transport, Guidelines for the evaluation of investments in public works in the sectors under the competence of the Ministry of Infrastructure and Transport, (2017) **[3]**;
- Ministry of Infrastructure and Transport, Appendix to the Addendum - Notice of submission of applications for access to mass rapid transit resources, (2018) **[4]**;
- UVAL, The feasibility study in local projects carried out in partnership: a guide and a tool (2014) **[5]**;
- European Commission, Handbook on External Costs of Transport, (2019) **[6]**.

6.1 Cost-Benefit Analysis Main Concepts

Cost-Benefit Analysis (CBA) is a technique designed to compare the efficiency of different alternatives (such as public policies, projects, regulatory interventions, etc.) in achieving a specific objective. It assesses whether the benefits a project brings to society (social benefits) outweigh its cost (social costs). A project is considered desirable if the benefits exceed the costs, meaning it provides a net gain to society. Among multiple alternatives, the option that maximizes the net benefit is preferred.

The underlying rationale of the analysis is that a community's resources are finite, and policymakers must allocate them to interventions that maximize the net benefit to society. The analysis seeks to determine whether the project is preferable to maintaining the current situation (status quo), implicitly comparing the project scenario with the reference scenario (i.e., the future scenario excluding the intervention).

In the case of this project, the cost-benefit analysis follows an "incremental" methodological approach, comparing two scenarios: the "Reference Scenario" (without the intervention) and the "Project Scenario" (with the intervention). This comparison is made by quantifying the costs and benefits that arise from the intervention.

Cost-Benefit Analysis can generally adopt different perspectives, with the methodological approach varying depending on the objective to be achieved and the reference parameters. The evaluation process used to summarize and determine the preferred scenario is the economic analysis, which assesses both the economic and social costs and benefits.

6.2 Performance Indicators

According to **[1]**, the key profitability indicators derived from the analyses are as follows:

- *NPV (Net Present Value)*: This represents the algebraic sum of the cash flows generated by a project, discounted at a rate that accounts for the opportunity cost of money, over a defined period. It provides the net expected benefit of the initiative as if it were available at the time the investment decision is made.
- *IRR (Internal Rate of Return)*: This is the discount rate at which future cash flows must be discounted over the analysis period (n year) to make their sum equal to the initial outlay at time 0. It assumes that the cash flows generated by the investment are reinvested at that same rate (r).
- *B/C (Benefit-Cost Ratio)*: This criterion is used to assess the acceptability and/or preferability of the investment project. It is calculated as the ratio of the discounted benefits to the discounted costs. A project is considered acceptable if the present value of benefits exceeds that of costs (i.e., B/C > 1). Among multiple investment projects, the one with the highest benefit-cost ratio is preferred.

6.3 Cost and Benefit Elements Included in The Socio-Economic Assessment

The procedure and impacts to be considered in Cost-Benefit Analysis (CBA) are well-established in the literature and international manuals **[3]**. The only delicate aspect – partly due to the scarcity of precise references in the literature – is the operational method for calculating user benefits through the concept of consumer surplus, which constitutes the "core" of CBA. However, recent Italian Guidelines substantially fill this gap, providing precise guidance on the methodology to be used, and highlighting some of the main errors to. This chapter briefly reviews what the two guidelines prescribe to consider in CBA, leaving the in-depth discussion of consumer surplus calculation to the following chapters.

The ministerial guidelines (MIT, 2017; Table 5, page 39 and following) do not address the specific categories of cost and benefit but clarify the nature of the effects to be considered, distinguishing between direct and indirect, and between internal and external effects.

Table 3: Nature of the effect to be considered

<table>
<tr><th></th><th>Direct effects</th><th>Indirect effects</th></tr>
<tr><td>Internal (for users and managers)</td><td>(a)</td><td rowspan="2">(c)</td></tr>
<tr><td>External (for the community)</td><td>(b)</td></tr>
</table>

Direct effects are divided into two categories: (a) "internal" effects, which are perceived by consumers and service providers, and (b) "external" effects, which primarily include environmental and non-environmental externalities such as pollution, safety. Indirect effects (c), on the other hand, are those economy impacts not captured by the direct effects. Both direct and indirect effects are described in each specific analysis of the following chapters.

6.4 Cost-Benefit Analysis Data and Parameters

6.4.1 Time Horizon of the Analysis

The time horizon represents the maximum number of years for which forecasts are provided regarding the future performance of the project. These forecasts are formulated for a period that corresponds to its economic useful life and extend over a sufficiently long time to capture its likely impact in the medium to long term. The reference periods include the project execution times.

For the project in question, as recommended in **[1]** and following a precautionary approach, a time horizon of 30 years has been assumed, starting from the year of activation.

6.4.2 Discount Rate

For the discounting of financial and economic flows and the calculation of the financial and economic Net Present Value, an appropriate discount rate is necessary. This rate is the one at which future values are discounted to their present value (year 2024). The discount rate has been set at 4% for the financial analysis and 3% for the economic analysis, as indicated by **[1]**.

6.4.3 Conversion Coefficients Between Financial and Economic Costs

The planned investments will involve the use of resources that have economic value, represented by their opportunity cost.

What differentiates financial costs from economic costs is the treatment of taxes. The general rule in CBA is that taxes do not represent a real consumption of resources by society, but rather a transfer from one party to another, and therefore can be disregarded in the economic evaluation. In practice, investment, operational, and maintenance costs are accounted for, through conversion factors, net of Value Added Tax (VAT) and all other indirect taxes. The conversion factor is used to adjust the costs by excluding taxes such as VAT and other indirect taxes. This is because, in economic evaluations, taxes are seen as transfers rather than actual consumption of resources. Therefore, the conversion factor helps in calculating the true economic cost by removing these tax components.

Starting from the costs identified in the Financial Analysis, a fiscal adjustment has been applied to investment and operational costs for the purposes of socio-economic evaluation. The fiscal adjustment involves applying different conversion rates to various costs. This adjustment is motivated by the fact that different types of costs (e.g., investment vs. operational) may be affected differently by taxes and subsidies. The conversion rates help to reflect the true economic value of these costs by adjusting for these fiscal impacts.

The conversion factors used are listed in the following tables.

Table 4: Conversion factor of financial for maintenance costs

Investments (excluding VAT) and Maintenance sustained by the Manager (extraordinary and ordinary)	Conversion factors
Materials and areas	1.000
Labor (persons employed in the construction and maintenance of the work, Persons assigned to the management of the infrastructure and the drivers)	0.503
Transport	0.754

Table 5: Conversion factor of financial for operating costs

Railway cost items (financial values excluding VAT) incurred by railway companies	Conversion factors
Materials	1.000
Staff	0.525
Traction energy	0.769

6.4.4 Growth Rates

The modelling simulations of the intervention scenarios are conducted by simulating both the reference scenario and the future project scenarios for the year of the activation, which various between the use cases and their scenarios. This year coincides with the completion of the works and start of the service.

To estimate the progression of effects in the years following the modelled year, a trend has been applied to all traffic-related components (user surplus, lost taxation, etc.).

This growth rates have been applied differently across the various use cases:

- Upgraded traditional railway MDS: 1.80 % (Sweden)
- Hybrid MDS based on air levitation: 1.00 % (Italy)
- Hybrid MDS based on magnetic levitation: 1.00 % (Italy)

6.4.5 Value of Time

Value of Time (VOT) represents the monetary value of the time saved by the individual user. This value is strictly dependent on the class of user considered and the type of services under analysis. Therefore, following paragraphs will examine the assumptions underlying the estimation of the VOT for different use cases. The VOT is defined as the weighted average of the VOT for different user classes, taking into account the percentage of users who actually use regional services.

In Italy, the percentage of user class is an input data derived from the various railway operators, that provide passenger services. Regarding the VOT for individual user classes, the values indicated for Italy in **[7]**, updated to 2023, were considered. These values are in line with suggestions provided by **[3].**

Table 6: Value of Time for Italy

User class	VOT [€/h]
Business	40.49
Commuting	18.33
Leisure	15.37

Finally, the value obtained is 21 €/h, which has been applied in the two Italian use cases:

- Hybrid MDS based on magnetic levitation
- Hybrid MDS based on air levitation

For the use case "Upgraded traditional railway MDS", the Value of Time (VOT) has been adjusted in both scenarios to reflect a more accurate value corresponding to Swedish conditions and the type of the service Pax/Freight.

- Scenario A (Freight): VOT for cargo transport has been considered 4 €/hour derived from **[3]**).
- Scenario B (Pax): the values indicated for Sweden in **[8]**, updated to 2024, is about 10.05 € per hour increased by 1.82% annually.

7 Use Case Scenarios

7.1 Upgraded Traditional Railway MDS

7.1.1 Scenario A

The Scenario A for evaluating the Upgraded traditional railway MDS configuration refers to an existing electrified railway line which links two major cities in Sweden, in a single track with a length of approximately 60 km, which has a speed limitation that makes it not possible to run high-speed trains in mixed traffic operation due to differences in maximum speed (passenger trains run at a maximum speed of 120 km/h and freight trains run at a maximum speed of 80 km/h). The line is characterized by a steep incline terrain, with gradients as high as 25‰ ca.

The main objective of this scenario is to evaluate whether it is possible to improve freight trains performances with the introduction of MDS technology with Uphill Boosters/Incline Pushers, giving them a similar dynamic performance to the passenger trains with which they will share mixed traffic.

This Scenario involves the analysis that will evaluate the implementation of the existing line with Upgraded traditional railway MDS technology, without any infrastructural upgrade intervention. This will lead to an evaluation of the applicability of the new technology on the basis of the minimum achievable requirements. This Scenario will be considered for mixed traffic using conventional passenger trains and upgraded MDS vehicles for freights.

7.1.1.1 Running Simulation

This chapter summarizes the results of the simulations included in chapter 9.1.1.1 of **[D7.2]**.

This scenario could benefit from the introduction of Incline Pushers, where additional power is introduced on uphill sections for freight trains. This case study aimed to achieve an increase in capacity of mixed traffic lines by upgrading the existing line with the introduction of uphill boosters, to allow heavy freight trains to maintain the maximum speed, and travel time similar to those of passenger trains, even in difficult situations of adhesion limit. The introduction of the linear motor makes the system more resilient to weather conditions.

To assess this Scenario, possible MDS vehicle configurations were evaluated with respect to two basic configurations of conventional rail vehicles, with the characteristics of the ones which are currently running on the line under study: a freight train and a passenger train.

With regard to the results, if we compare travel time and energy consumption between the considered train types, we can observe that, thanks to the booster, freight trains can behave in a similar way to the Regina train (Option 1) and achieve a travel time of 54 minutes. Thus, travel time is reduced of about 10 minutes (-15%) with respect to the freight travel without booster (64 minutes). However, consumption increases of 517.89 kWh (+23%) without energy recovery, while only of 111.10 kWh (+5%) with energy recovery.

When Option 1 is limited in power to take into account the maximum speed of the line (Option 2), travel time is close to 54 minutes, but the energy consumption increases only up to 467.14 kWh (+21%), which leads 10% saving with respect to Option 1, and 83.34 kWh (+3,8%) with energy recovery.

These results are very promising, as a significant reduction in travel time is achieved for the freight train, bringing it on a par with the passenger train, with which it will be able to run in mixed traffic.

Regarding energy consumption, although it is higher than in the original freight train, the total consumed energy is not relatively high because it is compensated by the potential increase in capacity and the shorter travel time compared with the original train.

The results from the simulation are summarized in the following Table 7, where an estimation of the mechanical energy consumption for each of the booster options is given. Reductions and increments are calculated with respect to the freight train in its normal travel without booster.

Table 7: Scenario A simulation results

New Line	Description	Travel time (min)	Travel time reduction (%)	Travel time reduction (min)	Consumption (GJ)	Consumption increase (%)	Consumption increase (kWh)
Regina		54.17			1.33		
Freight		63.77			7.95		
Booster Option 1	Freight like Regina	54.10	15.2	9.7	9.82	23.4	517.89
Booster Option 2	Option 1 limited to 140 km/h	54.52	14.5	9.3	9.63	21.1	467.14

7.1.1.2 Capacity Analysis

Rail traffic, indicated as the number of trains per day, consists of 13 double-trip passenger trains and 7 single-trip freight train . The total lane flow is 500,000 tonnes of goods per year , whit approximatively 0.4 million arrivals per year. Currently, the line is not considered a bottleneck, but mixed traffic operations have an impact on the robustness of operations.

The case does not consider an increase in the total amount of goods transported, so the reduction in travel time is the only gain that can influence capacity increase.

7.1.1.3 Transport Study

As stated in the previous paragraph, current passenger traffic supply consists of 13 double-trip passenger trains operated by SJ (Statens Järnvägar), and 7 single-trip freight train from a mix of operators . However, it can be also considered buses serving the route, having frequent departures up to every five minutes during peak traffic. Public transport's share of the total travel on the route is 25%, with buses account for 97% of it. Most of the passenger commuting nowadays takes place between major cities of the route, up to one of the biggest airport in Sweden, with nearly 4,000 employees. Additionally, there are airport buses services from both the Origin/Destination cities, as well as public transport from the airport nearest city’s centre. Moreover, many travellers choose to go to the airport by car.

For the freight services, no shift in demand has been considered from the existing demand of over 3,600,000 ton/year.

7.1.1.4 Operational Model

The main need to which an upgraded conventional vehicle with MDS technology on wheels responds, is to increase transportation efficiency. Below are the assumptions for the main characteristics of this system:

- Upgraded wagons operate within trainsets, controlled by locomotives and their drivers,
- MDS components will provide additional traction force in sections where the power of the traction unit in front of the train (one or more locomotives) is not sufficient,
- Freight wagon dimensions do not change with the upgrading,
- Technology dedicated for cargo,
- Interoperable infrastructure for upgraded and conventional trains,
- Grid connection to the medium voltage network for MDS substations,

- Operating speed – up to 160 km/h, if infrastructure allows it,
- Traction type: Linear Synchronous Motor with thrust force of up to 17 kN per equipped wagon,
- Dedicated onboard battery with voltage rating of 72 V,
- MDS components in the track segment are active only when the train is above them.

The operational context for this scenario includes environmental conditions, operational conditions, daily operations and example scenarios, vehicle dynamics, cargo handling, integration with existing infrastructure as well as futureproofing and scalability.

The operational scenario will not alter the current management of the line in terms of traffic control and safety. The rolling stock will be upgraded with booster components. Operational conditions that have been used as input for the CBA are:

- Designed to transport cargo, capable of increasing speed for freight trains on the corridor to the top speed of the line,
- Equipped with advanced safety features, including automated collision avoidance, emergency braking systems, and robust structural integrity for passenger protection,
- Evening and night operations: prioritizes cargo transportation,
- Track compatibility: able to operate on existing rail tracks, needs a specific design integration assessment, including maintenance aspects,
- No impact on current passenger station.

All these aspects will influence the operational costs, mainly CAPEX, and benefits; these values have been reported in **[D7.2]**.

7.1.1.5 CAPEX

For this scenario, the implementation of the linear motor in the station tracks is not necessary as the higher acceleration can only start when the last wagons pass the station switch. Therefore, no additional implementation on the passing and crossing tracks in stations will be considered. With a line length of over 70.00 km, minus approx. 4.00 km of flat line section as result from the simulations, this will lead to **66.00 km ca.** of linear motor installation, including both uphill and downhill sections (considering it is a single-track line).

The hardware costs per kilometre for the linear motor in the considered configuration for this study is estimated by Nevomo experts to a target price in line with the market of € 3.25 mio for a single track, including the active stator with all fixtures and cablings, power electronics like inverters, transformers and segment switches, and the control system. Additional planning and deployment costs of € 0.25 mio are also part of the installation of the linear motor.

This leads to a total investment cost of 66.00 km * (3.25 + € 0.25 mio) = **approx. € 232.05 mio** for the infrastructure part.

Some general measurements are needed before the MDS components can be installed. Infrastructure must fit to the requirements of the used system. Additionally, 41 curves below 400 m radius should be checked, if stability of the track is sufficient for faster running and for accelerating freight trains. 15 of these curves have radii below 300 m and might need specific analyses or inspections. These efforts are not only specific for the new traffic system and cannot be estimated for this study, as the condition of the route is unknown. However, for the needed studies and inspections, additional costs of **€ 100,000** are integrated in this analysis.

On the vehicle side, the retrofit of the freight wagons with mover magnets and needed system components is estimated with a total effort of € 36,000 per wagon. To guarantee the needed traction force, for this use case the freight trains (1 locomotive, 30 wagons, 1,300 t) need 20 equipped wagons each.

This leads to costs of 20 wagons * € 36,000 = € 720,000 per trainset. The assumption is that all 7 trains, which are running on this line per day, are configured as different trainsets from different destinations, and all 7 need to be fully equipped with 20 wagons.

This leads to total investment costs of 7 trainsets * € 720,000 = **€ 5.04 mio** for the rolling stock.

Especially in construction projects, unforeseen costs can occur. In order to include this factor in this analysis, a basic surcharge of 3% is applied to all previous cost blocks. These unexpected costs thus amount to a total of **€ 7.12 mio** in additional costs to be recognised.

Table 8: Investment costs for Upgraded traditional railway MDS – Scenario A

Upgraded traditional railway MDS – Scenario A	CAPEX [€]
Infrastructure	232,050,000.00
Infrastructure studies	100,000.00
Rolling stock	5,040,000.00
Unexpected costs	7,120,000.00
Sum CAPEX	244,310,000.00

Summarized, for this use case, the overall CAPEX is about **€ 244.31 mio**.

7.1.1.6 OPEX

Over time, assets tend to naturally deteriorate due to use, environmental factors, and aging. For estimating yearly maintenance costs, different factors can be taken into account. An estimation of 2.5% of the total investment is used to account for the regular maintenance required to keep these assets in good working condition, addressing issues before they escalate into more significant, costlier problems.

This percentage is widely accepted across various industries, from real estate to manufacturing, as a reliable standard. It is based on historical data and practical experience, reflecting a consensus that this percentage generally covers most maintenance needs without excess. While the 2.5% figure is an average, it provides a flexible starting point. Allocating this amount from the initial investment cost annually for maintenance is a prudent strategy. It reflects a realistic assessment of the ongoing costs necessary to preserve the value and functionality of the investment, ensuring that the asset continues to perform effectively over its lifespan. This percentage strikes a balance between underestimating and overestimating expenses, providing a reasonable and practical guideline for budgeting, and is used in this study for infrastructure and rolling stock investments.

This leads to additional yearly costs of 0.025 * € 232.05 mio = **5.80 mio €/year** for the maintenance of the new infrastructure's hardware, and 0.025 * € 5.04 mio = **0.13 mio €/year** for the retrofit parts in the rolling stock. In addition, regarding the annual operation cost, related to energy consumption, the unitary price for Sweden, mentioned in **[9]**, has been considered as 0.065 €/kWh.

The energy cost has been calculated by applying this price to the increased energy consumption of 111.1 kWh/train, derived from **[D7.2]**, considering 7 trains/day. Based on these data, the annual energy cost that calculated is 0.015 mio €/year.

Below, Table 9 summarizes the list of OPEX considered for this analysis.

Table 9: Operational and Maintenance costs for Upgraded traditional railway MDS – Scenario A

Upgraded traditional railway MDS – Scenario A	OPEX [€/year]
Rolling Stock Operation & Maintenance	126,000.00

Upgraded traditional railway MDS – Scenario A	OPEX [€/year]
Infrastructure Maintenance MDS	5,801,250.00
Sum OPEX	5,927,250.00

Summarized, for this use case, the overall OPEX is about **5.93 mio €/year**.

7.1.1.7 Direct Benefits & Externalities

Travel Time saving

The travel time saving has been calculated based on the analysis performed in **[D7.2]**, which considers a 10 min/ton reduction applied on the 3,652,500 ton/year demand.

The considered VOT is 4 €/hour. For more details, as presented in Section 6.4.4.

Externalities (CO_2 Emissions reduction)

The CO_2eq emissions reduction has been considered by calculating the balance between the increase in the energy consumption, of 111.1 kWh/train, and the saved energy consumption from the road. In this specific case, the latter does not exist, so the aforementioned difference is negative.

The CO_2eq emission factor that has been applied in the calculation is 0.013, which takes into account the resources of the electricity production in Sweden.

In order to calculate the CO_2eq cost, and in line with the EC's technical guidance, a shadow cost for the value of CO_2eq (actualized to 2024) has been used, recently established by the EIB as the best estimate of the cost of achieving the temperature target of the Paris Agreement. The value is 151 €/tCO_2eq.

Below, the following table summarizes the benefits considered for this analysis and their value.

Table 10: Direct Benefits and Externalities for Upgraded traditional railway MDS – Scenario A

Upgraded traditional railway MDS – Scenario A	Benefits and cost savings [€]

Travel Time Saving	472,910,000.00
Externalities	-50,000.00
Sum Benefits & Externalities cost savings	472,860,000.00

Summarized, for this use case, the overall benefits and externalities is about **472,86 mio €/year**.

7.1.1.8 Overview of CBA Results

In the previous sections of this chapter, the overall investment costs (CAPEX) and operational costs (OPEX), as well as the direct benefits and the externalities cost savings, have been outlined for the Scenario A, as seen in the following table:

Table 11: Overview of costs and benefits for the Upgraded traditional railway MDS use case – Scenario A

Upgraded traditional railway – Scenario A		
Sum CAPEX	mio €	244.31
Sum OPEX	mio €/year	5.93
Sum Benefits & Externalities cost savings	mio €	472.86

To perform a Cost-Benefit Analysis, these costs must be converted into their economic values using the specific conversion coefficients for the considered cost voices, as described in detail in Section 6.4.3.

The new economic costs can be used to calculate the different economic performance indicators described in Section 6.2, namely ENPV (Economic Net Present Value), B/C (Benefit-Cost ratio), and IRR (Internal Rate of Return). The following table summarize the obtained results:

Table 12: Overview of CBA results for the Upgraded traditional railway MDS use case - Scenario A

Use case	ENPV [mio €]	B/C	IRR
Upgraded traditional railway MDS – Scenario A	9.33	1.04	3.31%

The obtained results are positive, meaning that the overall expected benefits exceed the overall costs for the analysed scenario, showing the potential for more efficient mixed-traffic operations, enhancing the appeal of rail transport.

7.1.2 Scenario B

The Scenario B for evaluating the Upgraded traditional railway MDS configuration refers to the new railway line linking the two considered cities. As this corridor is a critical link in the Swedish network, a high-speed (250km/h) line has been proposed. This new line would allow a significant increase in capacity by doubling the number of tracks between the two cities, and by segregating traffic with different speeds, where passenger services would run mainly on the high-speed line whereas the freight services would remain in the existing line. The construction of a new high-speed line has very high investment costs, but is expected to have a significant impact on the capacity of the corridor.

The main objective of this use case is to evaluate if the trains that have been used until now (which have less performance than the ones required for this line) can be used in a line of these characteristics, improved with a booster, compared with conventional electric trains of higher power, that can meet the necessary requirements of this new line.

7.1.1.1 Running Simulation

This chapter summarizes the results of the simulations included in chapter 9.1.2.1 of **[D7.2]**.

This scenario involves an analysis that evaluated the implementation, on the existing line, of Upgraded traditional railway MDS technology, with all the technological and/or infrastructural upgrade interventions necessary for the system to function optimally and with the maximum attainable performance.

To assess this scenario, possible MDS vehicle configurations were evaluated, with two basic configurations of conventional passenger vehicles considered as references. The first reference vehicle corresponds to the passenger train with the characteristics of the one currently running on the line under study (Reference 1), while the second reference (Reference 2) includes the main characteristics of an electric passenger train capable of reaching speeds of 250 km/h over most of this route.

The objective was to combine the current train (1,590 kW) with a booster, to achieve similar performance but with lower energy consumption than with a 4,157 kW conventional train.

In order to analyse different MDS configurations, several booster options were considered to provide sufficient performance to achieve the desired speed and travel time.

As a variant of a railway line layout, another layout similar to the previous one, but with steeper gradients, was also analysed. The objective of this layout was to see if such a route, which would require less civil works but with greater gradient requirements, could be operated by trains with the considered characteristics.

As seen in **[D7.2]**, the current train is not able to meet the necessary speed requirements. For this reason, the results of the booster options have been compared with a conventional electric train of 4,157 kW, which can reach the required speed, assuming the installation of the linear motor along the entire line.

For the new line, from comparisons with the Regina train and with the normal running speed train (250 km/h, first reference) in the defined line (new line), reductions between 6.7% and 17.3% in travel time and increases between 17.4% and 35.9% in energy consumption were obtained for the different considered options.

Compared to the 4.1 MW train (Reference 2), option 1 increases travel time of 1.2 minutes (+4.6%), but saves 38 kWh (-6.8%); if a regeneration efficiency of 85% is considered, the energy consumption decrease would be 24.6 kWh (-6.8%). Option 2 presents similar results compared to the 4.1 MW train.

With respect to both references, even though the booster shows a great potential, note that there is not a completely clear preferable booster option over the others, because other factors may influence in its practical application. In relative terms, all options presented an elasticity, which was defined as the time travel reduction with respect to the energy consumption increase, equal to 1 in all options. In absolute terms, an energy efficiency factor, based on the total energy consumption per minute of travel, showed that Option 1 seems to be the best choice among the analysed booster options. However, the final chosen Option should consider other additional factors, such as the desired capacity of the line and the investment costs.

For the new line with steeper gradients, with respect to the 4.1 MW train, Option 1 needs 1.2 minutes more of travel time (+5.4%) with an energy consumption saving of 35.8 kWh (-7.4%). If a regeneration efficiency of 85% is considered, the energy consumption saving would be 24.3 kWh (-8.4%). Meanwhile, Option 2 presents similar results to the 4.1 MW train, because it presents a similar travel time (+0.2%) and an energy consumption saving of 6.2 kWh (-1.3%). If a regeneration efficiency of 85% is considered, the energy consumption saving would be 4,5 kWh (-1.6%). This also means that it is possible to achieve a similar behaviour to the 4.1 MW train with a Regina train equipped with a booster.

Therefore, the inclusion of a booster on the new line to reach 250 km/h makes it possible to use trains that would have less traction capacity without a booster. In this use case, this means that instead of using a train with a minimum of 4.1 MW, it would be possible to use a 1,590 kW train equipped with a booster. It should be noted that the simulations assume the installation of the linear motor along the entire line. In addition, results show that the inclusion of a booster in the new line to reach 250 km/h reduces energy consumption with respect to using a 4.1 MW train.

Considering the above trains and the above booster options, the simulation results are summarized in the following tables, where an estimation of the mechanical energy consumption for each of the booster options is made. It is also important to note that the tables below resume the results for the new line.

Table 13: Summary of travel time saving for the new line

			With respect to Regina		With respect to 4.1 MW train	
New Line	**Description**	**Travel time (min)**	**Travel time reduction (%)**	**Travel time reduction (min)**	**Travel time increase (%)**	**Travel time increase (min)**
Regina		29.0			12.1	3.1
Regina *(200 km/h)*		29.6	-2.1	-0.6	14.4	3.7
Train with 4.1 MW	250 km/h for 22 ‰	25.9	10.8	3.1		
Booster Option 1	60 kN for v>=95km/h	27.0	6.7	1.9	4.6	1.2

			With respect to Regina		With respect to 4.1 MW train	
New Line	Description	Travel time (min)	Travel time reduction (%)	Travel time reduction (min)	Travel time increase (%)	Travel time increase (min)
Booster Option 2	$P_{variable}$	26.1	10.1	2.9	0.8	0.2
Booster Option 3	Fmax 107 kN	25.6	11.8	3.4	-1.2	-0.3
Booster Option 4	a_{max}: 1.5 m/s^2	28.4	1.9	0.5	10.0	2.6
Booster Option 5	1.5 m/s^2 and 4.1MW	24.9	14.2	4.1	-3.8	-1.0
Booster Option 6	1.5 m/s^2 and Fmax	24.0	17.3	5.0	-7.3	-1.9

Table 14: Summary of energy consumption increase for the new line (no energy recovery)

			With respect to Regina		With respect to 4.1 MW train	
New Line	Description	Consumption (GJ)	Consumption increase (%)	Consumption increase (kWh)	Consumption reduction (%)	Consumption reduction (kWh)
Regina		1.58			21.9	123.3
Regina (200 km/h)		1.53	-3.1	-13.6	24.4	136.8
Train with 4.1 MW	250 km/h for 22 ‰	2.02	28.1	123.3		
Booster Option 1	60 kN for v>=95km/h	1.89	19.4	85.3	6.8	38.0
Booster Option 2	$P_{variable}$	2.00	26.7	117.3	1.1	6.0

			With respect to Regina		With respect to 4.1 MW train	
New Line	**Description**	**Consumption (GJ)**	**Consumption increase (%)**	**Consumption increase (kWh)**	**Consumption reduction (%)**	**Consumption reduction (kWh)**
Booster Option 3	Fmax 107 kN	2.09	32.3	141.7	-3.3	-18.5
Booster Option 4	Max accel 1.5 m/s^2	1.58	0.0	0.2	21.9	123.1
Booster Option 5	1.5 m/s^2 and 4.1MW	2.04	29.4	129.1	-1.0	-5.9
Booster Option 6	1.5 m/s^2 and Fmax	2.15	36.1	158.5	-6.3	-35.2

Table 15: Summary of energy consumption increase for the new line (85% energy recovery)

Consumption with 85% regeneration			With respect to Regina		With respect to 4.1 MW train	
New Line	**Description**	**Consumption (GJ)**	**Consumption increase (%)**	**Consumption increase (kWh)**	**Consumption reduction (%)**	**Consumption reduction (kWh)**
Regina		1.03			20.7	74.2
Regina (200 km/h)		0.96	-6.7	-19.1	26.0	93.4
Train with 4.1 MW	250 km/h for 22 ‰	1.29	26.1	74.2		
Booster Option 1	60 kN for v>=95km/h	1.20	17.4	49.6	6.9	24.6
Booster Option 2	$P_{variable}$	1.28	24.5	69.8	1.2	4.5
Booster	Fmax 107	1.33	30.0	85.6	-3.2	-11.4

Consumption with 85% regeneration			With respect to Regina		With respect to 4.1 MW train	
New Line	**Description**	**Consumption (GJ)**	**Consumption increase (%)**	**Consumption increase (kWh)**	**Consumption reduction (%)**	**Consumption reduction (kWh)**
Option 3	kN					
Booster Option 4	Max accel 1.5 m/s^2	1.03	0.0	0.0	20.7	74.2
Booster Option 5	1.5 m/s^2 and 4.1MW	1.31	27.7	79.0	-1.3	-4.7
Booster Option 6	1.5 m/s^2 and Fmax	1.39	35.9	102.4	-7.8	-28.2

Finally, tables below summarize the results for the new line with high inclinations.

Table 16: Summary of travel time saving for the new line with high inclinations

New Line (High Slopes)	Description	Travel time (min)	With respect to Regina: Travel time reduction (min)	With respect to Regina: Travel time reduction (%)	With respect to 4.1 MW train: Travel time increase (min)	With respect to 4.1 MW train: Travel time increase (%)
Regina	Reference speed 250 km/h	25.6			3.0	13.1
Regina (200 km/h)	Reference speed 200 km/h	25.6	0.0	0.0	3.0	13.1
Train with 4.1 MW	250 km/h for 22 ‰	22.6	3.0	11.6		
Booster Option 1	60 kN for v>=95km/h	23.8	1.8	6.9	1.2	5.4
Booster Option 2	$P_{variable}$	22.8	2.8	10.8	0.2	0.9

Table 17: Summary of energy consumption increase for the new line with high inclinations (no energy recovery)

New Line (High Slopes)	Description	Consumption (GJ)	With respect to Regina: Consumption increase (%)	With respect to Regina: Consumption increase (kWh)	With respect to 4.1 MW train: Consumption reduction (%)	With respect to 4.1 MW train: Consumption reduction (kWh)
Regina	Reference speed 250 km/h	1.34			23.1	111.4
Regina (200 km/h)	Reference speed 200	1.34	0.0	0.0	23.1	111.4

			With respect to Regina		With respect to 4.1 MW train	
New Line (High Slopes)	**Description**	**Consumption (GJ)**	**Consumption increase (%)**	**Consumption increase (kWh)**	**Consumption reduction (%)**	**Consumption reduction (kWh)**
	km/h					
rain with 4.1 MW	250 km/h for 22 ‰	1,74	30.0	111.4		
Booster Option 1	60 kN for v>=95km/h	1,61	20.4	75.6	7.4	35.8
Booster Option 2	$P_{variable}$	1,71	28.3	105.1	1.3	6.2

Table 18: Summary of energy consumption increase for the new line with high inclinations (85% energy recovery)

Consumptions with 85% of regeneration			With respect to Regina		With respect to 4.1 MW train	
New Line (High Slopes)	**Description**	**Consumption (GJ)**	**Consumption increase (%)**	**Consumption increase (kWh)**	**Consumption reduction (%)**	**Consumption reduction (kWh)**
Regina	Reference speed 250 km/h	0.81			22.8	66.2
Regina (200 km/h)	Reference speed 200 km/h	0.81	0.0	0.0	22.8	66.2
Train with 4.1 MW	250 km/h for 22 ‰	1.05	29.5	66.2		

Consumptions with 85% of regeneration			With respect to Regina		With respect to 4.1 MW train	
New Line (High Slopes)	**Description**	**Consumption (GJ)**	**Consumption increase (%)**	**Consumption increase (kWh)**	**Consumption reduction (%)**	**Consumption reduction (kWh)**
Booster Option 1	60 kN for v>=95km/h	0.96	18.6	41.9	8.4	24.3
Booster Option 2	$P_{variable}$	1.03	27.4	61.7	1.6	4.5

7.1.1.2 Capacity Analysis

Rail traffic, considered as the number of trains per day, consists of 13 double-trip passenger trains and 7 single-trip freight train. The total lane flow is 500,000 tonnes of goods per year, with approximately 0.4 million arrivals per year (excluding the two ends of the line section). The line is currently not considered a bottleneck, but mixed traffic operations have an impact on the robustness of operations.

Building a new track where only passenger commuters run at higher speeds will significantly increase the capacity between the cities.

7.1.1.3 Transport Study

As previously stated, current passenger traffic supply consists of 13 double-trip passenger trains from SJ and 7 single-trip freight train from a mix of operators (2021). Bus also serves the route, with frequent departures, every five minutes, during peak traffic. Public transport's share of the total travel on the route is 25%, with buses account for 97% of it. Most of the passenger commuting nowadays takes place between two major cities along the route, up to one of the biggest airport area in Sweden, with nearly 4,000 employees. Additionally, there is airport buses service both from the ends of the line under study, as well as by public transport from the abovementioned airport city's centre. Moreover, many travellers choose to go to the airport by car.

A travel modal choice model has been developed and calibrated in order to estimate the probability of passengers taking different transport modes. The modal split between different systems is shown in Table 19: Passenger demand (yearly) and market share data for Scenario B (current scenario and MDS) reported in **[D7.2]**. Market share values for the MDS scenario are calculated based on the travel modal split model developed and calibrated for this corridor, reported in **[D7.2]**. The only difference between baseline scenario (current scenario) and MDS scenario is 2 minutes travel time savings for rail for the MDS scenario compared to baseline (current scenario).

*Table 19: Passenger demand (yearly) and market share data for Scenario B (current scenario and MDS) reported in **[D7.2]***

Corridor and scenario	*Modal Split*			*Total demand(2024)*
	Rail	*Bus*	*Car*	
Current Scenario	570,443 *(10%)*	2,281,771 *(40%)*	2,852,214 *(50%)*	5,704,427
MDS Scenario	589,267 *(10%)*	2,273,214 *(40%)*	2,841,946 *(50%)*	5,704,427

7.1.1.4 Operational Model

The main need to which an upgraded conventional vehicle with MDS technology responds, is to be able to increase inclinations in the track design phase to reduce construction costs. The operational details for the system functions and elements are the same for both Scenario A and B, but the vehicles are different. The assumptions for main characteristics of this system are as follows:

- Technology dedicated for passengers, upgraded EMUs,
- MDS components will provide additional traction force in sections where the track inclination is more than the baseline case, in order to reduce construction costs,
- EMU dimensions do not change with the upgrading,
- Interoperable infrastructure design for upgraded and conventional trains, with significant track inclinations,
- Grid connection to the medium voltage network for MDS substations,
- Operating speed – up to 250 km/h, if infrastructure allows it,

- Traction type: Linear Synchronous Motor with thrust force of up to 25 kN per equipped car,
- MDS components in the track segment are active only when the train is above them.

The operational context for this scenario includes environmental conditions, operational conditions, daily operations and example scenarios, vehicle dynamics, cargo handling, integration with existing infrastructure as well as futureproofing and scalability.

The operational scenario will not alter the current management of the line in terms of traffic control and safety. The rolling stock will be upgraded with booster components. Operational conditions that have been used as input for the CBA are:

- Designed to transport passengers, capable of increasing accelerations in uphill sections of the corridor,
- Equipped with advanced safety features, including automated collision avoidance, emergency braking systems, and robust structural integrity for passenger protection,
- Track compatibility: able to operate on existing tracks designs, specific design integration assessment is needed, including maintenance aspects,
- No impact on current passenger station design.

All these aspects will influence the operational costs, mainly CAPEX, and benefits; the values have been reported in **[D7.2].**

7.1.2.5 CAPEX

The new considered high speed line between the Swedish cities is a double track line. So, it is needed to implement the MDS linear motor in all sections with high inclines (up to 22 ‰), and after the two planned station stops, where trains have to reaccelerate. The total length of the new optimized line is nearly 50.00 km, from which 24.00 km ca. must be equipped with linear motor in one direction and 15.00 km ca. in the other one. This leads to **39.00 km** of linear motor altogether. Additional equipment of station tracks is not needed.

The hardware costs per kilometre for the linear motor in the considered configuration for this study is estimated by Nevomo experts to a target price in line with the market of € 3.25 mio for a single track, including the active stator with all fixtures and cablings, power electronics like inverters, transformers and segment switches, and the control system. Additional planning and deployment costs of € 0.25 mio are also part of the installation of the linear motor.

This leads to total investment costs of 39.00 km * (3.25 + € 0.25 mio) = **€ 136.50 mio** for the infrastructure part.

By enabling trains to tackle steep gradients more effectively, incline pushers reduce the need for extensive earthwork, such as soil and rock excavation and filling, which are typically required to create gentler slopes for conventional rail systems. This not only conserves natural landscapes and minimizes environmental disruption, but also substantially lowers construction costs.

In the case of Scenario B, the proposed new branch line, the track vertical layout has been modified so that it better follows the orography and avoids tunnelling or building bridges. These modifications address only the vertical profile of the track, and do not account for any other possible limitations except for a maximum track inclination of 5%.

The evaluation of the difference in earth work between the two cases in Scenario B are graphically estimated, based on the available track design on paper and thus limited to the vertical alignment in this report. This cost estimation includes the following components:

- cost of tunnel,
- cost of bridges,
- cost for Rock/Soil excavation,
- cost for backfill.

Costs of earthworks for the original planning of the line are estimated with € 143.37 mio. Changing the planning parameters will reduce the costs down to € 97.90 mio. This leads to a total saving of **€ 45.47 mio**.

On the vehicle side, the retrofit of the passenger high speed trains with mover magnets and needed system components is estimated with a total effort of € 54,000 per wagon. To guarantee the needed traction force for this use case the high speed trains (54 m, 161 t, two coaches) need to be equipped with two mover magnets per train.

For this scenario, it was estimated that 4 trains per hour would operate on the line, with each round trip taking 90 minutes per each train. This means a total of 6 trains would be needed to cover the service. To ensure reliability, a 10% buffer was added, resulting in a total of 7 trains. For each complete train, 2 wagons would need to be retrofitted with the MDS technologies, with an estimated by Nevomo experts to a target price in line with the market of € 54,000 based on. The total costs for the vehicle part would amount to 7 trains × 2 wagons/train × € 54,000 = **€ 756,000**.

Especially in new technology projects, unforeseen costs can occur. In order to include this factor in this analysis, a basic surcharge of 3% is applied to all previous cost blocks related to the new technology. Theses unexpected costs thus amount to a total of **€ 4.12 mio** in additional costs to be recognised.

Table 20: Investment costs Upgraded traditional railway MDS – Scenario B

Upgraded traditional railway MDS – Scenario B	CAPEX [€]
Infrastructure	136,500,000.00
Earthworks (savings)	-45,470,000.00
Rolling stock retrofitting	760,000.00
Unexpected costs	4,120,000.00
Sum CAPEX	95,910,000.00

Summarized, for this use case, the overall CAPEX is about **€ 95.91 mio**.

7.1.2.6 OPEX

As already described in Scenario A, an amount of 2.5% of the initial investment is set as the annual maintenance costs also in this scenario.

This leads to additional yearly costs of 0.025 * € 136.00 mio = **2.38 mio €/year** for the maintenance of the new infrastructure hardware, and 0.025 * € 0.76 mio = **0.02 mio €/year** for the retrofit parts in the rolling stock.

In addition, regarding the annual operation cost, related to the energy consumption, the unitary price for Sweden mentioned in **[9]** has been considered, which is 0.065 €/kWh.

The energy cost has been calculated by applying this price on the increased energy consumption 49.6 kWh/train derived from **[D7.2]** for the Booster Option 1, considering 48 train/day/direction, which are 4 trains/hour in the peak hours (8 hours) and 2 trains/hour in the non-peak hours (4 hours). Based on these data, the annual Energy cost that has been calculated is 0.093 mio €/year.

Below, Table 21 summarizes the list of OPEX considered for this analysis.

Table 21: Operational and Maintenance costs for Upgraded traditional railway MDS – Scenario B

Upgraded traditional railway MDS – Scenario B	OPEX [€/year]
Rolling Stock Operation & Maintenance	18,900.00
Infrastructure Maintenance MDS	2,378,776.00
Sum OPEX	2,397,676.00

Summarized, for this use case, the overall OPEX is about **2.40 mio €/year**.

7.1.2.7 Direct Benefits & Externalities

Travel Time saving

Railway to MDS travel time saving – has been calculated based on the analysis done in the **[D7.2]** considering the Booster Option 1, which is a 2 min/pax reduction applied on the Reference Rail demand 570,443 pax/year (in 2024).

Road to MDS travel time saving – has been calculated based on the travel time reduction of the shift demand (from the Road) of 18,825 pax/year (in 2024), considering 20 min of reduction calculated as the difference between the project scenario's travel time and the actual road travel time (using Google Maps).

The VOT that has been considered is 10.05 €/hour. For more details, see Section 6.4.4.

Reducing operating costs of private vehicles

Private vehicle operating costs (VOC) are defined as the costs incurred by owners of road vehicles for their use, considering fuel consumption, lubricant consumption, repair and maintenance costs, insurance, and general expenses.

In relation to the project, the savings generated by the reduction of VOC are a function of the passengers who came from the private road mode.

The reduction of private vehicle operating costs was determined by multiplying the operating cost of private vehicles by the km*year saved (subtracted from private mobility), which has been estimated starting from the average km saved per user and the annual demand passed to the railway from private mobility.

The VOC that has been considered is €/vehicle.km 0.403. For more details, see Section 6.4.4.

Reduction of accidents

One of the objectives of the intervention is to increase the share of rail transport, with a view to enhancing public transportation. One of the estimated impacts is the reduction of accidents between vehicles and between vehicles and road users, such as pedestrians. Estimating the probability of accidents is extremely complex, and current models are typically focused on very small sections of the road network, usually intersections.

This effect can be considered related to the reduction in demand for private mobility. The analysis concerning the reduction of road accidents is limited to estimating the impact in monetary terms, without quantification.

The marginal cost of accidents for cars is 0.01 €/vehicle.km. This value is based on the data in **[6]** and is determined as the average marginal cost of accidents for cars in Sweden on both urban and non-urban roads, equal to 0.01 €/vehicle.km, actualized to 2024. The marginal cost of accidents for railways (passenger trains) in Sweden is 0.28 €/train-km, also actualized to 2024.

Reducing urban congestion

One of the impacts related to the shift of traffic from private cars to the railway system is the reduction of urban congestion. It is connected to the typical externalities associated with the massive presence of private motor vehicles in the area, such as congestion and space occupation.

The marginal cost of urban congestion is 0.309 €/vehicle.km (the average cost of urban and interurban trips in Sweden), actualized to the year 2024. This value is based on data in **[6]**.

Reduction of noise emissions

The reduction of noise emissions is a function of the variation in the distance travelled by each mode of transport. However, the negative impact of noise pollution is correlated with many factors, particularly the proximity and density of receptors relative to the source, as well as the time of day and the activities being carried out. Due to this, the analysis related to the reduction of noise emissions is limited to estimating the impact in monetary terms, without quantification.

Specifically, for calculating the marginal cost of noise emissions, a value of 0.004 €/vehicle.km has been assumed for car noise emissions, while the marginal cost of rail noise emissions is assumed to be 0.60 €/train-km. These values are derived from the **[6]**, actualized to 2024.

Externalities

CO_2 Emissions reduction – has been considered by calculating the balance between the increase in the energy consumption of 49.6 kWh/train, based on the analysis done in the **[D7.2]** considering the Booster Option 1, and the saved energy consumption from the road (937,546 vehicle.km/year).

The CO_2 emission factor which has been applied in the calculation is 0.013, which consider the resources of the electricity production in Sweden.

Air pollution reduction – has been considered by calculating both the contribution related to the on-site combustion of internal combustion engines and that related to non-exhaust emissions from the road vehicles. The non-exhaust contribution from road vehicles is associated with abrasion phenomena, including the combined wear of tires, brakes, and road surfaces.

Below, is a summary table of the environmental benefits previously discussed, with reference to the period 2034-2063.

Table 22: Air pollution reduction

EMISSIONS		From reduction of road transport [ton]	From increase in electric traction [ton]	Overall benefit [ton]
CLIMATE-ALTERING EMISSIONS	*CO_2eq*	3,605	-557	3,048
POLLUTING EMISSIONS	*PM 10*	0.81	-	0.81
	NOx	0.81	-	0.81
	NMVOC	1.44	-	1.44
	SO_2	0.01	-	0.01
	Pb	0.00	-	0.00

For the monetization of environmental benefits, the following unit marginal costs (actualized to 2024) have been applied to the tons of pollutant emissions reduction:

- 180,956 €/ton for PM2.5 (exhaust and non-exhaust) (average value for Sweden),
- 7,908 €/ton for NOx (average value for Sweden),
- 714 €/ton for NMVOC (in Sweden),
- 5,612 €/ton for SO_2 (in Sweden).

These values are derived from **[6]**.

Regarding the CO_2eq emissions cost, and in line with the EC's technical guidance, a shadow cost for the value of CO_2eq (actualized to 2024) has been used, recently established by the EIB as the best estimate of the cost of achieving the temperature target of the Paris Agreement. The value is 151 €/tCO_2eq.

The following table summarizes both the direct benefits both the monetized externalities savings:

Table 23: Direct Benefits and Externalities for Upgraded traditional railway MDS – Scenario B

Upgraded traditional railway MDS – Scenario B	Benefits and cost savings [€]
Travel Time Saving	19,360,000.00
Vehicle Operation Cost Saving	14,950,000.00
Externalities	17,770,000.00
Sum Benefits & Externalities cost savings	52,090,000.00

Summarized, for this use case, the overall benefits and externalities is about **52.09 mio €/year**.

7.1.2.8 Overview of CBA Results

As for Scenario A, the overall costs (both CAPEX and OPEX) and the direct benefits and externalities cost savings have been analysed, as shown in the following table:

Table 24: Overview of costs and benefits for the Upgraded traditional railway MDS use case – Scenario B

Upgraded traditional railway MDS – Scenario B		
Sum CAPEX	mio €	95.91
Sum OPEX	mio €/year	2.40

Sum Benefits & Externalities cost savings	mio €	52.09

After the conversions between financial and economic costs, as per Section 6.4.3, the CBA indicators have been calculated, showing the following results:

Table 25: Overview of CBA results for the Upgraded traditional railway MDS use case – Scenario B

Use case	ENPV [mio €]	B/C	IRR
Upgraded traditional railway MDS – Scenario B	-0.67	0.27	-12.06%

For this scenario, the B/C ratio is lower than 1, showing that the overall costs, especially the construction ones, are higher than the expected benefits., and despite a potential 30% reduction in earthwork costs, the low traffic volumes and the reduced demand lower the overall feasibility.

This scenario suggests that the linear motor technology could be more effective in regions with higher transport demand, potentially achieving a B/C ratio of 1 or more.

7.2 Hybrid MDS Based on Air Levitation

7.2.1 Analysed Scenario

This use case compares the performance of a conventional train, which usually runs on the current line (the ETR 421 train model, with four coaches), with that of a train of the same characteristics where the conventional bogies are replaced by air levitation bogies.

The objective is to compare the travel time and energy consumed by each type of train, to ascertain the impact of the higher traction and braking capacity, as well as the lower rolling resistance of the air levitation bogies.

7.2.1.1 Running Simulation

This chapter summarizes the results of the simulations included in chapter 9.2.1.1 of **[D7.2]**.

The Airlev method, a combination of proven technologies including levitation by air and propulsion with rotating permanent magnetic wheels, is the main focus of this use case. The objective is to design and develop a bogie that incorporates both technologies. This bogie will replace the ones on existing trains. The existing infrastructure will be retained and will be retrofitted with specific slabs for the operation of the hybrid MDS. This will enable the Airlev trains and traditional trains to use the same track.

This scenario could benefit from the introduction of hybrid MDS based on air levitation, because of the reduced rolling resistance and better control of traction and braking, which is not achieved with wheel-rail contact. Braking force is very limited, for example, when the tracks are slippery.

The reduction in travel time is achieved thanks to the slightly higher speed of the vehicle with the air levitation bogies, together with a higher acceleration and braking capacity. On the other hand, the increased speed will result in higher consumption and lower travel time. Simulations allowed the quantification of the magnitude of these variations.

Then, to assess these scenarios, two possible MDS vehicle configurations were evaluated, with respect to the basic configurations of a conventional rail vehicle which is currently running on the line under study.

The first configuration corresponds to air levitation bogies where each EDW (Electro Dynamic Wheel) has a traction capacity of 9.4 kN. The traction capacity, based on a wheel diameter of 700 mm, is equivalent to that of a conventional train (9.4 kN/wheel * 4 wheels/bogie * 2 bogies/coach * 4 coaches/train = 300 kN). The second configuration is the same as above, but considering a maximum power limitation of 3,400 kW, which is that of the conventional ETR.

Related to travel time and train position on the railway, for a given route and stops, the current passenger train is slightly slower and takes longer to complete the journey. This is primarily due to the fact that the current train is limited to running at 160 km/h, whereas the line allows running at 180 km/h. In contrast, the different air levitation configurations achieve similar performance, reducing the total travel time by approximately 30 seconds in the case of power limitation, and by 1 minute 12 seconds in the case of no power limitation.

In terms of energy consumption, the conventional vehicle consumes less energy, but this is because it only reaches 160 km/h, while in the two configurations with air levitation, the energy consumed is higher, especially in the case of no power limitation. If the conventional ETR could reach 180 km/h, the energy consumption results would have been very similar to those of air levitation.

Table 26 summarizes the results, in terms of travel time and energy consumption:

Table 26: Travel time and energy consumption analysis

Rolling stocks	Scenario	Travel time (h)			Energy consumption				Energy consumption (85% recovery)			
		Absolute value (min)	Reduction (min)	Reduction (%)	GJ	kWh	Increase (kWh)	Increase (%)	GJ	kwh	Increase (kWh)	Increase (%)
ETR 421	Current line	20.63	-	-	1.0	291.1	-	-	0.7	191.9	-	-
Airlev	Limited power	20.00	0.6	3.1	1.2	326.4	35.3	12.1	0.8	214.6	22.7	11.8
	unlimited	19.46	1.2	5.7	1.2	343.7	52.6	18.1	0.8	221.5	29.6	15.4

The main conclusion that can be drawn from the simulations is that the use of air levitation does not allow for significant improvements in travel time or energy consumption, and the results obtained are quite similar.

7.2.1.2 Capacity Analysis

The section of railway infrastructure between the two considered Italian cities is one of the most important mobility corridors for passengers and freight. The section of the line between the abovementioned cities features a flat plan-altimetric profile. With reference to the north-south direction, the maximum gradient slope reaches 4.5 ‰ uphill and 3.2 ‰ downhill. The alignment is predominantly rectilinear, with large radii of curvature, except for reduced radii in the approach sections to the two urban stations.

The railroad, which is about 45 km long, is used by ca. 150 services for all traffic segments. Analysing the current supply pattern, both regional and HS services run on this section. Furthermore, long-distance Intercity services connect the two cities with the biggest centres of Italy. Regional services allow to connect the two cities and the municipality along the line. These services play a crucial role for the demand that use them for home-works trips. The headway of these services is actually 12 minutes. In addition to passenger traffic, the line accommodates a moderate level of freight traffic, which utilizes sections of the conventional line infrastructure.

However, the considered section is not to be considered as a bottleneck for the line, as capacity is distributed over two lines side by side (one HS and one conventional), for a total of 4 tracks

7.2.1.3 Transport Study

The process that led to the definition of the railway demand in the year of the start of operations is better described in Section 7.3.1.3.

However, it is anticipated that, as in the Hybrid MDS based on Magnetic Levitation use case, also in the Hybrid MDS based on Air Levitation use case the calculation of the modal shift is based on the principle of the elasticity of passenger transport demand. This method makes it possible to estimate the variation in demand as a function of certain descriptive variables of the railway system (such as frequency, fares or reduction of travel time, etc.) or more in general, of any transport mode, whether public or private.

In this use case, the equipment of the MDS based on air levitation along the line could make possible to achieve an increase of the frequency of the services. More specifically, it was assumed to decrease the actual headway from 12 minutes to 10 minutes to make possible the scheduling of 6 trains/hour instead of the current 5 trains/hour. This will increase the frequency of the services in both directions by 20%.

To estimate the modal shift, it was necessary to choose an exact value for the elasticity of the passenger transport demand, related to the frequency of the services. Based on the existing literature **[11]**, the elasticity was assumed to be 0.2. This assumption is based on the observation that the frequency of the trains between the two cities is already high, consequentially it is not expected that the railway system could gain a large amount of additional demand thanks to the introduction of 1 train/hour.

It is also necessary to specify that no cross-effect due to the reduction in travel time has been considered, since the latter is estimated at just over one minute (less than 2% of in-vehicle time).

Given that a growth of population is not forecasted for these two cities, the railway demand in the line's first years of operation is calculated by summing the actual demand and the modal shift. The results, which are referred to a typical month, are highlighted in the following figure.

7.2.1.4 Operational Model

As mentioned in the previous chapter, the ultimate goal of this project scenario is to verify the feasibility of replacing the current regional services between the two Italian cities, with services provided with an MDS system based on air levitation in the same line, under a hybrid configuration. The main goal of the technology is to optimize capacity, and increment frequencies for the high commuting demand between the two cities.

Considering the observations regarding capacity and the results provided by the simulations, the future operational model aims to increase the service offered between the cities. In particular, it is planned to reduce the current headway to 10 minutes instead of the current, which is 12 minutes. Adding approximately 1 service each hour. This operational model was proposed in base of the theorized increase in frequency, that is also the base for the estimation of the induced demand for the use case (See Section 7.2.1.3 for details).

7.2.1.5 CAPEX

In the scenario where an Airlev bogie replaces a conventional bogie on an existing railway system, significant track modifications are required to facilitate the levitation mechanism. Specifically, a slab track needs to be installed between the two rails of the existing track. This modification is essential because the slab provides a smooth, flat surface that is critical for the effective operation of the air fenders, which are responsible for maintaining the train's levitation above the track.

The implementation of a slab track involves not only the cost of the concrete slab itself, but also the expenses related to its installation. The installation process typically requires specialized machinery and skilled labor, both of which add to the overall cost. The slab track needs to be precisely aligned and securely fixed, to ensure the safety and reliability of the levitation system. Given these considerations, the rough estimate for the capital expenditure required to install the slab track is approximately 600,000 €/km. This estimate includes both the cost of the concrete slab material and the associated labor and machinery costs for its installation.

When estimating the total cost for installing the slab track required for the Airlev bogie system, several key components must be considered in the composition of costs. These include material costs, labor, equipment, and ancillary expenses. Below is a more detailed breakdown of the estimated cost composition, with approximated figures based on common industry practices:

Material cots – the primary material involved is the concrete slab, which must be of sufficient strength and durability to support the high-speed levitation system. In addition, reinforcement materials like steel rebar may be required to reinforce the slab for long-term stability and performance.

<u>*Labor costs*</u> – labor is another significant component of the overall cost. Skilled workers are required for tasks such as:

- Preparation of the track bed: grading, levelling, and preparing the base for the slab,
- Formwork and rebar installation: Setting up the moulds and installing reinforcement bars before pouring the concrete,
- Concrete pouring and curing: concrete placement and ensuring proper curing for durability,
- Finishing and alignment: precision work to ensure that the slab is level and aligned correctly for the air fender system.

<u>*Equipment and machinery costs*</u> – installing a slab track requires specialized construction equipment, such as concrete mixers and pumps, cranes or other lifting equipment and laser levelling equipment.

<u>*Additional costs and overheads*</u> – other expenses that need to be considered include design and engineering cost, permits and inspections and contingency and risk management.

Table 27: Installation costs – air levitation

Cost Component	Estimated Cost per Kilometre
Material Costs	310,00
- Concrete Slabs	*250,000*
- Supporting Materials	*60,00*
Labor Costs	120,000
Machinery and Equipment	80,000
Engineering and Design	30,000
Site Preparation	40,000
Transportation and Logistics	20,000
Total Estimated Cost	600,000

The capital expenditure of € 1.60 mio per coach for the Airlev train system includes the cost associated with replacing the conventional bogie with an Airlev bogie and equipping the coach with the necessary technology to achieve air levitation, propulsion, and braking. Below, is a detailed breakdown of the cost components and their estimated values:

Bogie cost – the Airlev bogie is the cornerstone of the air levitation technology. It replaces the conventional bogie, which typically relies on wheels and friction, with a system that uses air fenders for levitation and rotating permanent magnetic wheels for propulsion and braking.

- Air Fenders: approximately € 300,000 per bogie. This includes the air compressors, accumulators, sound isolation chambers, and fenders necessary to maintain stable air pressure for levitation. The fenders are specifically arranged to lift the train and provide guidance, ensuring smooth operation even at high speeds.
- Electro-dynamic wheel: approximately € 250,000 per bogie. The EDW system is crucial for providing the propulsion and braking capabilities without relying on friction. This includes the cost of the rotating wheels with embedded permanent magnets and the stators that interact with these wheels to generate the Lorentz force needed for movement.

- Structural components and integration: approximately € 150,000. This covers the chassis modifications, integration of the air levitation and EDW systems, and the structural reinforcements required to accommodate these advanced technologies.

<u>*Coach modification cost*</u> – the Airlev system requires certain modifications to the existing coach structure to accommodate the new bogies and ensure optimal performance and safety.

- Coach structural modifications: approximately € 200,000. This includes alterations to the undercarriage to securely attach the Airlev bogies, reinforce the coach's frame, and adjust the suspension system to work with the new levitation technology.

The number of trains considered in the analysis, is based on an estimated frequency of 5 trains per hour on the line, with each train completing a round trip in 90 minutes. Therefore, a total of 18 trains will need to be purchased to meet the required fleet size.

Assuming that the number of coaches making up a train is the same as that of an ETR 421, the total investment cost for the rolling stock is equal to 18 trains * 4 coaches * 1.6 mio €/coach = **€ 115.2 mio**.

In the following table, the CAPEX for the analysed scenario is summarized.

Table 28: Investment costs for Hybrid MDS based on air levitation

Hybrid MDS based on air levitation	CAPEX [€]
Civil Works	44,400,000.00
Signalling system	3,700,000.00
Rolling stock	115,200,000.00
Unexpected Cost [3%]	4,899,000.00
Sum CAPEX	168,199,000.00

7.2.1.6 OPEX

The same approach used in the previous use case, regarding the infrastructure maintenance cost, has been applied in this case, so a percentage of 2.5% of the investment cost has been considered.

This leads to additional yearly costs of 0.025 * € 22.20 mio = **0.56 mio €/year** for the maintenance of the infrastructure.

In the other hand, the rolling stock maintenance and operation cost has been estimated at 6.20 €/train-km, considering the short distance of the services and the slight reduction in energy consumption. This leads to additional yearly costs of 6.20 €/train-km * 710,400 train-km/year = **4.41 mio €/year** for the maintenance and operation of the rolling stock.

In addition, regarding the annual operation cost, related to the energy consumption of the rolling stock, the unitary price for Italy mentioned in **[10]** has been considered, which is 0.134 €/kWh.

The energy cost has been calculated by applying this price on the increased energy consumption by:

- The addition 710,400 train-km/year for with the Air levitation technology, about 221.5 kWh/train (Traction energy),
- The existing 3,552,000 train-km/year (Electric trains), about + 29.6 kWh/train (Traction energy),
- The levitation energy, about 241,200 kWh/year.

The length of the railway line that has been considered is 37 km. This leads to additional yearly costs of ([710,400 train-km/year * 221.5 kWh/train] / 37 km) * 0.134 €/kWh = **0.98 mio €/year** for the energy consumption costs.

Below, a summary of the OPEX costs evaluated for this scenario.

Table 29: Operational and Maintenance costs for Hybrid MDS based on air levitation

Hybrid MDS based on air levitation	OPEX [€/year]
Rolling Stock Operation & Maintenance	4,404,480.00
Infrastructure Maintenance MDS	555,000.00
Sum OPEX	4,959,480.00

7.2.1.7 Direct Benefits & Externalities

Travel Time saving

Railway to MDS travel time saving – has been calculated based on the analysis done in the **[D7.2]**, which is about 1.3 min/pax reduction applied on the Reference Rail demand of 4,565,730 pax/year (in 2024).

Road to MDS travel time saving – has been calculated based on the travel time reduction of the shift demand (from the Road) of 140,400 pax/year (in 2024), considering about 22 min/pax reduction.

The VOT that has been considered is 21.00 €/hour, for more details see Section 6.4.4

Reducing operating costs of private vehicles

Private vehicle operating costs (VOC) are defined as the costs incurred by owners of road vehicles for their use, considering fuel consumption, lubricant consumption, repair and maintenance costs, insurance, general expenses.

In relation to the project, the savings generated by the reduction of VOC are a function of the passengers who came from the private road mode.

The reduction of private vehicle operating costs was determined by multiplying the operating cost of private vehicles by the km*year saved (subtracted from private mobility), which has been estimated starting from the average km saved per user and the annual demand passed to the railway from private mobility.

The VOC that has been considered is €/vehicle.km 0.403. For more details, see Section 6.4.4

Reduction of accidents

One of the objectives of the intervention is to increase the share of rail transport, with a view to enhancing public transportation. One of the estimated impacts is the reduction of accidents between vehicles and between vehicles and road users, such as pedestrians. Estimating the probability of accidents is extremely complex, and current models are typically focused on very small sections of the road network, usually intersections.

This effect can be considered related to the reduction in demand for private mobility. The analysis concerning the reduction of road accidents is limited to estimating the impact in monetary terms, without quantification.

The marginal cost of accidents for cars is 0.02 €/vehicle.km. This value is based on the data in **[6]** and is determined as the average marginal cost of accidents for cars in Italy on both urban and non-urban roads, equal to 0.02 €/vehicle.km, actualized to 2024. The marginal cost of accidents for railways (passenger trains) in Italy is 0.26 €/train-km, also actualized to 2024.

Reducing urban congestion

One of the impacts related to the shift of traffic from private cars to the railway system is the reduction of urban congestion. It is connected to the typical externalities associated with the massive presence of private motor vehicles in the area, such as congestion, pollution, and space occupation.

The marginal cost of urban congestion is 0.27 €/vehicle.km (the average cost of urban and interurban trips in Italy), actualized to the year 2024. This value is based **[6]**.

Reduction of noise emissions

The reduction of noise emissions is a function of the variation in the distance traveled by each mode of transport. However, the negative impact of noise pollution is correlated with many factors, particularly the proximity and density of receptors relative to the source, as well as the time of day and the activities being carried out. Due to this, the analysis related to the reduction of noise emissions is limited to estimating the impact in monetary terms, without quantification.

Specifically, for calculating the marginal cost of noise emissions, a value of 0.015 €/vehicle.km has been assumed for car noise emissions, while the marginal cost of rail noise emissions is assumed to be 1.07 €/train-km. These values are derived from **[6]**, actualized to 2024.

Externalities

CO_2 Emissions reduction –has been considered by calculating the balance between the increase in the energy consumption and the saved energy consumption from the road (4,212,000 vehicle.km/year).

The increasing in the train energy consumption, which has been derived from **[D7.2]**, is coming from:

- The addition 710,400 train-km/year for with the Air levitation technology, about 221.5 kWh/train (Traction energy),
- The existing 3,552,000 train-km/year (Electric trains), about + 29.6 kWh/train (Traction energy),
- The levitation energy, about 241,200 kWh/year.

The CO_2 emission factor which has been applied in the calculation is 0.2, which consider the resources of the electricity production in Italy.

Air pollution reduction – has been considered by calculating both the contribution related to the on-site combustion of internal combustion engines and that related to non-exhaust emissions from the road vehicles. The non-exhaust contribution from road vehicles is associated with abrasion phenomena, including the combined wear of tires, brakes, and road surfaces.

Below, is a summary table of the environmental benefits previously discussed, with reference to the period 2035-2064.

Table 30: Air pollution reduction

EMISSIONS		From reduction of road transport [ton]	From increase in electric traction [ton]	Overall benefit [ton]
CLIMATE-ALTERING EMISSIONS	*CO_2eq*	13,330	- 23,044	-9,715
POLLUTING EMISSIONS	*PM 10*	2.87	-	2.87
	NOx	3.01	-	3.01
	NMVOC	5.36	-	5.36
	SO_2	0.04	-	0.04
	Pb	0.00	-	0.00

For the monetization of environmental benefits, the following unit marginal costs (actualized to 2024) have been applied to the tons of pollutant emissions reduction:

- 210,566 €/ton for PM2.5 (exhaust and non-exhaust) (average value for Italy).
- 20,632 €/ton for NOx (average value for Italy).
- 1,121 €/ton for NMVOC (in Italy).
- 12,940 €/ton for SO_2 (in Italy).

These values are derived from the study **[6]**.

Regarding the CO_2eq cost and in line with the EC's technical guidance, a shadow cost for the value of CO_2eq (actualized to 2024) has been used, recently established by the EIB as the best estimate of the cost of achieving the temperature target of the Paris Agreement. The value is 151 €/tCO_2eq.

The following table shows a summary of the environmental benefits previously discussed.

Table 31: Direct Benefits and Externalities for Hybrid MDS based on air levitation

Hybrid MDS based on air levitation	Benefits and cost savings [€]
Travel Time Saving	122,620,000.00
Vehicle Operation Cost Saving	59,110,000.00
Externalities	16,550,000.00
Sum of Benefits and Externalities cost savings	198,280,000.00

7.2.1.8 Overview of CBA Results

In the previous sections, a breakdown of the different financial cost voices, both for investment and for operations & maintenance, has been given, together with the expected direct benefits & externalities.

Table 32: Overview of costs and benefits for the Hybrid MDS based on air levitation use case

Hybrid MDS based on air levitation – Analysed Scenario		
Sum CAPEX	mio €	168.20
Sum OPEX	mio €/year	4.96
Sum Benefits & Externalities cost savings	mio €	198.28

After the conversion between financial and economic costs, the economic performance indicators of Section 6.2 have been calculated, showing the following results:

Table 33: Overview of CBA results for the Hybrid MDS based on air levitation use case

Use case	ENPV [mio€]	B/C	IRR
Hybrid MDS based on air levitation	-64.42	0.59	-1.11%

The analysed scenario yielded a B/C ratio of 0.59 due to the fact that, despite a potential demand increase from reduced headways, travel times remain unchanged, and energy consumption only decreased by 2%. The socio-economic benefits do not compensate for the high retrofit costs.

This highlights the need for further technological development and analysis before air-levitated systems can optimize capacity.

7.3 Hybrid MDS Based on Magnetic Levitation

The third use case focuses on evaluating the implementation of a hybrid MDS based on magnetic levitation along an Italian route. This project aims to evaluate the feasibility and performance of a hybrid MDS on regional lines by integrating magnetic levitation technology with traditional rail systems. The route spans approximately 600 km and connects key cities in Italy. By enhancing speed, travel time, and optimizing capacity, this proposal seeks to address growing transportation demand while offering an efficient, sustainable, and cost-effective alternative to enhancing existing railway lines or building new HSR lines. The use case was analysed under two scenarios **[D7.2]**:

- **Scenario A:** A "series" configuration of the hybrid MDS based on maglev is theorized for the analysis. The MDS will be propelled by Linear Synchronous Motors (LSM) installed in the middle of the track. Newly designed pods, accommodating up to 70 passengers and capable of reaching speeds of 220 km/h, will operate on the current railway without requiring modifications to the track alignment with U-shaped sliders providing levitation directly on the existing rails. The focus of this scenario is on minimal technological upgrades while utilizing the existing rail infrastructure. Thus, the use case only considers the elimination of 3 level crossing without further modification to the existing track alignment. To enhance passenger comfort at higher speeds, the pods will feature a tilting angle of 6° through a mechanism using magnetic forces that compensates for the track's cant in curves. The series" configuration will allow the MDS to integrate seamlessly with the existing infrastructure.

- **Scenario B:** A "parallel" configuration of the hybrid MDS based on maglev is theorized for the analysis. This configuration foresees propulsion through a LSM as well but introduces levitation beams that run parallel to the track on both sides, and that will provide both guidance and levitations to newly designed pods with sliders that will adapt to the levitation beams. The pods, as in Scenario A, will accommodate up to 70 passengers and will be capable of reaching speeds of 220 km/h. The introduction of levitation beams will offer the advantage of different possible cants for regular trains with the existing built-in cant of the standard rails, and MDS pods with higher speeds with an additional built-in cant in the levitation beams. Therefore, the possible cant for levitating MDS pods can theoretically be increased as high as needed and can be realized technologically. Additionally, a very light tilting of the vehicle of a 1° angle will also add to the MDS pods for additional cant. The use case also foresees a modification of the existing track alignment with the elimination of 3 level crossings and the modification of 18 curves to increase the radii and allow for higher speeds.

7.3.1 Common analysis performed for Scenario A and Scenario B

In this use case, certain analyses supporting the calculation of the CBA were conducted only once to streamline the process. Simulations were run for both scenarios, with the results presented together in the same section, highlighting different configurations for each scenario. As the travel time results are very similar — Scenario B being only a few minutes shorter — the capacity analysis, transport study, and operational model were performed once and are assumed to apply equally to both scenarios. The induced demand and travel time savings benefits are considered the same for both scenarios. However, the costs related to both CAPEX and OPEX differ and are presented separately.

7.3.1.1 Running Simulation

This chapter summarizes the results of the simulations included in chapter 9.3.1 of **[D7.2]**.

This scenario could benefit from the introduction of hybrid MDS based on magnetic levitation, where a group of pods is used in a virtual coupling configuration. In this way, this case study aimed to achieve an increase in the capacity of the traffic line by significantly reducing the travel time while maintaining a similar energy consumption to that of the current conventional trains operating on this line.

The reduction in travel time was achieved by the increase in speed that comes from the additional cant in curves, obtained by the tilting of the new vehicle which is made possible by magnetic levitation technology in the series configuration, and through physical modification of the cant for the parallel configuration. The analysis performed to obtain the feasibility to increase speed in curves is reported in section 9.3.1 of **[D7.2]**.

Maintaining similar energy consumption by increasing the speed of travel was achieved by optimising the aerodynamic drag of the capsules, which was improved thanks to virtual coupling, which allows the pods to ride closer together, and the slipstream effect and airflow between the pods results in a reduction of the aerodynamic drag of the pods, which ultimately translates into a reduction of energy consumption.

To assess these scenarios, two possible MDS vehicle configurations have been simulated, with respect to the basic configurations of a conventional rail vehicle which is currently running on the line under study (ETR 421).

In the first configuration, maximum acceleration of 0.75 m/s^2. This acceleration leads to a maximum tractive effort of 35 kN. This option has been limited to 1,500 kW of power. In order to be able to implement acceptable virtual coupling conditions, a maximum braking deceleration of 1.2 m/s^2 was set, leading to a maximum braking effort of 52.32 kN. This maximum deceleration is also justified as a way of establishing a braking capacity similar to that originally proposed (of 1.5 m/s^2) but within the usual maximum deceleration margins for conventional trains.

In the second configuration, the maximum acceleration is1.5 m/s^2. This acceleration leads to a maximum tractive effort of 71 kN. This option has been limited to 2,263 kW power. The maximum braking deceleration is 1.5 m/s^2, which leads to a maximum braking effort of 71 kN.

Two infrastructure configurations were considered. Scenario A, for the existing infrastructure, and Scenario B at 220 km/h with optimized infrastructure and higher cant deficiency obtained by infrastructural modifications with the levitation beams.

The simulation was conducted for the approximately600 km line with 16 stops, in order to include acceleration/deceleration phases. The results of the simulation for an ETR 421 train indicate that existing trains take longer to complete the journey compared to MDS pods analysed in different coupling configurations. The MDS pods reduced the total travel time from almost 6 hours with the ETR to times ranging between 3.96 and 4.07 hours for Scenario B and between 4.02 and 4.13 hours for scenario A, depending on the pod configuration, achieving an average travel time reduction of approximately 25% for the entire line (Between 17% and 48% for different Origin-Destination relations).

This simulation did not account for congestion restrictions; therefore, a further analysis was performed to obtain more realistic benefits related to travel time reduction. As a first step, all the sections composing this historical line have been identified. At this stage, only the even direction was considered, and it was assumed that traffic conditions are the same in the opposite direction.

In order to assess the interaction between trainsets, the average number of trains occupying each section was estimated. This value was calculated taking into account passenger traffic on the line under analysis, from 3 p.m. to 7 p.m. It was assumed that these trains are evenly distributed in a typical hour; consequently, it was possible to obtain the headway (in minutes) as the ratio between 60 and the average number of trains occupying a specific section.

The second hypothesis introduced in order to estimate the maximum time saving involves the impossibility of overtaking. Therefore, it will be equal to the average headway minus a minimum distance that guarantees traffic safety (multiplied by two, since this must be guaranteed both at the rear and at the front of the train). This value depends on the type of signalling installed on the line and, in this specific use case, this may vary in a range between 5 and 4 minutes depending on the section of line considered.

By subtracting the maximum time saving to the actual travel time, the calculation of the minimum travel time on a section was estimated.

The time required for a pod to travel a single route is known from simulations carried out in previous deliverables **[D7.2]**. The latter was increased by 5%, as is usually done when constructing the timetable.

In order to calculate the potential time savings, it is necessary to compare similar travel times and the maximum time savings due to the interaction between the convoys. Since both are lower limits beyond which it is not possible to descend (either for dynamic reasons, or due to traffic safety issues), the assumed travel time is equal to the maximum of the two values listed above.

In this way, it was possible to estimate the time saving considering the other trains that run along the line being analysed. For example, in the current state, an intercity service between the two termini takes about 7 hours to reach the destination. By introducing MDS technology and assuming the same nodes are served, the service would take about 4 hours and 40 minutes.

When comparing the energy consumption of the different configurations, the current conventional train consumes less energy than the pods with virtual coupling, without considering braking energy recovery technology. For these simulations, consumption increases between 10.5% and 14.8% for Scenario A and between 12.9% and 22.7% for Scenario B. However, when simulating the scenarios with braking energy recovery technology, all pod configurations for both scenarios result in lower energy consumption than the existing ETR 421 train, with results varying between 3.4% and 4.9% for Scenario A and between 0.8% and 2.4% for Scenario B. The great advantage of virtual coupling has no impact from the operational point of view. While in a conventional vehicle its length remains constant at all times of the operation, in a pod convoy the number of pods can be decided according to the demand needs in a given time slot, so that in low-demand considerations the convoy could be formed by one or two pods, reducing then the consumption to a quarter or a half. In this case, the new proposal is clearly more advantageous than the traditional fixed trainset solution.

On the other hand, to see the beneficial effect of virtual coupling on consumption reduction, a simulation has also been made for infrastructure configuration B with 0.75 m/s^2 for absolute braking (ERTMS L3), where the pods run at a greater distance from each other.

On the other hand, since the main factor influencing consumption is aerodynamic drag, better aerodynamic design will undoubtedly result in lower energy consumption.

Finally, when comparing ERTMS L3 with virtual coupling, it is also possible to estimate the improvement in energy consumption due to the use of virtual coupling (VC) instead of ERTMS L3, due to the aerodynamic optimization caused by the slipstream effect when the vehicles drive closer together. Table 34 and Table 35 summarize the results in terms of travel time and energy consumption:

Table 34: Travel time analysis

Simulation	Scenario	Travel time		
		Absolute value (h)	Reduction (h)	Reduction (%)
ETR 421	**Current line**	5.39	0.0	0.0
Pod 0,75 m/s^2	**A – V Coupling**	4.13	1.3	23.4
	B – V Coupling	4.07	1.3	24.5
	B – ERTMS L3	4.07	1.3	24.4
Pod 1,50 m/s^2	**A – V Coupling**	4.02	1.4	25.3
	B – V Coupling	3.96	1.4	26.5

Table 35: Energy consumption analysis

		Energy	Energy consumption (85%

Simulation	Scenario	consumption			recovery)		
		GJ	kWh	Variation (%)	GJ	kWh	Variation (%)
ETR 421	**Current line**	13.9	3,862,3	0.0	10.4	2,879.2	- 25,45
Pod 0,75 m/s²	**A – V Coupling**	15.4	4,268.4	10.5	13.2	3,673.0	- 4,90
	B – V Coupling	15.7	4,361.5	12.9	13.6	3,769.6	- 2,40
	B – ERTMS L3	17.1	4,739.2	22.7	13.8	3,825.6	- 0,95
Pod 1,50 m/s²	**A – V Coupling**	16.0	4,432.7	14.8	13.4	3,7309	- 3,40
	B – V Coupling	16.3	4,526.6	17.2	13.8	3,829.1	- 0,86

In this use case, and in order to compare conventional vehicle and pod configurations as similar as possible, pods with the same aerodynamic characteristics and with the same front end have been used, so there is no doubt that improving the aerodynamics of the pods will significantly reduce energy consumption. However, it is possible to obtain reductions for the pod convoy that would allow to achieve a consumption practically equal to that of the conventional vehicle currently in service, but with an increase in average speed and a consequent very significant decrease in travel time.

7.3.1.2 Capacity Analysis

The current scenario on the corridor features sections that are intensively used, and sections that are much less so. MDS pods/vehicles will use the lines promiscuously, necessitating their integration with existing traffic, which includes less than 1000 services in both directions. These services comprise Fast Regional (RV) trains, regional/metropolitan (REG) trains, Intercity (IC) trains, long-distance HS (ES*) trains, and freight (M) trains. Scheduling new overtaking manoeuvres, however, inevitably results in a slowdown of non-MDS trains, with a potential worsening of travel time compared to the current scenario. A specific analysis was conducted to estimate the effects of capacity and congestion in the technically feasible travel time obtained in the simulation (See section 7.3.1.1 for details).

An analysis of the different sections that compose the line has been done, wherein the traffic and utilisation of these segments depend on the differences in the speed between the type of services, the undergoing infrastructure upgrading, the type of signalling system installed, among others.

7.3.1.3 Transport Study

The analysis performed in **[D7.2]**, serves as an input for the demand forecasting analysis, which methodology is explained in this paragraph. Specifically, in **[D7.2]** the total number of trips between each Origin and Destination (O/D) at the current state was estimated. For the obtained displacement matrix, the modal share of railway was determined and a specific matrix for railway trips was obtained. This analysis represents the first step to develop the number of journeys in a set year.

The next step was to define the year for the theorized start of operations of the MDS system. This evaluation is based on the estimated time horizon when the line will be retrofitted with MDS technologies and other aspects such as the estimated time for the equipment of the ERTMS level 2 on the complete line. Thus, the first year of operation of this line was estimated to be 2039.

Then, the demand for the first year of operations of the system was estimated. The increase of railway passenger demand is related to two different factors. The first is the growth of population in the analysed catchment areas **[D7.2]**, and the second is the modal shift from road to rail considering the performances of the new system.

The population growth factor was calculated to estimate the contribution of the population growth in the variation of the number of journeys. This factor is the ratio of the population difference between the line's first year of operation (2039) and the year to which the current demand estimate refers (2019), and the population in the latter year. Two datasets for each year were used obtained from open-data made available by ISTAT – Istituto Nazionale di Statistica. **[12]** However, population forecast data are not available for all municipalities. Therefore, as a first approximation, it has been assumed that the growth of the municipality would be equal to the growth of the entire province. Furthermore, for those municipalities for which no increase in population is expected, it was assumed that there would be no change in the number of trips. Growth population factors at first year of operation of the line have been identified, which ranges from 0% to 11%. By applying this factor and by symmetrising the demand between O/D pairs, the travel demand matrix was obtained.

As mentioned before, the modal shift represents the second factor assumed for the analysis that leads to an increase of the passenger demand on railway systems. Users' modal choice derives from numerous factors, such as the cost of travel, the access time to the system, the frequency of service, the in-vehicle travel time, etc. In order to calculate how much journeys shift from road to rail, the elasticity of the transport demand was studied. The latter makes it possible to estimate the modal shift value for each O/D, based on a series of variables that influence the generalised cost of transport. In this case, the modal shift was calculated from the reduction in travel time. In detail, the number of users switching from road to rail transport modes, is given by the factor for travel demand elasticity, defined as the responsiveness of the demand for transportation services to changes in factors such as price, income, travel time, or service quality. It is typically expressed as a percentage change in travel demand in response to a 1% change in one of these factors. For this use case, an elasticity factor related to the variation of travel time was used.

Considering the simulations already presented in Section 7.3.1.1**,** it was necessary to assess that using an unambiguous value for the elasticity of demand related to the reduction of travel time, could lead to an overestimation of the modal shift, due to different characteristics of the trips along the line being analysed. Thus, based on **[11]**, for values of time savings of less than 30%, the elasticity of demand coefficient was assumed to be 0.5, while in the opposite case a value of 0.3 is assumed. Following the presented analysis, the modal shift was estimated.

Moreover, an average value of 16% of users that choose regional services was obtained according to the demand data, updated to September 2023 and included in the third mobility report of the same year **[13]**. Considering that it is an average value, it does not take into account the distances connecting the different stations along the axis of the line being analysed.

Since the distance between origin and destination (O/D) is a fundamental variable influencing the user's choice between high-speed rail (HSR) and regional services, the percentage was recalculated based on the distances between HSR nodes. For the O/D pair with the longest distance, the original 16% value was used to define the users of regional railway services. An approximation was then made based on the distance, reaching a maximum value of 25% for the O/D pair with the shortest distance. The share for users of regional railway services for all the O/D pairs in between was calculated proportionally. The percentage of users choosing regional services over HSR services ranges from 17 to 25% over the different O/D pairs.

Finally, applying the different percentages, the travel demand matrix expected at the project status was calculated.

7.3.1.4 Operational Model

To define the future operation model, an analysis was performed regarding the services that currently use the railway corridor being studied, in order to build a base for the development of the new operational model and, more specifically, to identify how many and what type of services could be replaced with pods using MDS technology.

The steps composing this first analysis are summarized as follows:

- Identification of services provided,
- Identification of the O/Ds involved,
- Classification of the type of services,
- Collection of the main characteristics of the service (travel time, capacity offered, etc.).

Using RFI's traffic management system, it has been possible to extract all the services that currently use this line, both for the entire length of the line and partially.

For each of the existing services, the main information has been collected, such as: origin, destination, type of service (Regional, Intercity, etc), travel time and intermediate stops. Currently, considering an average weekday, more than 400 trains per direction run along the line.

To assess which services could be provided with MDS technology in the future scenario, a set of criteria were chosen depending on the O/D and the type of service. If both origin and destination of a service are located along the line under analysis, then the latter can potentially be transformed into a MDS service in the future, provided that the MDS journey is better and/or faster. A further step is the analysis of the type of service. All services that fall under the previous condition and are configured as regional or fast regional services have been theorized as MDS services in the future operation model.

For hybrid solutions, where either the origin or destination of the service is located within the routes under analysis, two variables were taken into account: the distance of the station not included in the line and the type of service. If the distance is under 20 km and the type of service is regional or fast regional, the service will be theorized in the future model to be provided partially with MDS pods for the section included in the line, while the remaining, assuming a transhipment, will be provided with traditional trains. For the sake of simplicity, and in order not to introduce new transport models that would need additional modifications in stations, services with origin and/or destination not present along the line that run in higher lengths of tracks that will not be retrofitted with MDS were excluded, and the feasibility to convert them in partially MDS services can be evaluated in further studies.

Considering these assumptions, a total of over 150 services per day, corresponding to approximately 28,000 train-km, are presumed to be replaced by MDS pods in the project scenarios. Thus, a calculation was made to estimate the number of pods that could accommodate the existing and future demand. The first step was to estimate a load factor for the existing services. This load factor was calculated using two different sources. The first one was from the Union Internationale des Chemins de Fer (UIC), which presents yearly railway statistics for European countries. It estimates for regional trains in Italy an average of 150 passengers per train in 2022 **[17]**. Assuming that a typical train used for regional services (ETR 421 with four coaches) has 466 seats, a load factor of 32% was estimated. The second source was from the Italian Autorità di Regolazione dei Trasporti (ART), which presents yearly statistics related to railway demand and supply **[18]**. For 2022, it estimated a total of 46.2 billion passenger/km and 338.4 million train/km, allowing to infer an average of 137 passengers per train. Using the same value for an estimated number of seats per train, a load factor of 29% was obtained. It was then decided to assume a load factor of 35% for the analysis, taking into consideration that the line is on an important corridor of the Italian network.

To calculate the number of pod-km that would accommodate the existing and future demand, an increase in the load factor was assumed for the future scenario. This is because services with better vehicle performance tend to have higher load factors. For instance, according to **[17]**, a railway undertaking with only HSR services in Italy sees an average of 350 passengers per train. Considering the average capacity of 472 seats per train, an estimated ridership of more than 70% is obtained, which is much higher than the one calculated for regional trains.

Based on this and considering that the future estimated demand is 11% higher than the existing demand and represents about 7% of the capacity in terms of offered seats, no additional services were theorized. An increase in the load factor for the future scenario for services provided with MDS pods was assumed at 40% (See Section 7.3.1.3 for details),

Overall, it is estimated that the total number of pod-km provided on an average weekday (considering both directions) will amount to approximately 275.000 pod-km per day. Additionally, 210 train-km per day will be required to cover the sections of the services outside the line being analysed. These sections will not be retrofitted with MDS and are expected to continue operations with traditional trains, with transhipments to MDS services in the sections along this line

7.3.2 Scenario A

7.3.1.1 CAPEX

For this scenario, the implementation of a linear motor is required along the whole line and also in the specific MDS tracks at the stations, because the new operated MDS vehicles will not have an onboard propulsion system for reaching the travel speed. The scenario A configuration

(Hybrid MDS based on maglev with "series" configuration) will use the existing rails for the levitation function, therefore additional levitation beams are not needed. With a line length of approximately 600 km of double track, considering internal tracks within stations, and 16 stations along the line, the needed length of linear motor would be approximately 1,150 km all together.

The hardware costs per kilometre for the linear motor in the considered configuration for this study is estimated by Nevomo experts to a target price in line with the market of 3.25 mio €/km for a single track, including the active stator with all fixtures and cablings, power electronics like inverters, transformers and segment switches, and the control system. Additional planning and deployment costs of 0.25 mio €/km are also part of the installation of the linear motor.

This leads to total investment costs of 1,127.3 km * (3.25 + € 0.25 mio) = **€ 3,945.55 mio** for the infrastructure part.

Some general measurements are needed before the MDS components can be installed. Infrastructure must fit to the requirements of the used system (e.g. track distance, stability for dynamic loads, track quality). These efforts are not only specific for the new traffic system and cannot be estimated for this study in detail, as the condition of the route is unknown. But for the needed studies and inspections additional costs of **€ 100,000** are integrated in this cost calculation.

For the bridges, there will be no construction changes planned, as the weight and axle load of the new pod will be lower than for today's rail cars. It has to be checked if dynamic loads, because of higher velocities, would reach limits. In those cases, speed will be limited to the maximum allowed limit given by maximum allowed dynamic load of the bridge. This is very specific and needs a detailed study on each bridge. For this study, it is assumed that the stability of the existing bridges is strong enough. For the tunnels, there are no restrictions or major changes anticipated.

For single-level crossings – in cases where the vehicle will operate at increased velocities over 160 km/h – the single-level crossings should be rebuilt into multi-level ones due to safety issues. For low-speed sections (under 160 km/h and service operations), it can be allowed to leave them unchanged.

On the line being analysed, there are currently five level crossings. One of the crossings is at the station area, where speed will not be increased

The line speed of the other four level crossings will be increased over 160 km/h up to 220 km/h. Therefore, those four crossings must be closed or reconstructed to multi-level crossings. For this study, it is assumed that one crossing can be closed, because there is a multi-level crossing very nearby. The remaining three level crossings must be reconstructed. The estimated costs are set to € 5.0 mio for each level crossing, so that the total costs are calculated to be 3 * € 5.0 mio = **€ 15.0 mio**.

Changes in vehicle command and control system, signalling system and Telecommunication system are estimated by CCS tech developers at 50.000 €/km for an estimated track length of 571 km * 2, the CCS costs are estimated to be of **€ 57.2 mio.**

On the vehicle, side both scenarios involve the use of newly designed lightweight pods capable of carrying 70 people and achieving speeds of up to 220 km/h. For the cost estimation of such a new pod, the comparison to a modern high-speed train was used. In modern trains, the overall costs can be separated in four main component groups: 40 % of the costs are allocated to the on-board engine and propulsion system, 15 % to the bogies and drive gear, 20% to the interior and 25 % to the rest of the vehicle (structure, general technical equipment like air-condition). With this separation by components, and the costs per seat, it is possible to estimate the cost of the new pod.

For the new pod, the costs for interior, structure and general technical equipment are taken over unchanged from the ICE 3 neo, adjusting the value per offered seat, assuming that this will be the comparable standard also for the new pod designs. Since the pods will not have an engine or an onboard propulsion system, these costs could be excluded. The bogies equipped with magnets for propulsion and levitation system will be more expensive than standard bogies. Based on experiences with the prototype at the Nevomo test facility and the costs of regular bogies of passenger coaches, the costs are estimated at € 1.5 mio per set of bogies for one pod **[19].** The following table shows the complete list of costs, that result in a total cost of € 4.01 mio per pod. The costs per seat is estimated to be significantly below the costs of a classic high-speed train.

Table 36: Rolling Stock costs

	ICE3neo			MDS pods	
	439			70	
Component	**Costs**				
	Per train		**per seat**	**per seat**	**Per pod**
Total Rolling Stock costs	**100%**	**€ 35,000,000**	**€ 72,727**	**€ 57.306**	**€ 4,011,390**
Bogies	15%	€ 5,250,000	€ 11,959	N.A.	N.A.

On-board engine / Propulsion	40%	€ 14,000,000	€ 31,891	N.A.	N.A.
Rest of the vehicle (structure, general tech, like AC)	25%	€ 8,750,000	€ 19,932	€ 19,932	€ 1,395,216
Interior (seats & such)	20%	€ 7,000,000	€ 15,945	€ 15,945	€ 1,116,173
Two MDS Lev bogies	N.A.	N.A.	N.A.	€ 21,429	€ 1,500,000

The calculation of the number of pods required to carry out the defined services on the line takes into account the services to accommodate the existing and the new demand.

An in-depth analysis, aimed to define how many and what kind of services are currently provided by the Italian railway undertakings, has been performed. For each of the identified services, considering the current timetable, the type of train and its offered capacity (calculated as the sum of the number of seats and the standing places) was assigned. Furthermore, it was assumed that all regional services, whose origin and destination would be between the two termini, would be operated with MDS services (See Section 7.3.1.4 for details). In order to quantify the number of pods that are needed to provide the services, firstly the travel time of each service was estimated, considering the actual number of stops – assuming that for each station 1 minutes is necessary to complete all the operations – and the time required to travel each route, taking into account the current passenger traffic on the line.

To evaluate the number of services that a pod could provide during a single day, the operating hours of the service have been divided by the total travel time. Finally, multiplying the latter by the number of pods that guarantee the actual passenger demand, the number of pods for day that is requested to provide the services has been calculated.

The number of pods necessary both to serve the existing and future demand, and to switch the actual services to Maglev services is 144. This leads to total investment costs of 170 pods * € 4.01 mio = **€ 681.9 mio** for the rolling stock.

Finally, in order to consider unforeseen costs in the analysis, a basic surcharge of 3% is applied to all previous cost blocks. These unexpected costs thus amount to a total of **€ 140.99 mio** in additional costs to be recognised.

Table 37: Investment costs for Hybrid MDS based on magnetic levitation – Scenario A

Hybrid MDS based on magnetic levitation – Scenario A	CAPEX [€]
Infrastructure (MDS components)	3,945,550,000.00
Infrastructure (track alignment, consisting of level crossings elimination)	15,000,000.00
Infrastructure (signalling)	57,200,000.00
Infrastructure studies	100,000.00
Unexpected costs	140,993,584.00
Rolling stock	681,900,000.00
Sum CAPEX	4,840,800,000.00

Summarized, as presented in Table 37, for this use case the overall CAPEX is about **€ 4,840.80 mio**.

7.3.1.2 OPEX

The same methodology applied in previous use cases to assess infrastructure maintenance costs has been used here. A rate of 2.5% of the infrastructure investment costs has been considered, resulting in additional annual costs of 0.025 * € 3,664 mio = **91.6 mio €/year** for infrastructure maintenance.

Similarly, the maintenance and depreciation costs for rolling stock have been estimated to be 2.5% of the rolling stock investment costs, considering the necessity to maintain the rolling stocks in optimal conditions, resulting in a total cost of 0.025 * € 681.9 mio = **17.05 mio €/year.**

For the maintenance, depreciation and operational costs of traditional trains used for regional services, a value of 12.44 €/train-km was used, based on the values of operational costs for trains ranging from 161 to 480 offered seats, obtained from the service contract of Trenitalia, for the provision of regional services in the proximity of the analysed line **[20]**. This value was divided into 5 cost items, based in percentages obtained in previous internal studies carried out by RFI (Personnel on Board: 36%, Rolling Stock Depreciation: 18%, Maintenance: 26%, Inspection and Cleaning: 11%, and Energy: 9%).

These approximate values were used to obtain the additional operational costs for MDS pods. The values were divided by the number of seats for a train traditionally used for regional services (ETR 421 with four coaches), in order to estimate a cost per seat. The cost was then multiplied by the 70 posts expected in the newly designed pods for MDS services. For the MDS scenario, the Personnel on Board cost was excluded considering the expected Grade of Automation (GoA) of the pods. Additionally, the Maintenance and Rolling Stock Depreciation costs were also excluded, considering the abovementioned assumption that they account for a yearly cost of 2,5% of the investment costs for the rolling stock. Finally, the energy cost per km was incremented by 15%, considering the simulations results that suggest the energy consumption will increase between 10% and 17% for the MDS scenario (See Section 7.3.1.1 for details). Thus, a value of 0.41 €/pod-km was obtained for the operational costs related to Energy and Inspection and Cleaning of MDS pods. Table 38 presents in detail the estimated costs for the operation of traditional trains vs MDS pods. This analysis resulted in a total cost of 0.41 €/pod-km * 82,206,495.60 pod-km/year = **33.45 mio €/year**.

Table 38: Vehicle operational costs for traditional vs MDS services

<table>
<tr><th>Cost Item</th><th>Regional Train</th><th>Impact</th><th>Pod</th><th>Notes</th></tr>
<tr><td>Personnel on Board</td><td>4.44 €/train-km</td><td>36%</td><td>0.00 €/pod-km</td><td>Excluded for the operational costs of MDS pods due to GoA</td></tr>
<tr><td>Rolling Stock Depreciation</td><td>2.22 €/train-km</td><td>18%</td><td rowspan="2">2.5% of Investment cost</td><td rowspan="2">A different assumption was used for depreciation and maintenance costs, in line with the other use cases</td></tr>
<tr><td>Maintenance</td><td>3.25 €/train-km</td><td>26%</td></tr>
<tr><td>Inspection and Cleaning</td><td>1.39 €/train-km</td><td>11%</td><td>0.21 €/pod-km</td><td>Same cost per seat for MDS pod and traditional train</td></tr>
</table>

Energy	1.15 €/train-km	9%	0.20 €/pod-km	15% increase in energy consumption per seat for the MDS pod compared to traditional trains
Total	12.44 €/train-km	100%	0.41 €/pod-km	Only energy and inspection and cleaning items included in the pod operational costs
Seats Offered	466	-	70	Based on a ETR 421 model with four coaches

An additional cost related to the operation of remaining train-km for services that have their origin or destination outside of the line being analysed and will have to operate with traditional trains on the parts of the line that will not be retrofitted with MDS was included in the calculations. These services are estimated to require 62,856.9 train-km/year of traditional train operations. The cost is then estimated to be 12.44 €/train-km * 62,856.9 train-km/year = 0.78 mio €/year.

Finally, an estimation of the operational costs for the current scenario was performed and subtracted from the operational cost of the future scenario, as it is considered that the current operational costs would be reduced and replaced by the operational costs of the pods, thus providing yearly savings in the OPEX. The estimated operational costs saved in the future scenario were obtained using the train-km estimated for the current scenario and the operational costs for regional trains. The cost is then estimated to be 8,298,091.80 train-km/year * 12.44 €/train-km = 103.20 mio €/year.

Table 39 presents a summary of the OPEX.

Table 39: Operational and Maintenance costs for Hybrid MDS based on magnetic levitation – Scenario A

Hybrid MDS based on magnetic levitation – Scenario A	OPEX [€/year]
Rolling Stock Operation & Maintenance	-51,920,674.55
Infrastructure Maintenance MDS	91,593,125.0

Sum OPEX	39,672,450.45

7.3.1.3 Direct Benefits & Externalities

Travel Time savings

The main direct benefits obtained for the use case are related to travel time savings. Two different types of travel time savings were estimated, one referred to as Railway to MDS, that estimated the difference between the travel time with current services along the line and the estimated travel time with MDS services in the project scenario, and one referred to as Road to MDS, that estimated the difference between the travel time through road transportation and the estimated travel time with MDS services.

Railway to MDS travel time saving – it represents the input to estimate both the demand attracted by the system at the expense of the road through an elasticity factor (See Section 7.3.1.3 for details) and the direct benefits for existing railway users. The travel time was estimated for each of the services that would be replaced by MDS, using the simulations performed in [D7.2] and accounting for traffic constraints, as presented in Section 7.3.1.1.

Road to MDS travel time saving – the difference between the current travel time by car between different O/D pairs, and the estimated time to connect the same O/D pairs with MDS services was estimated. This travel time saving values were used to estimate the direct benefits for new users, through the calculated induced demand (See Section 7.3.1.3 for details)

The VOT for users in Italy has been estimated at 21 €/hour, as presented in Section. 6.4.4.

Reducing operating costs of private vehicles

Private vehicle operating costs (VOC) are defined as the costs incurred by owners of road vehicles for their use, considering fuel consumption, lubricant consumption, repair and maintenance costs, insurance, general expenses.

In relation to the use case, the savings generated by the reduction of VOC are a function of the passengers who would switch from the private road mode.

The reduction of private vehicle operating costs was determined by multiplying the operating cost of private vehicles by the km*year saved (subtracted from private mobility), which has been estimated starting from the average km saved per user and the annual demand passed to the railway from private mobility.

The VOC that has been considered is 0.403 €/vehicle.km. For more details, see Section 6.4.4.

Reduction of accidents

One of the objectives of the intervention is to increase the share of rail transport, with a view to enhancing public transportation. One of the estimated impacts is the reduction of accidents between vehicles and between vehicles and road users, such as pedestrians. Estimating the probability of accidents is extremely complex, and current models are typically focused on very small sections of the road network, usually intersections.

This effect can be considered related to the reduction in demand for private mobility. The analysis concerning the reduction of road accidents is limited to estimating the impact in monetary terms, without quantification.

The marginal cost of accidents for cars is 0.02 €/vehicle.km. This value is based on the data in **[6]** and is determined as the average marginal cost of accidents for cars in Italy on both urban and non-urban roads, equal to 0.02 €/vehicle.km, actualized to 2024. The marginal cost of accidents for railways (passenger trains) in Italy is 0.52 €/train-km, also actualized to 2024.

Reducing urban congestion

One of the impacts related to the shift of traffic from private cars to the railway system is the reduction of urban congestion. It is connected to the typical externalities associated with the massive presence of private motor vehicles in the area, such as congestion and space occupation.

The marginal cost of urban congestion is 0.27 €/vehicle.km (the average cost of urban and interurban trips in Italy), actualized to the year 2024. This value is based on data in **[6]**.

Reduction of noise emissions

The reduction of noise emissions is a function of the variation in the distance travelled by each mode of transport. However, the negative impact of noise pollution is correlated with many factors, particularly the proximity and density of receptors relative to the source, as well as the time of day and the activities being carried out. Due to this, the analysis related to the reduction of noise emissions is limited to estimating the impact in monetary terms, without quantification.

Specifically, for calculating the marginal cost of noise emissions, a value of 0.02 €/vehicle.km has been assumed for car noise emissions, while the marginal cost of rail noise emissions is assumed to be 1.07 €/train-km. These values are derived from **[6]**, actualized to 2024.

Externalities

CO_2 Emissions reduction – has been considered by calculating the balance between the increase in the energy consumption by 49,6 kWh/train, based on the analysis done in **[D7.2]** considering the Booster Option 1, and the saved energy consumption from the road (105,736,935 vehicle.km/year).

The CO_2 emission factor which has been applied in the calculation is 0.2, which consider the resources of the electricity production in Italy.

Air pollution reduction – has been considered by calculating both the contribution related to the on-site combustion of internal combustion engines and that related to non-exhaust emissions from the road vehicles. The non-exhaust contribution from road vehicles is associated with abrasion phenomena, including the combined wear of tires, brakes, and road surfaces.

Below, is a summary table of the environmental benefits previously discussed, with reference to the period 2035-2064.

Table 40: Air pollution reduction

EMISSIONS		From reduction of road transport [ton]	From increase in electric traction [ton]	Overall benefit [ton]
CLIMATE-ALTERING EMISSIONS	*CO_2eq*	354,967	70,358.96	284,607.81
POLLUTING EMISSIONS	*PM 10*	80.92	0.12	80.80
	NOx	80.23	-	80.23
	NMVOC	141.31	-	141.31
	SO_2	0.94	-	0.94
	Pb	0.03	-	0.03

For the monetization of environmental benefits, the following unit marginal costs (actualized to 2024) have been applied to the tons of pollutant emissions reduction:

- 210,566 €/ton for PM2.5 (exhaust and non-exhaust) (average value for Italy),
- 20,632 €/ton for NOx (average value for Italy),
- 1,121 €/ton for NMVOC (in Italy),
- 12,940 €/ton for SO_2 (in Italy).

These values are derived from **[6]**.

Regarding the CO_2eq cost, and in line with the EC's technical guidance, a shadow cost for the value of CO_2eq (actualized to 2024) has been used, recently established by the EIB as the best estimate of the cost of achieving the temperature target of the Paris Agreement. The value is 151 €/tCO_2eq.

In the following table, a summary of the different expected direct benefits and externalities cost savings is reported, which have been used to perform the Cost-Benefits Analysis.

Table 41: Benefits and Externalities for Hybrid MDS based on magnetic levitation

Hybrid MDS based on magnetic levitation – Scenario B	Benefits and cost savings [€]
Travel Time Saving	7,019,600,000.00
Vehicle Operation Cost Saving	1,482,300,000.00
Externalities cost savings	1,553,563,839.49
Sum of Benefits and Externalities cost savings	10,055,383,338.48

7.3.1.4 Overview of CBA Results

For the Scenario A, the financial costs and expected benefits and externalities are summarized in the table below.

Table 42: Overview of costs and benefits for the Hybrid MDS based on magnetic levitation use case – Scenario A

Hybrid MDS based on magnetic levitation – Scenario A		
Sum CAPEX	mio €	4,840.81
Sum OPEX	mio €/year	39.67
Sum Benefits & Externalities cost savings	mio €	10,055.38

The CBA is performed by calculating the economic performance indicators discussed in Section 6.2, after the conversion between financial and economic costs. The results of the analysis are expressed in the following.

Table 43: Overview of CBA results for the Hybrid MDS based on magnetic levitation use case – Scenario A

Use case	ENPV [mio €]	B/C	IRR
Hybrid MDS based on magnetic levitation – Scenario A	1,124.11	1.31	4.67%

These results show that, despite an increase of energy consumption, due to the significant travel time reduction, increased rail modal share, and reduced externality, the overall benefits exceed the overall costs for a positive result. This means that the assumed application, thanks to the higher speed reachable in curves, could enhance the regional line performance and its attractiveness.

7.3.3 Scenario B

7.3.2.1 CAPEX

For this scenario, the implementation of a linear motor is required along the whole line and also in the specific MDS tracks at the stations, because the new operated MDS vehicles will not have an on-board propulsion system for reaching the travel speed. The scenario B configuration (Hybrid MDS based on magnetic levitation in parallel configuration) will use the levitation beams for the levitation function, therefore existing rails will not be used for levitation. With a line length of approximately 600 km of double track, considering internal tracks within stations, and 16 stations along the line, the needed length of linear motor would be approximately 1,150 km all together. The needed length of levitation beams will be also approximately 1,150 km.

The hardware costs per kilometre for the linear motor in the considered configuration for this study is estimated to 3.25 mio €/km for a single track, including the active stator with all fixtures and cablings, power electronics like inverters, transformers and segment switches, and the control system. Additional planning and deployment costs of 0.25 mio €/km are also part of the installation of the linear motor.

The hardware costs per kilometre for the levitation system in the decided configuration for this study is estimated by Nevomo experts to a target price in line with the market of 2.2 mio €/km for a single track, including the passive aluminium rails with all fixtures. Additional planning and deployment costs of 0.2 mio €/km are also part of the installation of the levitation system.

This leads to total investment costs for the linear motor and parallel levitation beams of 1,127.3 km * (3.25 + € 0.25 mio) + 1,118.6 km * (2.2 + € 0.2 mio) = **€ 6,687.5 mio** for the infrastructure part.

For the second scenario, it was checked if smaller changes at the track alignment can lead to better speed profile. It is the goal to avoid critical speed drops and the needed braking and reaccelerating that comes with it. Therefore, the allowed speeds were optimized. 13 relevant curves have been identified, where changing the track alignment could bring benefits for a better speed profile. Changing the curve radius on an existing line is usually very critical and the possibilities have to be checked in detail. In this study, it is not possible to do a complete infrastructure planning. So, it is only be checked if it might be anyhow feasible.

The results in the following table show differences in the possibilities of adapting the curves. On five of the curves (green) it might be feasible to change the length of transition curves and reach higher cants within the curves. For eight other curves (yellow), it might also be interesting to check the specific surroundings, as the changes might not be too big, so it could be feasible to change the alignment.

More critical are the other five curves (red) and especially the last one in the table (dark red). Theses curve needs to be changed from ca. 600 m radius to ca. 1.100 radius, which might hardly be possible. Nevertheless, it can be checked, what could be changed by reasonable costs, so that at least parts of the required speed increase of 65 km/h can be realized in this curve.

For this feasibility study, these detailed checks cannot be done, and it is assumed that the changes at the alignment are technically feasible for adapting to each type of curve, with costs ranging from €0.25 to €5 mio.

Together with the same costs for the elimination of level crossings as in the scenario A (€ 15.0 mio), this leads to total costs of **€ 43.25 mio** for the infrastructure alignment.

Some additional general measurements are needed before the MDS components can be installed as in scenario A. Infrastructure must fit to the requirements of the used system (e.g. track distance, stability for dynamic loads, track quality). These efforts are not only specific for the new traffic system and cannot be estimated for this study in detail, as the condition of the route is unknown. But for the needed studies and inspections additional costs of **€ 100,000** are integrated in this cost calculation.

Cost of upgrading Command and Control System, Signalling System and Telecommunication System are same as in scenario A and lead to costs of **€ 57.2 mio**.

On the vehicle side, both scenarios involve the use of newly designed lightweight pods capable of carrying 70 people and achieving speeds of up to 220 km/h. The costs for one pod and the needed number of pods are the same as in scenario A and lead to total investment costs of 170 pods * € 4.01 mio = **€ 681.90 mio** for the vehicle part.

Especially in new technology projects, unforeseen costs can occur. In order to include this factor in this analysis, a basic surcharge of 3% is applied to all previous cost blocks. These unexpected costs amount to a total of **€ 221.50 mio**.

Table 44: Investment costs for Hybrid MDS based on magnetic levitation – Scenario B

Hybrid MDS based on magnetic levitation – Scenario B	CAPEX [€]
Infrastructure (MDS components)	6,630,190,000.00
Infrastructure (track alignment including level crossings elimination and curve modifications)	43,250,000.00
Infrastructure (signalling)	57,200,000.00
Infrastructure studies	100,000.00
Unexpected costs	221,500,000.00
Rolling stock	681,900,000.00
Sum CAPEX	7,634,200,000.00

Summarized for this use case, the overall CAPEX is about **€ 7,634.20 mio**.

7.3.2.2 OPEX

As per Scenario A (7.3.1.2), the same methodology has been used here. A rate of 2.5% of the infrastructure investment costs has been considered, resulting in additional annual costs of 0.025 * € 6,124.6 mio = **153.12 mio €/year** for infrastructure maintenance.

Similarly, the maintenance and depreciation costs for rolling stock have been estimated to be

2.5% of the rolling stock investment costs, resulting in a total cost of 0.025 * € 681.9 mio = **17.05 mio €/year**, resulting in the same value calculated in Scenario A.

For the maintenance, depreciation and operational costs of traditional trains used for regional services, the same value of 12.44 €/train-km seen in the previous Scenario was used, based on the values of operational costs for trains ranging from 161 to 480 offered seats, obtained from **[20]**. A 5 cost items subdivision has been performed, considering the percentages obtained in internal RFI studies (Personnel on Board: 36%, Rolling Stock Depreciation: 18%, Maintenance: 26%, Inspection and Cleaning: 11%, and Energy: 9%), which approximate values have been used to obtain the additional operational costs for MDS pods.

The values were divided by the number of seats for a train traditionally used for regional services (ETR 421 with four coaches), in order to estimate a cost per seat. The cost was then multiplied by the 70 posts expected in the newly designed pods for MDS services. For the MDS scenario, the Personnel on Board cost was excluded considering the expected Grade of Automation (GoA) of the pods. Additionally, the Maintenance and Rolling Stock Depreciation costs were also excluded, considering the abovementioned assumption that the represent the 2,5% of the rolling stock CAPEX. Finally, the energy cost per km was incremented by 15%, assuming that the energy consumption will increase between 10% and 17% for the MDS scenario (See Section 7.3.1.1 for details). Finally, a value of 0.41 €/pod-km was obtained for the operational costs related to Energy and Inspection and Cleaning of MDS pods. Table 38 presents in detail the estimated costs for the operation of traditional trains vs MDS pods. This analysis resulted in a total cost of 0.41€/pod-km * 82,206,495.60 pod-km/year = **33.45 mio €/year**.

Table 45: Vehicle operational costs for traditional vs MDS services

Cost Item	Regional Train	Impact	Pod	Notes
Personnel on Board	4.44 €/train-km	36%	0.00 €/pod-km	Excluded for the operational costs of MDS pods due to GoA
Rolling Stock Depreciation	2.22 €/train-km	18%	2.5% of Investment cost	A different assumption was used for depreciation and maintenance costs, in line with the other use cases
Maintenance	3.25 €/train-km	26%		
Inspection	1.39 €/train-	11%	0.21 €/pod-	Same cost per seat for MDS

and Cleaning	km		km	pod and traditional train
Energy	1.15 €/train-km	9%	0.20 €/pod-km	15% increase in energy consumption per seat for the MDS pod compared to traditional trains
Total	12.44 €/train-km	100%	0.41 €/pod-km	Only energy and inspection and cleaning items included in the pod operational costs
Seats Offered	466	-	70	Based on a ETR 421 model with four coaches

An additional cost related to the operation of remaining train-km for services that have their origin or destination outside of the line being analysed and will have to operate with traditional trains on the parts of the line not retrofitted with MDS. These services are estimated to require approximately 210 train-km of traditional train operations. The cost is then estimated to be 12.44 €/train-km * 62,856.9 train-km/year = 0.78 mio €/year

Finally, an estimation of the operational costs for the current scenario was estimated and subtracted from the operational cost of the future scenario, as it is considered that the current operational costs would be reduced and replaced by the operational costs of the pods. The estimated operational costs saved in the future scenario were obtained using the train-km estimated for the current scenario and the operational costs for regional trains. The cost is then estimated to be 8,298,091.80 train-km/year * 12.44 €/train-km = 103.20 mio €/year.

Table 46 presents a summary of the OPEX considered in this analysis.

Table 46: Operational and Maintenance costs for Hybrid MDS based on magnetic levitation - Scenario B

Hybrid MDS based on magnetic levitation – Scenario B	OPEX [€/year]
Rolling Stock Operation & Maintenance	-51,920,674.55
Infrastructure Maintenance MDS	153,116,125.00 €

Sum OPEX	101,195,450.45

For more details, in section 7.3.1.2 the assumptions have been illustrated for vary elements.

7.3.2.3 Direct Benefits & Externalities

As Scenario A, the main direct benefits obtained for the use case are related to travel time savings. Two different types of travel time savings were estimated, one referred to as Railway to MDS, that estimated the difference between the travel time with current services along the line and the estimated travel time with MDS services in the project scenario, and one referred to as Road to MDS, that estimated the difference between the travel time through road transportation and the estimated travel time with MDS services.

Railway to MDS travel time saving – it represents the input to estimate both the demand attracted by the system at the expense of the road through an elasticity factor (See Section 7.3.1.3 for details) and the direct benefits for existing railway users. The travel time was estimated for each of the services that would be replaced by MDS, using the simulations performed in [D7.2] and accounting for traffic constraints, as presented in Section 7.3.1.1

Road to MDS travel time saving – the difference between the current travel time by car between different O/D pairs, and the estimated time to connect the same O/D pairs with MDS services was estimated. This travel time saving values were used to estimate the direct benefits for new users, through the calculated induced demand (See Section 7.3.1.3 for details)

The VOT for users in Italy has been estimated at 21 €/hour, as presented in Section. 6.4.4.

Reducing operating costs of private vehicles

Private vehicle operating costs (VOC) are defined as the costs incurred by owners of road vehicles for their use, considering fuel consumption, lubricant consumption, repair and maintenance costs, insurance, general expenses.

In relation to the use case, the savings generated by the reduction of VOC are a function of the passengers who would switch from the private road mode.

As Scenario A, the reduction of private vehicle operating costs was determined by multiplying the operating cost of private vehicles by the km*year saved (subtracted from private mobility), which has been estimated starting from the average km saved per user and the annual demand passed to the railway from private mobility.

The VOC that has been considered is 0.403 €/vehicle.km. For more details, see Section 6.4.4.

Externalities

<u>*CO_2 Emissions reduction*</u> – has been considered by calculating the balance between the increase in the energy consumption by 49,6 kWh/train, based on the analysis done in **[D7.2]** considering the Booster Option 1, and the saved energy consumption from the road (105,736,935 vehicle.km/year).

The CO_2 emission factor which has been applied in the calculation is 0.2, which consider the resources of the electricity production in Italy.

Air pollution reduction – has been considered by calculating both the contribution related to the on-site combustion of internal combustion engines and that related to non-exhaust emissions from the road vehicles. The non-exhaust contribution from road vehicles is associated with abrasion phenomena, including the combined wear of tires, brakes, and road surfaces.

As Scenario A, For the monetization of environmental benefits, the following unit marginal costs (actualized to 2024) have been applied to the tons of pollutant emissions reduction:

- 210,566 €/ton for PM2.5 (exhaust and non-exhaust) (average value for Italy),
- 20,632 €/ton for NOx (average value for Italy),
- 1,121 €/ton for NMVOC (in Italy),
- 12,940 €/ton for SO_2 (in Italy).

These values are derived from **[6]**.

Regarding the CO_2eq cost, and in line with the EC's technical guidance, a shadow cost for the value of CO_2eq (actualized to 2024) has been used, recently established by the EIB as the best estimate of the cost of achieving the temperature target of the Paris Agreement. The value is 151 €/tCO_2eq.

In the following table, a summary of the different expected direct benefits and externalities cost savings is reported, which have been used to perform the Cost-Benefits Analysis.

Table 47: Benefits and Externalities for Hybrid MDS based on magnetic levitation – Scenario B

Hybrid MDS based on magnetic levitation – Scenario B	Benefits and cost savings [€]

Travel Time Saving	7,019,600,000.00
Vehicle Operation Cost Saving	1,482,300,000.00
Externalities	1,553,563,839.49
Sum Benefits and Externalities cost savings	10,055,383,338.48

For more details, in section 7.3.1.3 the assumptions have been illustrated for each benefit and externalities that have been considered.

7.3.2.4 Overview of CBA Results

For this scenario, the following table summarize both the calculated financial costs (CAPEX and OPEX) and the expected Benefits and Externalities.

Table 48: Overview of costs and benefits for the Hybrid MDS based on magnetic levitation use case – Scenario B

Hybrid MDS based on magnetic levitation – Scenario B		
Sum CAPEX	mio €	7,634.21
Sum OPEX	mio €/year	101.20
Sum Benefits & Externalities cost savings	mio €	10,055.38

These costs have been converted into their economic values, using the conversion factors expressed in Section 6.4.3, in order to calculate the ENPV, the B/C ratio and the IRR to evaluate the economic performance of the scenario. In the following table, the obtained results are showed.

Table 49: Overview of CBA results for the Hybrid MDS based on magnetic levitation use case – Scenario B

Use case	ENPV [mio €]	B/C	IRR
Hybrid MDS based on magnetic levitation – Scenario B	-1,343.87	0.78	1.39%

The higher costs of the technology in this configuration, due to magnetic levitation and guidance, result in a B/C ratio of 0.70, are higher than the expected benefits – associated with the modification of curve radius in the track alignment – which result marginal when compared to the overall time savings obtained from the additional cant deficiency provided by the MDS technologies: the identified benefits for Scenario B are similar to Scenario A, but the increased CAPEX due to the additional components for maglev levitation leads to a negative B/C ratio.

The possible application of this technology to different contexts (e.g., shorter lines, more homogeneous in terms of service coverage and technical characteristics) could generate total benefits exceeding total costs.

8 Socio-Economic Cost-Benefit Analysis

8.1 Results

These tables summarize the economic performance indicators for different transport systems, considering the ENPV (Economic Net Present Value), B/C (Benefit-Cost ratio), and IRR (Internal Rate of Return) across the different analysed scenarios.

Table 50: Economic performance indicators results summary

Use case	Scenarios	ENPV [mio €]	B/C	IRR
Upgraded traditional railway MDS	A	9.33	1.04	3.31%
	B	-67.07	0.27	-12.06%
Hybrid MDS based on air levitation	A	-64.42	0.59	-1.11%
Hybrid MDS based on magnetic levitation	A	1,124.11	1.31	4.67%
	B	-1,343.87	0.78	1.39%

Essentially, the upgraded rail system and magnetic levitation (Scenario A) and Hybrid MDS based on magnetic levitation (scenario A) show positive economic returns, while the other scenarios exhibit B/C ratios lower than one.

8.2 >>Sensitivity Analysis

Uncertainty is an unavoidable element in project analysis. Whenever one evaluates the costs of a project or attempts to assess the producer/consumer surplus or the external effects of a given project, estimates are made that are necessarily approximations. Uncertainty increases when such estimates are projected into the future, as required by cost-benefit analysis.

Sensitivity analysis allows for evaluating the impacts of uncertainty and identifying the project's "critical" variables. The analysis is conducted by modifying the values associated with each individual variable and evaluating the effect of such a change on the ENPV and other analysed indicators.

For this study, a sensitivity analysis was conducted on the main variables considered in the CBA. Specifically, the variables analysed are:

- Investment costs.
- Operation and maintenance costs.
- Shift demand.

The analysis was carried out individually on each variable to assess its impact on the overall results. The structured spreadsheet allows for an immediate reconstruction of the effect of percentage changes for each analysed component.

Since the results obtained for the economic profitability indicators are positive for some use cases and negative for others, sensitivity analysis was performed by applying variation ranges in both directions that improves or worsens the results.

The sensitive analysis has been applied on all the use cases and their scenarios, despite the negative results for most of them, in order to evaluate the limits of these analysis and how far they are from stability.

As shown in the following tables, for the positive result scenarios, it is possible to calculate the decrease of the main economic performance indicators (ENPV & B/C ratio) by increasing 10%, 20% and 30% the investment costs (CAPEX) and operation and maintenance costs (OPEX) individually, and by decreasing of 10%, 20% and 30% the Shift demand.

On the other hand, for the negative result scenarios, it is possible to calculate the increase of the main economic performance indicators (ENPV & B/C ratio) by decreasing of 10%, 20% and 30% the investment costs and operation and maintenance costs individually, and by increasing of 10%, 20% and 30% the shift demand.

Table 51: Sensitive analysis results for Upgraded traditional railway MDS – Scenario A

Upgraded traditional railway MDS – Scenario A		
	ENPV	B/C

		Value	Diff.%	Value	Diff.%
CAPEX	-30%				
	-20%				
	-10%				
	0	9.33	0%	1.04	0%
	10%	-7.32	-178%	0.97	-6.27%
	20%	-23.98	-357%	0.92	-11.80%
	30%	-40.63	-535%	0.86	-16.72%
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
OPEX	-30%				
	-20%				
	-10%				
	0	9.33	0%	1.04	0%
	10%	-7.96	-185%	0.97	-6.50%
	20%	-26.89	-388%	0.91	-12.71%
	30%	-47.47	-609%	0.84	-18.58%
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
Shift demand	-30%	-68.14	-830%	0.73	-30.00%
	-20%	-42.32	-553%	0.83	-20.00%
	-10%	-16.49	-277%	0.93	-10.00%
	0	9.33	0%	1.04	0%
	10%				
	20%				
	30%				

Table 52: Sensitive analysis results for Upgraded traditional railway MDS – Scenario B

Upgraded traditional railway MDS – Scenario B

		ENPV		B/C	
		Value	Diff.%	Value	Diff.%
CAPEX	-30%	-48.60	-28%	0.34	25.23%
	-20%	-54.76	-18%	0.31	15.51%
	-10%	-60.91	-9%	0.29	7.20%
	0	-67.07	0%	0.27	0%
	10%				
	20%				
	30%				
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
OPEX	-30%	-51.71	-23%	0.32	20.13%
	-20%	-56.23	-16%	0.30	13.41%
	-10%	-61.35	-9%	0.29	6.66%
	0	-67.07	0%	0.27	0%
	10%				
	20%				
	30%				
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
Shift demand	-30%				
	-20%				
	-10%				
	0	-67.07	0%	0.27	0%
	10%	-65.26	-3%	0.29	7.33%
	20%	-63.46	-5%	0.31	14.67%
	30%	-61.66	-8%	0.33	22.00%

Table 53: Sensitive analysis results for Hybrid MDS based on air levitation

Hybrid MDS based on air levitation – Analysed Scenario					
		ENPV		B/C	
		Value	Diff.%	Value	Diff.%
CAPEX	-30%	-32.83	-49%	0.74	25.28%
	-20%	-43.36	-33%	0.68	15.55%
	-10%	-53.89	-16%	0.63	7.21%
	0	-64.42	0%	0.59	0%

	10%				
	20%				
	30%				
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
OPEX	-30%	-49.05	-24%	0.65	10.89%
	-20%	-54.17	-16%	0.63	7.00%
	-10%	-59.30	-8%	0.61	3.38%
	0	-64.42	0%	0.59	0%
	10%				
	20%				
	30%				
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
Shift demand	-30%				
	-20%				
	-10%				
	0	-64.42	0%	0.59	0%
	10%	-46.09	-28%	0.71	19.89%
	20%	-26.57	-59%	0.83	41.09%
	30%	-5.84	-91%	0.96	63.60%

Table 54: Sensitive analysis results for Hybrid MDS based on magnetic levitation – Scenario A

Hybrid MDS based on magnetic levitation – Scenario A					
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
CAPEX	-30%				
	-20%				
	-10%				
	0	1124.11	0%	1.31	0%
	10%	821.06	-27%	1.21	-7.82%
	20%	518.00	-54%	1.12	-14.50%
	30%	214.94	-81%	1.05	-20.28%
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
OPEX	-30%				

	-20%				
	-10%				
	0	1124.11	0%	1.31	0%
	10%	1069.77	-5%	1.29	-1.50%
	20%	1015.43	-10%	1.28	-2.95%
	30%	961.10	-15%	1.26	-4.36%
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
Shift demand	-30%	-308.26	-127%	0.91	-30.49%
	-20%	169.20	-85%	1.05	-20.33%
	-10%	646.65	-42%	1.18	-10.16%
	0	1124.11	0%	1.31	0%
	10%				
	20%				
	30%				

Table 55: Sensitive analysis results for Hybrid MDS based on magnetic levitation – Scenario B

Hybrid MDS based on magnetic levitation – Scenario B					
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
CAPEX	-30%	89.94	-107%	1.02	31.11%
	-20%	-388.00	-71%	0.92	18.79%
	-10%	-865.94	-36%	0.84	8.59%
	0	-1343.87	0%	0.78	0%
	10%				
	20%				
	30%				
		ENPV		**B/C**	
		Value	Diff.%	Value	Diff.%
OPEX	-30%	-965.11	-28%	0.83	6.69%
	-20%	-1091.36	-19%	0.81	4.36%
	-10%	-1217.62	-9%	0.79	2.13%
	0	-1343.87	0%	0.78	0%
	10%				
	20%				
	30%				

		ENPV		B/C	
		Value	Diff.%	Value	Diff.%
Shift demand	-30%				
	-20%				
	-10%				
	0	-1343.87	0%	0.78	0%
	10%	-866.42	-36%	0.86	10.16%
	20%	-388.96	-71%	0.94	20.33%
	30%	88.50	-107%	1.01	30.49%

As demonstrated by the tables above, the sensitivity analysis conducted for the Cost-Benefit Analysis (CBA) across various use cases evaluates the impact of varying key input parameters (Investment Costs, Operation & Maintenance (O&M) Costs, and Demand Shift) by ±10%, ±20%, and ±30% on both the Economic Net Present Value (ENPV) and Benefit-Cost (B/C) ratios. The results reveal distinct trends among the different use cases.

Some use cases exhibit stability such as the Magnetic Levitation scenario A, as even with changes in these parameters, they maintain positive ENPV and B/C ratios, indicating resilience to fluctuations in cost or demand. In contrast, other use cases show less stability such as the Rail vehicle upgraded scenario A, where even minor adjustments lead to significant declines s in economic performance due to low traffic volumes of the line selected for the specific use case. Additionally, some use cases already show negative ENPV or B/C ratios in the baseline scenario (all the other scenarios), with the sensitivity analysis highlighting how far these cases are from achieving stability. This analysis offers valuable insights into the financial robustness of each use case, identifying areas where further optimization may be required to improve economic outcomes.

To establish the boundaries of the analysis for all use case scenarios and determine the percentage change required in various input parameters (such as investment cost, O&M costs, and demand shifts) to achieve an ENPV of 0 and a B/C ratio of 1, the following calculations have been summarized in the table below. In this table, green cells indicate the percentage adjustments needed to achieve ENPV = 0 and B/C = 1 for scenarios with already positive results, while red cells indicate the percentage changes required for scenarios with negative results.

Table 56: Analysis limits (ENPV=0 & B/C=1)

	ENPV = 0 & B/C = 1

Upgraded traditional railway MDS – Scenario A	Investment costs	6%
	Maintenance & Operating costs	5%
	Shift demand	-3%
Upgraded traditional railway MDS – Scenario B	Investment costs	<-100%
	Maintenance & Operating costs	<-100%
	Shift demand	>100%
Hybrid MDS based on air levitation – Scenario A	Investment costs	-54%
	Maintenance & Operating costs	-95%
	Shift demand	42%
Hybrid MDS based on magnetic levitation – Scenario A	Investment costs	37%
	Maintenance & Operating costs	300%
	Shift demand	-24%
Hybrid MDS based on magnetic levitation – Scenario B	Investment costs	-28%
	Maintenance & Operating costs	>100%
	Shift demand	28%

8.3 Additional Scenario Considering “Airport Shuttle” Use Case

This use case aims to perform a preliminary assessment of the introduction of a hybrid MDS based on magnetic levitation on the railway line connecting the urban node of one of the considered cities in the Hybrid MDS based on magnetic levitation use casewith one of the biggest airport, located near the considered city. This use case was analysed as an extension to the Hybrid MDS based on magnetic levitation Scenario A, creating an additional scenario where the cost and benefits to introduce MDS technologies in the city-airport line are integrated to the original use case. However,, it can also be considered a standalone use case. A specific analysis can be performed by looking at the differences in costs and benefits between the original 2 scenarios and the new scenarios. Nevertheless, the preliminary nature of this analysis has led to it being considered an integration of the previous study.

The line has a junction near a first station of the considered city. From here, it is possible to connect to the historic regional line, reaching a second station, or enter the city centre reaching the third main station of the city.

The length of the lines for this additional use case are presented as follows:

- Third main station – airport station: approx. 30.0 km of double track line
- Additional track at the airport station: 0.5 km
- First city station – Second city starion: Nearly 4.0 km of double track line

The hardware costs per kilometre for the linear motor in the considered configuration for this study is estimated by Nevomo experts to a target price in line with the market of € 3.25 mio for a single track, including the active stator with all fixtures and cablings, power electronics like inverters, transformers and segment switches, and the control system. Additional planning and deployment costs of € 0.25 mio are also considered for the retrofitting of the infrastructure.

This leads to total investment costs for the additional line of more than 71.0 km * (€ 3.25 + € 0.25 mio.) = **€ 249.2 mio** for the infrastructure retrofitting. For the needed studies and inspections additional costs of **€ 100,000** are integrated in this cost calculation.

Changes in vehicle command and control system, Signalling system and Telecommunication system are estimated by CCS tech developers at 50.000 €/km. for an estimated track length of approx. 71 km, the CCS costs are estimated to be of **€ 3.56 mio.**

The current operational model includes four medium and short-distance services departing from the airport. One, in particular, connects the airport to the abovementioned third main station in the city centre. This service does not have any intermediate stops, ensuring a travel time of 32 minutes. The other three services, however, do not enter the branch leading to this city centre's station but continue towards the second considered city's station, reconnecting to the historic line.

Currently, on an average weekday, the total train*kilometres for this operational model are 13,596.47. It is assumed, that 146 additional vehicles will be needed to replace the existing services above mentioned, these are also needed to meet the mobility requirements of the future users who will be able to use the above-mentioned services. This leads to total investment costs of 178 pods * € 4.01 mio = **€ 714.03 mio** for the rolling stock.

Finally, in order to consider unforeseen costs in the analysis, a basic surcharge of 3% is applied to all previous cost blocks. These unexpected costs thus amount to a total of **€ 7.59 mio** in additional costs to be recognised.

For the future operational model, which is expected to start in the first year after the introduction of the MDS, it is assumed that all the services mentioned above will be operated with MDS rolling stock. to quantify the number of pod-km, it is necessary to consider the variation in demand between the current state and the projected scenario.

The preliminary demand analysis, unlike the Hybrid MDS based on air levitation use case, is based on the observation of current transportation, specifically the number of seats offered. It can be reasonably estimated that the demand represents about 45% of the seats offered, as demand for the services is considerably higher than traditional regional services.

Similarly to what was done for the sections of the main Hybrid MDS based on magnetic levitation line, it was assumed that demand variation is driven by both external factors to the railway system and intrinsic variables. To determine the number of users in the project scenario, the following factors were considered:

- Increase in demand due to population growth;
- Increase in demand due to reduced travel times.

For more details on the methodology used to assess future demand, refer to section 7.3.1.3.

With the total number of trips available for an average weekday, it was possible to evaluate the number of pod-km to be provided in the future model, which amounts to 68,827.8. pod-km per day.

In this section the CBA main inputs (CAPEX, OPEX and Benefits) for Scenario A of the line extension (airport to city centre) have been summarized as shown in the following tables:

Table 57: CAPEX summary for hybrid MDS based on magnetic levitation – additional scenario considering "airport shuttle"

Magnetic levitation – Line Extension scenario	CAPEX [€]
Civil Works	252,859,996.44 €
Vehicle command and control system	3,560,000.00 €
Rolling Stocks	714,027,242.0 €
Other Costs	100,000.00 €
Unexpected Cost [3%]	7,585,800.00 €
Sum CAPEX	974,473,042.00 €

Table 58: OPEX summary for hybrid MDS based on magnetic levitation -additional scenario considering "airport shuttle"

Magnetic levitation – Line Extension scenario	OPEX [€/year]
Rolling Stock Operation & Maintenance	35,102,178.00
Infrastructure Maintenance MDS	6,187,500.00
Sum OPEX	41,289,678.00

Table 59: Benefits summary for hybrid MDS based on magnetic levitation -additional scenario considering "airport shuttle"

Magnetic levitation – Line Extension scenario	Benefits [mio €]

Travel Time Saving	5,881.09
Vehicle Operation Cost Saving	25.41
Externalities cost savings	-42.15
Sum Benefits and Externalities cost savings	5,864.35

Impact of the extension line on the Magnetic Levitation scenario A main scenarios:

In this section a combination has been done between the main scenarios of the Magnetic levitation which has been analysed in chapter 6 and the line extension (airport to city centre) in order to estimate the improvement that could be gained by developing the magnetic levitation on the whole line from the considered airport and the other end of the line studied in the Hybrid MDS based on magnetic levitation use case.

This combination has been estimated considering the total discounted costs and benefits from both scenarios (airport connection in addition to the Hybrid MDS based on magnetic levitation) and calculate the economic performance indicators.

In the following table, a summary of these results has been shown:

Table 60: Combination between (additional use case) and (MDS based on Magnetic Levitation use case) CBA results

Use case	Scenarios	ENPV [mio €]	B/C
Magnetic levitation – (also considering the airport connection)	A	3,469.13	1.88

Based on the results presented in the table above, it is evident that the economic performance indicators have improved. This improvement is attributed to the increase in benefits, which has outpaced the rise in costs following the extension of the airport line. The following figure illustrates the increase in the Benefit-Cost (B/C) ratio compared to the same scenarios without the airport to city extension.

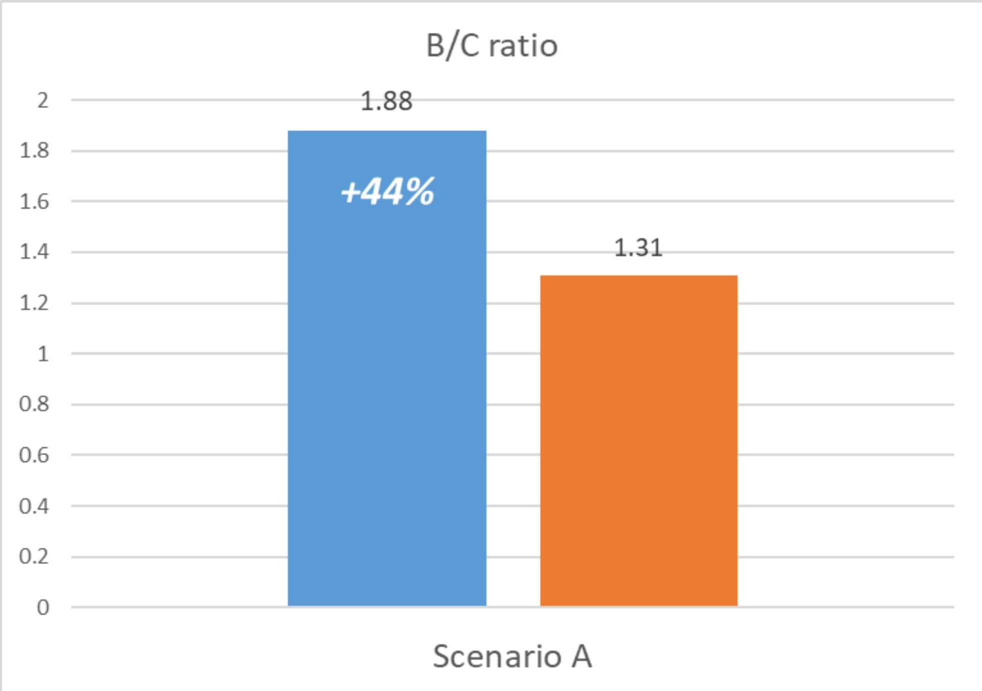

Figure 2: B/C ratio improvement

8.4 Results Interpretation & Outlook to Other Possible Cases

Given the restricted scope, timing and resources, the project evaluated three specific use cases, with their natural restrictions. However, MaDe4Rail sees additional benefits and areas of application beyond the evaluated specific use cases and is therefore providing additional outlook and interpretations of the given results in this chapter. further analyses on possible MDS applications beyond the three considered use cases are given in **[D7.4]**.

Upgraded traditional railway MDS

Upgrading existing rail operations with MDS provides a broad variety of use cases and hybrid applications, as described in **[D7.1]** and as an outlook in **[D7.4]**, the evaluated use case of an incline section in Sweden is therefore only a snapshot of potential benefits and applications of the technology.

For the Swedish use case, the positive and promising results are mainly based on the possible improved performance using the existing infrastructure, as an outcome of the higher propulsion force and therefore steeper gradients. The use case also gives insightful views on how railway infrastructure planning could be changed with such kind of a supporting technology in place.

Scenario A, which focuses on improving an existing line for freight trains, emerged as the most promising case from the analysis performed. The relatively low investment costs are offset by the benefits gained from the increased attractiveness of railway operations thanks to the enhanced track characteristics. The majority of upfront costs stem from refurbishing the track with the linear motor system, overshadowing all other aspects of the CAPEX. Additional operational costs include maintenance of these new components, and the extra energy required to run freight vehicles at higher speeds contributes to the OPEX.

The primary benefit of traction boosters is the significant reduction in travel time for freight, making operations comparable to passenger trains and enabling a much more efficient mixed-traffic operation, thereby optimizing line capacity. This is particularly advantageous for time-sensitive goods, and it could also increase the attractiveness of rail transport for freight operators.

Scenario B explored a different possibility for the same route, incorporating segments of the linear motor system to enhance traction on uphill gradients during the design phase of a new high-speed rail (HSR) line. This approach allows for steeper gradients, potentially reducing infrastructure costs by optimizing tunnelling, bridges, and track routing. In this case, however, the time savings are not significant, and the main cost-saving measure is related to reducing tunnelling, bridge building, and earthworks, while the CAPEX contribution of the new components outweighs the estimated savings. As with Scenario A, additional operational costs arise from the extra energy required to run passenger vehicles on steeper gradients, thereby increasing OPEX. In this scenario, the estimated savings are insufficient to justify the system implementation costs. Further case studies should be conducted with a focus on infrastructure savings, taking into account land acquisition, construction-related costs, and externalities associated with earthworks, tunnelling, and bridges.

Hybrid MDS based on air levitation

The exploration of a hybrid MDS utilizing air levitation on the considered Italian railway line represents a search for a solution to the challenges of increasing rail capacity and efficiency in this high-demand corridor. The application of air levitation technology, combined with the novel electro-dynamic wheels (EDW) for propulsion and braking, was expected to provide key advantages that address the core issues of the existing rail infrastructure:

- Airlev trains, due to their reliance on air levitation, could reduce friction between the train and the track. This reduction in friction would enable the trains to operate at higher speeds, directly decreasing the travel time between the two cities. The increased speed potential (up to 180 km/h) could improve the overall transportation efficiency in this busy corridor.

- Traditional rail systems often suffer from wear and tear due to the high friction forces between the train wheels and the tracks. The Airlev system could mitigate this issue by evenly distributing the train's load across the entire track, reducing stress on the infrastructure. This would result in fewer maintenance interventions, minimizing disruptions to line usage and enhancing the longevity of the track infrastructure.
- The Airlev system, with its ability to operate alongside conventional trains on the same track, offers a hybrid solution that allows for a gradual transition to more advanced transportation technologies. This compatibility is crucial for maintaining current operations while progressively upgrading the system. Additionally, the potential to use the tracks for freight transportation during off-peak hours could maximize the utility of the rail infrastructure, contributing to optimized overall capacity.
- The inclusion of EDW for propulsion and braking is a significant advancement. The EDW technology provides a frictionless method for accelerating and decelerating trains, which is critical for safely increasing the number of trains on the track. The system's ability to generate substantial Lorentz forces (up to 7 kN with optimized wheels) ensures that even on slopes with gradients up to 2.5 degrees, the trains can maintain safe and efficient operations.

The hybrid MDS based on air levitation promises a scalable and adaptable solution that can be applied to various railway lines facing capacity challenges. However, the configuration was found to have a lower maturity level compared to the other analysed configurations. The results of the technical and socio-economic feasibility analysis indicated that, at its current state, the technology does not offer distinctive benefits for the analysed line that would justify the investment. As the technology matures, additional analyses will be necessary to assess the potential benefits it could provide for capacity optimization and maintenance reduction in existing lines.

Hybrid MDS based on magnetic levitation

The implementation of a hybrid Maglev Derived System (MDS) for the Italian line presents a significant opportunity to upgrade regional rail services that currently suffer from low vehicle performance and infrequent schedules, making them less attractive for transport users. Analysis indicates that the introduction of a hybrid MDS based on maglev could result in substantial travel time reductions, leading to significant benefits. In particular, Scenario A showed a positive economic evaluation, with a benefit-cost (B/C) ratio greater than 1, demonstrating that even with minimal infrastructure changes, the integration of MDS technology offers significant gains.

However, in Scenario B, the benefits do not fully cover the costs, particularly those associated with civil works, such as the installation of additional levitation beams for performance improvements. In this case, costs exceed expected benefits, highlighting the need for further evaluation of similar lines in different geographical contexts. This would allow for more detailed studies to assess the solution's efficiency under varying conditions.

An additional use case—the "Airport Shuttle"—was evaluated by extending the analysed line to include connections between the considered city's main stations and the nearest Airport. The results were highly positive, showing strong socio-economic feasibility, proving that MDS technology can significantly enhance the performance of existing heterogeneous rail lines while optimizing capacity. This could also strengthen rail's position as a primary mode of access to airports in Europe from city centres, boosting its appeal for travellers.

The capital expenditure (CAPEX) for MDS is considerably lower than that of traditional HSR lines. Hybrid MDS systems based on maglev technology are estimated to cost around €7 million per kilometre for the series configuration and €12 million per kilometre for the parallel configuration. This is significantly less than the costs associated with conventional HSR lines, which can reach up to €25 million per kilometre in Spain **[13] [14]**, and €61 million per kilometre in Italy **[15]**, with some segments peaking at €96.4 million per kilometre **[16]**.

This cost advantage is primarily due to MDS's ability to upgrade existing lines without requiring the extensive infrastructure needed for HSR, such as new bridges, tunnels, and very straight alignments. Furthermore, MDS rolling stock with infra-driven propulsion systems is expected to result in a 30% reduction in CAPEX per seat compared to ICE 3 neo models, making it a cost-effective alternative for rail upgrades.

New high-speed railway lines often require decades for planning, approvals, and construction. In contrast, upgrading existing lines with MDS technology can provide enhanced transport services much sooner, supporting the critical shift to rail needed to meet the EU's sustainability goals. Additionally, new HSR lines tend to bypass smaller cities due to their alignment requirements. MDS upgrades, using smaller, flexible pods instead of long trainsets, offer the potential to serve these cities, providing more versatile and widespread coverage.

Overall, the introduction of hybrid MDS solutions not only holds promise for improving travel times and rail capacity but also represents a more flexible, cost-effective alternative to building new high-speed lines. Further studies on different lines and geographic contexts are needed to fully understand its potential and scalability.

9 Additional/Optional Compact Study – Intermodal Terminal

To broaden the perspective on various use cases, this chapter explores possible solutions for implementing linear motor propulsion in container terminals, with the aim of enhancing efficiency, sustainability, and overall operational performance. It also specifies one possible application for an Italian terminal.

Currently, the movement of trains and wagons in container terminals is carried out by diesel shunting locomotives, as classical electrification by catenary system is not feasible. However, rail shunting with diesel locomotives raises several concerns, since they emit pollutants such as nitrogen oxides (NOx), particulate matter (PM), and carbon dioxide (CO_2), which contribute to air pollution and climate change. In a shunting yard, where locomotives often idle or operate at low speeds, these emissions can accumulate in localized areas, negatively impacting air quality.

Additionally, diesel locomotives are typically noisy, particularly at low speeds during shunting activities. This can pose for both workers in the yard and nearby residents or businesses. Moreover, diesel locomotives consume fuel even when idling, which contributes to higher operating costs. Efficient shunting practices are crucial to minimize fuel consumption and reduce overall operating expenses.

Efficient shunting operations are also essential to reduce dwell and maximize the throughput of goods in the rail yard. Inefficiencies can lead to congestion, delays, and increased operational costs.

Given these concerns, it is sensible to consider new solutions using MDS technologies in terminals. Seven different use cases are worth exploring.

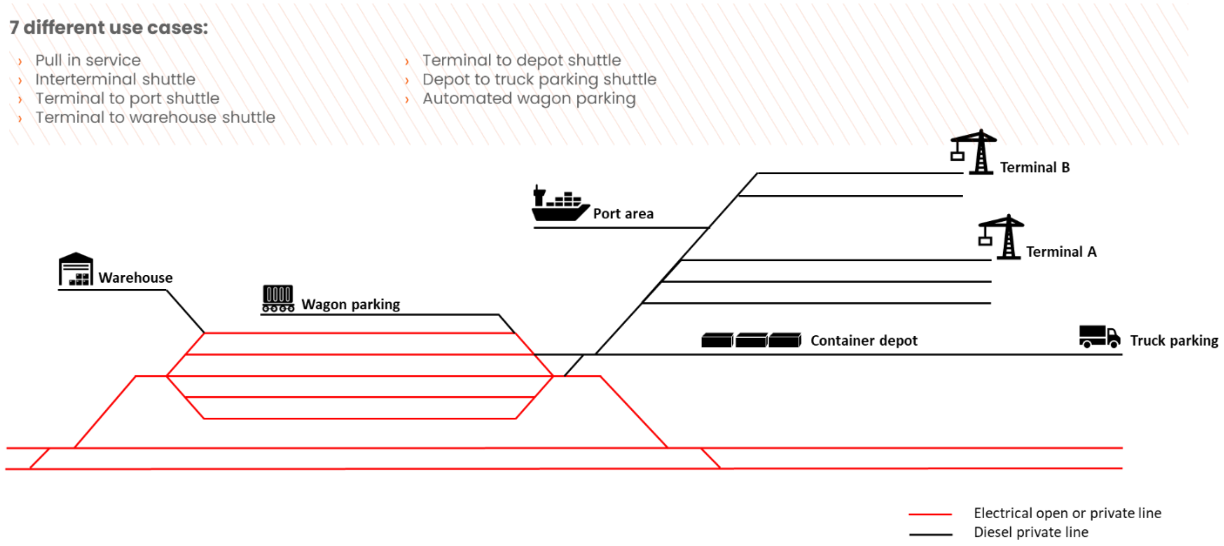

Figure 3: Possible terminal use cases

The seven different use cases can be briefly described as follows:

- *Pull in service*: Arriving trains are shunted into the terminal, to the loading/unloading facilities. After loading and unloading are completed, they are shunter back to the departure station, where an electric long-distance locomotive takes over for onward travel.
- *Interterminal shuttle*: In areas with multiple terminals (e.g. large industrial zones), regular cross-connections can be established between terminals to improve operational efficiency.
- *Terminal to port shuttle*: Using MDS technology, an automated and fast connection between two bi-modal terminals can create the effect of a virtual tri-modal terminal, enhancing logistical integration.
- *Terminal to warehouse shuttle*: An automated direct connection between a terminal and a warehouse can significantly increase efficiency. A dedicated wagon fleet can be loaded at the terminal and shuttled directly into warehouse tracks.
- *Terminal to depot shuttle*: Since storage space is often limited at terminal premises, mid-term container depots can be connected via an automated MDS service, complemented by reach stackers at the depot.
- *Depot to truck parking shuttle*: In dense areas, it may be useful to connect an offsite depot with a truck parking facility. Fully automated shuttle wagons, combined with reach stackers, can help alleviate congestion at heavily utilized terminals.

* *Automated wagon parking*: Unused wagons can be automatically moved to parking tracks and reactivated as needed, streamlining space utilization and operations.

For the specific terminal case, the first described use case of pulling in the arrived trains into the terminal tracks by MDS technology will be estimated.

9.1 Description of the As-Is Situation in the analysed terminal

This case study assesses the potential implementation of a new propulsion system at the container terminal inside an Italian terminal infrastructure. The infrastructure is owned by three different entities. Currently, long-distance electric locomotives utilized seven fully electrified arrival tracks, with diesel shunting locomotives managing internal movements. Containers are loaded and unloaded by reach stackers.

With a focus on sustainability, efficiency, and reduction of greenhouse gas emissions, this study explores the feasibility of adopting an advanced propulsion system based on MDS technology. The goal is to enhance operational efficiency and environmental performance at the terminal by upgrading vehicle to handle pull in operations, moving trains from the arrival station to the various terminal tracks.

The layout of the terminal includes an arrival and departure station with several electrified tracks, where trains can be moved by long-distance electric locomotives. After removing the long distance locomotives, the wagons are shunted by diesel locomotives via shunting tracks to the different terminal tracks. The terminal consists of three distinct areas, each with three or four tracks, managed by different infrastructure operators. Nearby, there is an additional area for handling single-wagon loads, as well as a private container terminal track. Two industrial tracks, currently unused, are also part of the infrastructure.

The current operations at the container terminal involve a complex and collaborative setup across three different terminals, each with distinct infrastructure ownership. Despite this complexity, all operations are centrally managed by a single operator. Trains arrive on seven fully electrified arrival tracks, using long-distance electric locomotives. Upon arrival, these locomotives are decoupled and, if a departing train is ready, they are coupled to it for the next journey. Diesel shunting locomotives are then used to manoeuvre trains, pulling them from the arrival station to the designated shunting tracks, subsequently pushing them onto the terminal tracks. The loading and unloading of containers are managed by reach stackers, ensuring smooth and efficient handling of goods within the terminal.

The terminal operates 24 hours per day from Monday to Friday, and 16 hours per day on weekends, from 6 a.m. to 10 p.m. During these operational hours, approximately 60 trains are handled per week, resulting in 120 shunting operations. Currently, the terminal operator uses two diesel shunting locomotives for these tasks, which can lead to delays during peak hours due to limited shunting capacity.

9.2 Description Solution Design

The new MDS technology, utilizing a linear motor and upgraded vehicles, can automate and electrify shunting operations. In this system, a pair of equipped wagons will function like a shunting locomotive, moving the wagon park from the arrival tracks to the terminal tracks. While this automation will replace diesel shunting locomotives and the need for locomotives drivers, operational workers will still be required to prepare and couple vehicles. Shunting procedures will be performed automatically.

Not all tracks need to be fully equipped with the new infrastructure. The technology can be implemented selectively, due to the fact that only the initial sections of the tracks require linear motor equipment.

For the complete terminal, including its various areas, the total track length that needs to be equipped with the linear motor would be 6,4 km. The breakdown is as follows:

- 4x Entrance tracks (a 200 m): 800 m
- Shunting connection: 1.200 m
- 2x Shunting tracks (a 600 m): 1.200 m
- 4x Terminal tracks (a 300 m) + 200 m connection: 1.400 m
- 3x Terminal tracks (a 250 m) + 300 m connection: 1.050 m
- 3x Terminal tracks (a 250 m): 750 m

The control of the MDS technology can be implemented in phases. The first step could involve remote control by a shunting operator stationed on the vehicles, similar to current operations but replacing diesel locomotives with an electric propulsion system. The second step would involve remote control from a central control room at the terminal, using cameras and sensors installed on the vehicles. The final step would enable fully automated movement, where wagons are moved from starting point to a defined destination based solely on an authorized command.

The operational concept will follow the steps seen in figures below:

1. The container train arrives at the arrival station, the electrical long distance locomotive is decoupled from the train by the loco driver.

2. The two MDS equipped wagons move remote controlled from central control centre, or automatically to the train, and got coupled to the wagon park by operative staff. This might be no longer necessary if DAC (Digital Automated Coupling) will be used in the near future.
3. The wagon park is shunted to the terminal tracks, remote controlled from central control centre or automatically.
4. MDS wagons will be decoupled from the wagon park by operational staff. Container train will be loaded and unloaded with reach stackers. MDS equipped wagons can handle other trains or go to parking position.
5. After the container is fully loaded, the MDS equipped wagons will shunt the container wagons back to the arrival tracks.
6. The MDS wagons will be decoupled and moved away to another track or parking position. The long distance loco can use a parallel track to reach the front of the wagon group.
7. The long distance locomotive will be coupled to start the long distance run.

To implement this concept, a set of four wagons (each shunting device is composed of two MDS retrofitted wagons) may suffice to meet today's demand of 60 trains per week, provided that the wagons of arriving trains are not equipped with MDS components. Since the terminal is in a well-developed industrial area, connecting to the power grid will not be a critical issue. The same applies to the availability of space for additional equipment, such as inverter stations and smaller cabinets for segment switches at that terminal location. At a later stage, when the intermodal trains would arrive with already equipped wagons, the operations will be further simplified then reducing the need of the MDS shunter devices.

9.3 Description of the Aim of Optimization

The aim of optimization in rail operations, particularly through automation reaching Grades of Automation (GoA) 3/4, is to enhance sustainability, address workforce challenges, and improve operational efficiency. This advanced level of automation, which enables driverless or unattended train operations, helps mitigate the impact of skilled labor shortages by reducing the reliance on human intervention.

In addition to solving staffing issues, this automation enhances safety, reliability, and energy management, leading to significant reductions in greenhouse gas emissions. By optimizing resource usage and maximizing both capacity and performance, the rail network can become a more sustainable and efficient transportation solution, addressing both environmental concerns and workforce limitations.

9.4 Performance Analysis

The calculation of the needed forces to pull-in or push-out a full trainset at operational speed of 20 km/h, with low accelerations of 0.05-0.1 m/s², is based on a comparison of scenarios with small or no inclination, and with or without locomotive, as expressed in Table 61.

Table 61: Force calculation trainset shunting [Nevomo calculation scheme]

	0.2‰ gradient with loco		0.2‰ gradient no loco		0‰ gradient with loco		0‰ gradient no loco	
m_{wag}	1600		1600		1600		1600	
m_{loc}	85		0		85		0	
M	0.28		0.28		0.28		0.28	
A	0.00		0.00		0.00		0.00	
B	1340.00		1340.00		1340.00		1340.00	
v	20	[km/h]	20	[km/h]	20	[km/h]	20	[km/h]
i	2.000	mm/m	2.000	mm/m	0.000	mm/m	0.000	mm/m
mover force dens	2.8	[kN/m]	2.8	[kN/m]	2.8	[kN/m]	2.8	[kN/m]
mover L/wag	14	[m]	14	[m]	14	[m]	14	[m]
F_{train} res	21.54	[kN]	21.54	[kN]	21.54	[kN]	21.54	[kN]
F_{track} res	33.06	[kN]	31.39	[kN]	0.00	[kN]	0.00	[kN]
SUM RES	54.60	[kN]	52.93	[kN]	21.54	[kN]	21.54	[kN]
m of mover	19.5	[m]	18.9	[m]	7.7	[m]	7.7	[m]
# of wagons	2	[-]	2	[-]	1	[-]	1	[-]

In order to calculate, the following force definitions have been used:

$$F_{train} = \frac{\left(M + 0.001962 * m_{wag}\right) * v^2 + A * v + B + 11.772 * m_{wag}}{1{,}000}$$

$$F_{track} = \frac{i * 9{,}81 * (m_{wag} + m_{loc})}{1{,}000}$$

where the main considered parameters are those expressed in Table 62.

Table 62: Parameters for force calculation

m_{wag} = trainset mass wagons	Mover force dens = force in kN per meter of mover
m_{loc} = loco mass	mover L/wag = mover lengths per wagon (double container wagon)
M = mass factor	F_{train} res = calculated train resistance force
A = acceleration factor	F_{track} res = resistance to overcome the inclination
B = drag coefficient	SUM res = cumulated resistance
v = velocity	m of mover = resulting total mover length needed to overcome the resistance
i = Inclination	# of wagons = number of wagons to be equipped to pull-in / push-out a trainset

In the context of the terminal's use case, the calculation results indicate that utilizing just 1 or 2 wagons (depending on the max. gradient in this section, as calculated in Table 61for 0‰ or 2‰) would be sufficient for shunting (moving or switching) a complete trainset at a maximum speed of 20 km/h. Here's a more detailed breakdown:

- Shunting Operation: this refers to the process of moving train cars or entire trainsets within a rail yard or terminal. It involves assembling, disassembling, or repositioning trains for loading, unloading, or maintenance purposes.
- Wagons Required: the mention of 1 or 2 wagons implies that the shunting operation can be effectively carried out with minimal equipment. A wagon in this context could refer to specialized MDS retrofitted shunting wagon designed to handle the specific task of moving trainsets within the terminal.
- Trainset: a trainset typically includes a locomotive and a series of connected freight cars. In this use case, the term suggests the entire composition of the train that needs to be shunted within the terminal.

- Speed Limitation: the maximum speed of 20 km/h for shunting operations is likely a safety measure. Shunting often involves complex manoeuvres in confined spaces, so lower speeds reduce the risk of accidents and ensure precise movements.
- Each terminal has its own unique layout, infrastructure, and operational requirements, which influence the equipment and procedures used, the indicated numbers are therefore specific to the terminal.

For this study the detailed parameters of the infrastructure are not available, and it cannot be assured that infrastructure is completely flat. By stating that gradients up to 2‰ could be possible in the area of the terminal, it is assumed that a group of 2 wagons is needed to move full trains with up to 1,600 tons of weight. By having two of these "double wagon shunting devices", the flexibility in operation will increase. the calculation results suggest that the terminal could efficiently manage its shunting needs without requiring extensive resources. This optimization can lead to cost savings, reduced wear and tear on equipment, and improved overall efficiency in terminal operations, being reflected in the benefits part of the economic feasibility study.

9.5 Calculate Business Case

To evaluate the economic viability of the terminal use case, a business case evaluation based on Net Present Value (NPV) was performed.

The logic involves estimating future cash inflows and outflows, discounting them to their present value using an appropriate discount rate, and then calculating ENPV by subtracting the initial investment from the sum of these discounted cash flows. A positive ENPV indicates that the project is likely profitable, as the present value of earnings exceeds the costs, while a negative ENPV suggests potential losses. This approach helps businesses make informed decisions by quantifying the expected financial returns and comparing them to the investment required.

On the benefit side, the MDS system will replace current diesel shunting locomotives resulting in reduced shunting costs for the terminal case, as the system will be able to pull-in and push-out trainsets. The reduced shunting costs, of about € 3.7 mio, can result in higher demand for the terminal. In fact, for this case study it is assumed that the demand will increase by 30% of the current operational scheme (meaning 18 additional trains shunted every week).

Based on the terminal operator's input, the following parameters can be considered:

Benefits:

- Current operational scheme status-quo: 3,120 trains per year (60 trains per week x 52 operational weeks per year),
- Estimated demand, based on the reduction of shunting costs and 30% demand increase: 4,056 trains per year (78 trains per week x 52 operational weeks per year),
- Each train is shunted twice (pull-in / push-out), resulting in 8,112 shunts per year,
- Costs per shunt: 465 €/shunt, based on the terminal's operator pricelist 2024, resulting in around € 3,000,000 per year, leading to potential savings

Cost parameters:

- Project timeframe = 30 years (depreciation),
- MDS system dimensions:
    - Infrastructure side = 6,3 km to be equipped with MDS propulsion system,
    - Vehicle side = 4 wagons to be equipped with MDS propulsion system, to be used as shunting wagons instead of diesel locos (later, if trainsets would already include equipped wagons, the additional shunting ones would not be needed).
- CAPEX:
    - Infrastructure cost = 3.5 mio €/km x 6.3 km,
    - Wagon retrofit = 36,000 €/wagon x 4 wagons,
    - Total CAPEX = € 22.2 mio,
    - Assumption= 100% to be financed with equity/debt (different grant regimes shown in the sensitivity analysis).
- OPEX:
    - Infrastructure maintenance = 2.5% of CAPEX per year,
    - Energy consumption per pushed / pulled train = ~96 kWh per cycle,
    - Unitary energy cost = 0,13 €/kWh
    - Total energy costs = 101,000 €/year,
    -
- Additional financial costs to be considered:
    - Expected IRR on equity = 4%
    - Interest on debt = 3%

Considering the unitary cost **[12]**, t energy consumption was calculated for a reference train of 20 double-container wagons, showing high energy efficiency of the system when compared to alternative loco setups. The following Table 63 shows the input parameters used in the energy calculation, which results are reported in Table 64

Table 63: Input factors for energy calculation

Input factors	Value
Track length [km]	3
Loco mass [t] / vehicle traction mass [t]	56
Empty platform mass [t]	19.8
Cargo mass [t]	70.2
Total mass of platform with cargo	90
Number of containers / wagons	20
Average speed [km/h]	25
Diesel price [€/l]	1.54
Electricity price [€/kWh]	0.08
Hydrogen price [€/kg]	5.00
Energy density - Diesel [kWh/l]	10.96
Energy density - Hydrogen [kWh/kg]	33.6
Energy cost - Diesel [€/kWh]	0.14
Energy cost - Hydrogen [€/kWh]	0.15

Table 64: Energy calculation

Loco data			
	Diesel - Electric	Electric	Hydrogen

Coeff A (speed-independent parameters)	158.4	167.7	165
Coeff B (speed-dependent parameters linearly)	1.2	1.4	1.3
Coeff C (speed-dependent parameters in the quadrant)	0.03	0.03	0.03
Energy efficiency [-]	0.3	0.76	0.3
Energy consumption - one way [kWh]			
	Diesel - Electric	Electric	Hydrogen
Empty vehicles	257.92	107.79	268.67
Full vehicles	1,058.54	442.38	1,102.65
Energy consumption - both way [kWh]			
Diesel - Electric	Electric	Hydrogen	MDS
1,316.46	550.17	1,371.32	96.12
Energy consumption per wagon [kWh/container]			
Diesel - Electric	Electric	Hydrogen	MDS
65.82	27.51	68.57	4.81
Price per container [€/wagon]			
Diesel - Electric	Electric	Hydrogen	MDS
9.23	2.11	10.2	0.37

Given the number of assumed operations (4,056 trains per year) and the calculated energy consumption, in combination with typical CO_2 emissions based on the used energy source, MDS can result in significant lower CO_2 emissions compared to the alternatives.

Per kWh, the CO_2 emissions are estimated based on **[12]**.

Table 65: CO_2 emissions

g CO_2/kWhPE		
Diesel	0.270	kg CO_2/kWhPE
HVO	0.195	kg CO_2/kWhPE
Hydrogen		
- grey	0.315	kg CO_2/kWhPE
- green	0,.010	kg CO_2/kWhPE
Electric		
- energy mix ITA	0.244	kg CO_2/kWhPE
- green electricity	0.010	kg CO_2/kWhPE

Resulting in the following savings, based on the used propulsion mode:

Table 66: CO_2 emission saving based on propulsion mode

	Classical Train operations						MDS	
	REFERENCE Diesel – Electric	Diesel – HVO	Electric (ITA)	Electric (green)	Hydrogen (grey)	Hydrogen (green)	MDS (ITA)	MDS (green)
CO_2 Emissions p.y. in kg CO_2	1,441,687.06	1,041,218.43	544,486.87	22,315.04	1,752,054.56	55,620.78	95,127.01	3,898.65
CO_2 Emissions p.y. in t CO_2	1,441.69	1,041.22	544.49	22.32	1,752.05	55.62	95.13	3.90
compared to today Diesel [%]	0.0%	-27.8%	-62.2%	-98.5%	21.5%	-96.1%	-93.4%	-99.7%
compared to today Diesel [tons]	0.00	-400.47	-897.20	-1,419.37	310.37	-1,386.07	-1,346.56	-1,437.79

Compared to the Reference with diesel shunting, the MDS solution (considering the typical Italian electrical grid mix) would result in 93.4% less CO_2 emissions per year, with a total reduction of 1,346 tons of CO_2 emitted per year, equal to 1,500,000 km of truck CO_2 emissions or 39times drives around the world, based on the typical truck emissions of 855 g CO_2/km.

Assuming that the wagons will not run fully automated at the beginning, but semi-automated / remote controlled via an operations manager, the resulting operational costs is about 230,714 €/year. In the following table, a summary of the main data to estimate the operational resources to operate the MDS is given.

Table 67: Estimation of operational resources to operate the MDS

Operations resources estimation	
Trains per year	4,056
Operational weeks	*52*
Trains per week	*78 (considering 30% demand growth)*
Trains per shift	4.1
Trains per hour	0.5
Shifts per week	19
Operations Manager per shift	1
Total headcount for ops	2.7
Cost per Operations Manager [€]	85.000
Total operational cost [€/year]	230.714

Business Case results:

Based on the comprehensive CBA conducted, the project presents a compelling positive business case for the automation and electrification of terminals. This analysis highlights several key financial metrics, that underscore the project's potential profitability and efficiency.

Table 68: CAPEX, OPEX and Externalities summary

Factor	Status quo (Reference Scenario)	MDS installed (Project Scenario)
CAPEX [€]	0	22.2 mio
OPEX [€/shunt]	465	200
OPEX [€/year] **thereof:** **- Depreciation** **- Operational staff** **- Maintenance MDS** **- Energy costs**	3.77 mio thereof no further details available, as all costs included in the shunting fee	1.03 mio thereof: - 0.15 mio - 0.23 mio - 0.55 mio - 0.10 mio
OPEX savings [€/years]	0	2,74 mio
OPEX savings [%]	0%	72.7%
CO_2 emissions [tons/year]	1,442	95
CO_2 emissions saving [tons/year]	0	1,347
CO_2 emissions saving [%]	0%	93.4%

The financial results are highly depending on the financing schemes per country. Depending on the countries, different grant and subsidy schemes are applied.

The co-financing from national or European funds for intermodal infrastructure is usually in the range of 50 – 80% of the total investment costs, e.g. in Germany intermodal infrastructure is subsidized with a maximum of 80%[1], while in Italy there is currently no grant regime for intermodal terminals.

The grants vary a lot from program to program and country to country, that's why for this case the results are shown in a sensitivity analysis in relation to the grant-percentages.

Table 69: Sensitivity analysis results based on subsidies

Sensitivity Analysis	Subsidies								
grant scenarios	0%	10%	20%	30%	40%	50%	60%	70%	80%
ROE [%]	10%	11%	13%	15%	18%	23%	29%	40%	62%
Payback [years]	10.3	9.0	7.7	6.6	5.5	4.4	3.4	2.5	1.6
IRR [%]	4%	6%	8%	11%	15%	19%	26%	38%	61%
NPV [mio €]	0.25	2.98	5.71	8.44	11.17	13.90	16.63	19.36	22.09

In conclusion, these financial metrics collectively demonstrate that the automation and electrification project is not only feasible but also highly advantageous, promising significant returns and enhancing operational efficiencies in terminal operations.

On top to the calculated benefits additional benefits could arise from the application. These benefits were not evaluated and are, therefore, just named here:

- Higher demand, resulting in higher track access charges for RFI, based on additional freight trains,
- Higher demand, resulting in increased handling charges for the terminal operator,

[1]Source:

https://www.eba.bund.de/DE/Themen/Finanzierung/Kombinierter_Verkehr/kombinierter_verkehr_node.html;jsessionid=B59770761773E458643E41BD4BE8C8A4.live11292#doc1527882bodyText2

- Better service and higher quality, due to automation and reduced dependency of shunting services (reduced process times),
- Less trucks on street, resulting in reduction of CO_2 emissions,
- Less noise, increasing the acceptance of rail services.

10 Comparative Analysis with Pure Maglev and Hyperloop

The Cost-Benefit Analysis presented in this document provides valuable insight on how MDS could perform in different functional and geographical contexts, considering three different use cases identified in previous deliverables of the project and additional business cases. Along with MDS, there are several innovative solutions that could bring benefits to the railway industry, and more in general, to the whole transportation sector, both under development (e.g., hyperloop) and already fully operational (e.g., pure maglev). As part of the scope of the project, a comprehensive analysis of the aforementioned solutions has been already provided in **[D2.1]**.

To better contextualize and understand the findings of the conducted CBAs for MDS, it can be useful to compare them with Cost-Benefit considerations related to other innovative transportation systems. By evaluating different perspectives, this comparative approach allows for a deeper understanding of how cost-related considerations – both CAPEX and OPEX – as well as the expected benefits of MDS can be framed within a broader discussion. This, in turn, helps to assess their effectiveness as innovative guided transport solutions in comparison to other relevant alternatives. For this reason, this chapter presents a qualitative evaluation of both pure maglev and hyperloop systems, analysing their key cost components and potential benefits. The results of these considerations are then compared with those obtained from the CBA conducted on MDS. From this structured comparison, it becomes possible to critically assess the viability of MDS as a competitive guided transport solution relative to these alternative technologies.

10.1 Comparative Cost-Benefit Analysis of Pure Maglev Technology

Pure maglev systems, mainly developed and under operation in Asian countries, utilise linear motors for traction and power supply, balancing electromagnetic forces between the train and track to counteract gravity, thereby avoiding wear from wheel-rail and catenary contact **[22]**.

As analysed in previous Work Packages, the commissioning of MDS does not necessarily require the construction of new dedicated infrastructure corridors but offers the possibility to utilise existing railway assets by integrating the necessary technologies to support the operation of the various required subsystems. However, on the other hand, this principle does not apply to the deployment of pure maglev systems, which inherently require purpose-built infrastructure. The realisation of these systems necessitates significant capital investment for the construction of new linear infrastructure, as conventional railway tracks cannot accommodate its specific operational requirements.

This distinction has a direct impact on two fundamental aspects: CAPEX for infrastructure development and environmental impact. The construction of new guided transport systems entails a series of complex engineering and regulatory considerations, including the need to balance system performance with passenger comfort. This often translates into the execution of large-scale civil engineering works such as tunnels and viaducts to ensure optimal ride quality, safety, and operational efficiency, which induces higher CAPEX.

Based on data from currently operational infrastructures, HSR generally requires an investment of up to $25 million per kilometre, whereas building a pure maglev system may entail costs ranging between $50 million and $100 million per kilometre **[23]**. Meanwhile, MDS can utilise existing railway lines to increase speed along the route and, more generally, enhance the performance of traditional rail systems. Based on the preliminary cost analysis performed in the previous chapter, upgrading the current infrastructure with the necessary technologies for MDS operations requires between $4 million and $7 million per km, depending on the specific application and configuration. Therefore, the construction of new pure maglev infrastructures requires the acquisition of additional land, which is often scarce or unavailable, particularly in highly urbanised and densely populated areas (e.g., metropolitan regions). This constraint not only complicates the planning and execution phases but also significantly increases project costs and duration. Furthermore, when compared to the integration of MDS into the existing rail network, the construction of new infrastructure entails a more pronounced environmental impact due to land consumption, potential ecological disruption, and the increased carbon footprint associated with large-scale civil works. Moreover, introducing a new transport system such as pure maglev would require the purchase of new vehicles. On the other hand, depending on the application considered, the development of an MDS infrastructure may only need to retrofit the existing rolling stock.

Given these considerations, optimizing the capacity and efficiency of the current rail transport system through the deployment of MDS technology could represent a more sustainable and cost-effective alternative to large-scale infrastructure expansion, although further research to better define the deployment cost of MDS technologies are needed.

Another key consideration related to the need of high land consumption in urban and peri-urban areas is the accessibility to stations. By integrating the MDS system into the existing railway network, the system could make use of the existing railway nodes and allow quick access to users. However, the construction of new infrastructures for pure maglev systems makes it necessary to set up new stations which, considering the current land consumption, would have to be located outside the cities, increasing the access time to the system compared to the current.

Regarding the OPEX, several factors have to be considered such as energy consumption, depreciation of vehicles, maintenance, personnel on board, etc. Simulation analyses conducted in the previous chapters have shown that, in some cases, the energy consumption required for MDS operations is comparable to that of traditional railway systems, with only a slight increase. However, pure maglev systems achieve greater energy efficiency than conventional trains, with estimated savings of around 20% to 30% **[23]**. As a result, they could be more energy-efficient than MDS vehicles. In addition, compared to a private vehicle, pure maglev trains are able to reduce CO_2 emission (per person) of 75% **[24]**.

Compared to traditional railway systems, the different propulsion technology – particularly the elimination of contact forces – offers significant advantages in terms of maintenance, as it drastically reduces mechanical wear on the transport system. However, the implementation of MDS technologies on the existing railway infrastructure presents maintenance as one of the key technical open points, requiring a redefinition of maintenance processes – both in terms of execution and scheduling. Additional research is needed to better define how these procedures affect the maintenance cost.

The impact of transportation in terms of sustainability and environmental footprint, especially in urban and residential areas, is also measured in terms of noise emissions. These emissions originate from multiple sources, including wheel-rail interaction, aerodynamic resistance, and propulsion systems. Aerodynamic noise becomes predominant at high speeds (200-300 km/h), whereas mechanical noise is more significant at lower speeds. Trains utilising magnetic levitation technology, such as pure maglev and MDS, eliminate direct contact between rolling stock and infrastructure, significantly reducing noise emissions. This results in a lower environmental impact and enhances onboard passenger comfort. Currently operational pure maglev trains reach maximum speeds exceeding 400 km/h due to the elimination of wheel-rail contact, which minimizes friction to only aerodynamic resistance. As discussed in previous chapters, the implementation of magnetic levitation-based technologies enhances operational performance by increasing both capacity and attractiveness. Travel time is one of the key variables influencing users' modal choice. Reducing it increases the attractiveness of a transportation system and, in the case of low-emission public transport systems, contributes to the reduction of greenhouse gas emissions.

From this overview, it emerges that determining the B/C ratio for MDS and pure maglev systems is challenging due to various factors such as geography, demand, and infrastructure requirements. However, key cost and benefit variables can be compared. Pure maglev incurs higher CAPEX due to dedicated infrastructure, land acquisition, and procurement of new rolling stocks, whereas MDS leverages existing railway assets, reducing initial CAPEX and enhancing accessibility. While pure maglev has lower OPEX in terms of energy consumption, MDS' maintenance costs remain an open point, requiring further research. In terms of benefits, MDS has a lower environmental impact during construction, as it does not require new infrastructure, whereas both systems offer similar advantages in operation, such as low noise and greenhouse gas emissions. Pure maglev excels in energy efficiency and speed, though MDS has the potential to achieve higher velocities taking into consideration infrastructural limitations and regulatory constraints. Additionally, MDS' seamless integration into existing rail networks makes it a more attractive and practical solution, particularly in urban settings where maglev infrastructure may be restricted to peripheral areas, impacting total travel time.

Ultimately, pure maglev is justified in high-demand corridors, while MDS offers a cost-effective way to enhance railway competitiveness by leveraging existing infrastructure without requiring additional large-scale investments.

10.2 Comparative Cost-Benefit Analysis of Hyperloop Technology

The hyperloop concept has emerged as a disruptive innovation in the field of high-speed transportation. Envisioned to achieve ultra-high speeds through low-pressure tubes and magnetic levitation and propulsion, hyperloop holds the potential for reduced travel times, lower energy consumption, and enhanced connectivity. It could serve as an alternative to medium-range intercity travels by air **[25]**. However, the economic, environmental, and operational feasibility remains highly debated. This paragraph presents a qualitative CBA of hyperloop, to compare its expected advantages and challenges with those of MDS through the results of the CBA conducted in the previous chapters.

A primary concern for hyperloop is its high infrastructure cost. It has been initially estimated that the cost of a hyperloop route between Los Angeles and San Francisco could be approximately €10 million per kilometre **[26]**. However, subsequent feasibility studies have suggested that this figure is a significant underestimation. For instance, the feasibility study for the Abu Dhabi-Dubai Hyperloop corridor placed the estimated cost at €83 million per kilometre **[27]**. Similarly, according to **[25]**, hyperloop cost per km exceeds initial estimates by a factor of five or more. A comparison with existing high-speed transportation systems further illustrates these concerns.

The Shanghai Maglev, a commercially operating magnetic levitation train, cost approximately €40 million per kilometre for infrastructure alone. Given that hyperloop requires both high-precision vacuum tube construction and specialized terminal facilities, its infrastructure costs are likely to surpass those of maglev and HSR. The possible need for tunnelling, elevated tracks, and right-of-way acquisitions could further escalate costs, particularly if adopted in urban and geographically constrained areas **[25]**. Additionally, costs related to vehicle procurement and the certification of the technology must be considered. Unlike MDS, which can be integrated into existing railway networks, hyperloop requires dedicated infrastructure. The rigid alignment requirements, such as minimal curvature and controlled gradients, pose further constraints on route selection and network scalability, leading to higher costs **[27]**.

On the operational side, while hyperloop could potentially count on lower costs than those of existing transportation systems – due to theorized reduced friction and energy efficiency – there are several challenges that may offset these benefits. The infrastructure might require specialized maintenance operations and higher energy consumption compared to MDS and traditional rail systems to maintain the vacuum within the tubes. A key additional cost consideration is the continuous energy demand required to sustain the low-pressure environment, as vacuum pumps must operate constantly to compensate for air leaks and ensure stable conditions. Unlike conventional rail or pure maglev, where energy costs are primarily tied to vehicle propulsion, hyperloop's infrastructure itself consumes energy, adding long-term operational expenditures that are often overlooked in early feasibility estimates **[28]**. It is also noted that the energy required to maintain low-pressure tube conditions may offset operational savings **[25]**. Consequently, further analyses are necessary to better understand operational and maintenance costs associated with hyperloop, derived from the technological diversity compared to existing systems.

Moreover, hyperloop – as an emerging transportation technology – is anticipated to incur higher development costs, particularly in achieving safety standards comparable to existing transport systems. In contrast, traditional railways or pure maglev do not face significant development costs as their underlying technologies are already at high TRLs, while MDS are designed to integrate with existing railway infrastructure, potentially leading to lower development expenses. Finally, hyperloop presents regulatory challenges that could delay large-scale implementation, due to the fact that it is a developing technology. Unlike traditional systems, which operate under established safety standards, hyperloop lacks a comprehensive regulatory framework **[25]**.

From a benefits perspective, the analyses highlight that hyperloop presents several potential benefits, particularly in terms of theorized travel time reduction and energy efficiency. Feasibility studies suggest that a hyperloop system could potentially achieve speeds exceeding 1.000 km/h, cutting intercity travel durations to a fraction of conventional modes **[29]**. Moreover, expected benefits include decreased road congestion due to the potential modal shift of passenger and freight transport to hyperloop systems and a greater contribution to sustainability. Unlike aviation, which rely on fossil fuels, hyperloop is envisioned to be fully electric with the possibility to operate on renewable energy sources. The Midwest Connect Feasibility Study estimated that a hyperloop corridor could result in a reduction of 2.4 million tons of CO_2 emissions over 30 years, translating into $126 million in emissions savings **[30]**. Nevertheless, the full life-cycle environmental impact of hyperloop remains uncertain. The construction phase – including materials production, land development, and energy-intensive vacuum infrastructure – could introduce significant environmental costs, especially in regions where renewable energy infrastructure is limited.

Considering these factors, the Cost-Benefit ratio of hyperloop remains more uncertain than that of MDS due to economic, technological, and regulatory challenges. Hyperloop's infrastructure-intensive nature results in significantly higher CAPEX, whereas MDS leverages existing railway corridors, reducing costs. Initial estimates of hyperloop's construction costs have been consistently adjusted upward due to feasibility challenges and cost overruns. Operationally, while hyperloop's reduced aerodynamic drag and electric propulsion suggest energy efficiency, these gains are offset by the continuous power required for vacuum pumps and decompression systems, raising long-term energy sustainability concerns. Unlike MDS, hyperloop depends on entirely new regulatory frameworks, increasing development complexity, costs, and deployment timelines. Additionally, its need for dedicated, low-curvature infrastructure limits flexibility and scalability compared to MDS, which integrates seamlessly into existing networks. Despite its potential for ultra-high-speed travel, hyperloop's high financial risks and lack of commercial-scale implementation make its short-to-medium-term viability uncertain. In contrast, MDS provides a more stable and scalable alternative with high-speed capabilities, an established basis for a regulatory framework, and adaptable infrastructure.

Ultimately, while hyperloop is an ambitious innovation, its economic, operational, and regulatory uncertainties suggest a less favourable cost-benefit balance in the near term. Until these challenges are resolved, MDS emerges as a more pragmatic and viable option for high-speed transportation expansion.

11 Conclusion

Deliverable D7.3 presents a Cost-Benefit Analysis (CBA) for three use cases in the MaDe4Rail project **[D7.1]**, alongside two additional use cases assessed using alternative socio-economic appraisal methods. For each case, a detailed evaluation of capacity and operational models is provided for various scenarios. These assessments underpin an analysis of both investment and operational costs, as well as the potential benefits of implementation.

Use Case 1: Upgraded Traditional Railway

This use case focuses on the potential enhancements to railway operations in Sweden by integrating an "Upgraded Traditional Railway" MDS. The assessment evaluates two different scenarios aimed at improving the efficiency passenger and freight services on both existing and planned railway lines by the introduction of linear motors:

- Scenario A: This scenario involves upgrading a 65 km single-track electrified railway line for mixed passenger (13 regional trains/day at 120 km/h) and freight traffic (7 trains/day at 80 km/h). By integrating a linear motor, freight trains can handle steeper inclines (up to 25‰) and align speeds with passenger trains, improving overall capacity utilization. Despite a 23% rise in energy consumption (reduced to 5% with energy recovery technology), the benefits — such as time savings and reduced externalities — outweigh the costs of the upgrade, yielding a Benefit-Cost (B/C) ratio of 1.04. This scenario shows the potential for more efficient mixed-traffic operations, enhancing the appeal of rail transport.
- Scenario B: This scenario examines a linear motor in the design of a new 49 km high-speed rail (HSR) line. It enables conventional trains to reach speeds of up to 250 km/h on steep gradients (24‰), optimizing infrastructure like tunnels and bridges while reducing energy consumption by 7%. However, low travel demand results in a B/C ratio of 0.27, largely due to the high construction costs (€ 4.3 billion, with € 143 million allocated to earthworks). Despite a potential 30% reduction in earthwork costs (€ 45 million savings), the low traffic volumes reduce overall feasibility. This scenario suggests that the linear motor technology could be more effective in regions with higher transport demand, potentially achieving a B/C ratio of 1 or more.

Use Case 2: hybrid MDS based on air levitation

This case analysed a hybrid MDS with air levitation on a ca. 50 km double-track line (75 services/day). The goal was to enhance capacity, frequencies, and energy efficiency. However, the single scenario yielded a B/C ratio of 0.59. Despite potential demand increases from reduced headways, travel times remained unchanged, and energy consumption only decreased by 2%. The socio-economic benefits, including new users and lower operational costs (OPEX), did not compensate for the high retrofit costs (~ € 95 million/km for double track), driven by the need for additional track slabs. This highlights the need for further technological development and analysis before air-levitated systems can optimize capacity.

Use Case 3: hybrid MDS based on magnetic levitation

This use case focused on the introduction of a hybrid MDS based on magnetic levitation on a ca. 600 km double-track line, handling about 800 trains per day. Two scenarios were analysed:

- Scenario A: This scenario involves minimal infrastructure changes, integrating MDS technology with existing tracks. Maglev-based MDS offers significant benefits by reducing travel times, increasing rail modal share, and lowering externality costs (traffic accidents, pollution, noise). Despite increased energy consumption considering no breaking energy recovery technology (10-22% depending on acceleration and coupling configurations), and higher number of pods required to provide the services, Scenario A produced a positive B/C ratio of 1.31, attributed mainly to increased speed in curves (up to 25% faster).
- Scenario B: This scenario proposes optimizing the alignment, increasing curve radii, and adding levitation beams parallel to the rails to enhance the line's cant. However, the higher costs of the technology in this configuration, due to magnetic levitation and guidance, result in a B/C ratio of 0.78. The benefits associated with the modification of curve radius in the track alignment were marginal compared to the overall time savings obtained from the additional cant deficiency provided by the MDS technologies. While the identified benefits related to these modifications were similar to Scenario A, the increased CAPEX due to the additional components for maglev levitation made the total benefits slightly below total costs. The possible application of the technology to different contexts (e.g., shorter lines, more homogeneous in terms of service coverage and technical characteristics) could generate total benefits exceeding total costs as well.

In addition to analysed original line, the impact of introducing a hybrid MDS system based on maglev technology was also analysed for another connected use case: the "airport shuttle," identified among the 19 use cases from the market consultation workshops conducted in WP7. This evaluation included an additional scenario that incorporated infrastructure linking the two main stations from one of the cities with its main international airport. This ca. 30 km double-track line is dedicated exclusively to passenger services and supports all existing regional train connections between the city centre and the airport. The inclusion of this section significantly improves the benefit-cost (B/C) ratio of the use case in Scenario A, improving the B/C indicator to 1.88 This demonstrates strong potential for the socio-economic feasibility of the "Airport Shuttle" use case. Upgrading the railway line would further strengthen rail's role as the primary mode of access to the airport, enhancing its appeal as the main transportation option for reaching it.

Additional Business Case: Terminal

Linear motor propulsion through MDS technology was analysed in a business case at an Italian terminal, showing substantial potential for operational efficiency, sustainability, and cost-effectiveness. By replacing diesel shunting locomotives with electric, semi-automated solutions, fuel consumption, OPEX, and CO_2 emissions could be reduced by 72.7%, € 2.74 million annually, and 93.4%, respectively. With a projected demand increase of 30% and a positive Net Present Value (NPV) of up to € 22.09 million (depending on grant schemes), this solution offers a scalable framework for future growth. A high return on equity (up to 62%) underscores the financial viability of this use case.

Outlook

The preliminary analyses conducted in this document highlight the potential of MDS technologies, although further detailed cost assessments are needed as they evolve beyond TRL 2. This includes refining assumptions regarding infrastructure impacts, as detailed in **[D8.1]**. While performance improvements remain the most promising aspect of these systems, dedicated studies must delve deeper into capacity impacts to fully assess MDS's potential and compare the feasibility to introduce MDS with that of introducing other innovative and traditional transport systems such as traditional railway, traditional maglev and hyperloop systems. In this perspective, a structured comparison has been provided in Chapter 10, to better understand how cost-related considerations and expected benefits of MDS can be framed within a broader discussion considering, however, that the analyses are high-level and require more in-depth and structured investigations to provide a comprehensive assessment.

It's important to consider that MDS technologies offer a significant advantage by enabling performance improvements on existing infrastructure, a key benefit in Europe, where building new lines can be challenging. Moreover, these systems support mixed-traffic operations, harmonizing speeds across train types.

Finally, it's important to emphasize the broader socio-economic benefits of adopting innovative rail technologies like MDS. They have the potential to enhance regional connectivity, operational efficiency, and sustainability, aligning with Europe's ambitious environmental goals. MDS technologies represent a promising step toward a more efficient, sustainable, and connected transport network for the future.

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