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Deliverable D 6.2

MDS operations and maintenance overview and evaluation

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Report contributors		
Name	**Beneficiary Short Name**	**Details of contribution**
Jesus Felez Gregorio Romero Jose Antonio Lozano	UPM	Chapter 1, 3, 4, 5, 6, 7.7, 8 Review of the document
Arbra Bardhi Stefano Ricci	DITS	Chapter 7.2, 7.7
Michael Meyer zu Hoerste	DLR	Chapter 7.7 Review of the document
Gerardo Fasano	GESTE	Review of the document
Lorenzo Andrea Parrotta	IRONLEV	Chapter 7.4
Carlos Casanueva William Zhendong Liu	KTH	Chapter 7.5, 7.7.1 Review of the document
Francesco Inzirillo	MERMEC	Chapter 7.3, 7.7
Aleksandra Fabisiak Michael Schultz-Wildelau	NEVOMO	Chapter 7.4, 7.5, 7.7

Riccardo Ioncoli Giovanni Malafronte Emmanuele Vaghi Stefano Giulianelli	RFI	Chapter 7.1, 7.6
Camilo Patino Puerta Giovanni Di Blasio	RFI	Review of the document
Michel Gabrielsson Pär Farnlof	TRV	General discussions and review
Yunlong Guo Dirk Jan Schipper Rolf Dollevoet	TUD	Chapter 7.5

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1 Executive Summary

Railway operations involve the management and coordination of a wide range of tasks required to ensure the safe and efficient transport of passengers and goods by rail. It encompasses all activities related to the operation of a railway system and is undoubtedly a key aspect for it's proper functioning and for the high level of customer acceptance of this service.

This deliverable deals with the dimensions that affect the operation of maglev-derived systems (MDS), considering also hybrid configurations where such systems would existing railway systems . The deliverable has also identified and evaluated the design methodology and constraints for operation in typical and perturbed regimes for MDS, considering capacity planning & timetabling, CCS, TMS, station design, management and maintenance, and customer acceptance assessments of a new way of travelling, also including miscellaneous aspects such as access control and buckling up, control of luggage arrangement, resulting dwell times, etc.

First, a preliminary analysis of the state of the art for the different aspects considered and analysed in this deliverable, based on the operations of existing pure maglev systems.

This is followed by a summary of the previous analyses related to operations already covered in previous deliverables, including some aspects related to KPIs, operational context and key operational parameters.

Chapter 7:"Operational Models" represents the core of the deliverable, identifying and evaluating the design methodology and constraints for the operational procedures in typical and perturbed regimes.

Firstly, the different operational models have been identified. This was followed by an assessment of capacity planning and timetabling, taking into account factors affecting capacity, methods for calculating capacity, an assessment of the capacity of rail services affected by hybrid operations with MDS and an assessment of key performance indicators for MDS.

In relation to CCS&TMS, based on the analyses carried out in the previous phases of the project, potential risks for the full reuse of CCS systems have been highlighted, taking into account the interoperability of the new MDS systems with respect to lines in commercial operation and possible impacts.

The next chapter addresses key station management and design considerations in relation to the identified configurations for MDS and their potential interaction with the existing railway system, including station design and requirements, platform design for MDS vehicles, and station planning and management.

The chapter on asset management and maintenance covers strategies for asset management and maintenance, , maintenance planning and procedures, as well as potential benefits and issues in terms of maintenance for the three MDS configurations considered in the project.

The next chapter includes aspects and considerations related to the assessment of customer acceptance of a new way of travelling that would derive from the introduction of MDS and the definition/redefinition of related elements, considering both passenger and freight services.

The last chapter of the deliverable presents the proposal of an evaluation framework and methodology for MDS, including the benchmarking technique and the definition of indicators to assess the constraints and design methodology for operation in typical and perturbed regimes.

The evaluation framework proposed by MaDe4Rail is based on the methodology proposed in (IMPACT-2, 2021), adapted to the specificities of the MDS. Because of the scope of the MaDe4Rail project, only the KPIs model and the Customer Experience model have been considered.

Regarding the KPIs model, the three separate sub-models corresponding to Life-Cycle Costs (LCC), Reliability & Punctuality and Capacity have been taken into account, providing different considerations and constraints specific to MDS. Accordingly, and based on the above considerations and constraints for the MDS, several KPIs have been proposed to be considered in the general KPI model for MDS.

The second part of the evaluation framework and methodology includes the Customer Experience Model, also based on the one proposed in (IMPACT-2, 2021), adapted to the specificities of the MDS. In this case, MaDe4Rail only addresses various considerations and constraints specific to MDS systems, related to the Comfort & Services category, as the other two categories considered in the general model are outside the scope of the project.

Finally, the deliverable presents the main conclusions of these studies.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
5S methodology	Sort, Set in Order, Shine, Standardize, Sustain
ATO	Automated train operation
BTM	Balise Transmission Module
CBM	Condition based maintenance
CCS	Control, Command and Signalling
CE	Customer Experience
ECM	Entity in Charge of Maintenance
EMC	Electromagnetic Compatibility
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
EVC	European Vital Computer
FRMCS	Future Railway Mobile Communication System
GHG	Greenhouse gases
GNSS	Global Navigation Satellite System
GoA	Grade of Automation
GSM-R	Global System for Railway Mobile communications
HSGT	High-speed ground transportation
HSR	High-speed railway
ICE	German Intercity Express
IM	Infrastructure Managers
IP	Innovation Program
KPI	Key Performance Indicators
LCC	Life-Cycle Costs
MDS	Maglev Derived System

Abbreviation / Acronym	Description
MSM	Medium speed magnetic levitation
OBU	On-Board Unit
OCS	Operation Control System
PDCA	Plan, Do, Check, Act
PSO	Public Service Obligations
RBM	Risk-Based Maintenance
RCM	Reliability Centred Maintenance
RFT	Run To Failure
RU	Railway Undertakings
S2R	Shift2Rail
SPAD	Signal Passed at Danger
TDS	Train Detection System
TGV	Train a Grand Vitesse – High-Speed Train
TMS	Traffic Management System
TOD	Transit-oriented development
TPM	Total Productive Maintenance
TRL	Technologically Readiness Levels
TSI	Technical Specifications for Interoperability
TSI INF	Technical Specifications for Interoperability relating to the infrastructure
TSI PRM	Technical Specifications for Interoperability relating to accessibility for persons with disabilities and persons with reduced mobility

3 Background

The present document constitutes the Deliverable D6.2 “MDS operations and maintenance overview and evaluation” in the framework of the Flagship Project HORIZON-ER-JU-2022-FA7-02 – Maglev-Derived Systems for Rail (MaDe4Rail) as described in the EU-RAIL MAWP.

4 Objective/Aim

Railway operations involve the management and coordination of a variety of tasks required to transport passengers and goods safely and efficiently by rail. Railway operation encompasses all activities related to the operation of a railway, being undoubtedly a key aspect for the proper functioning of the railway and for this service to have a high degree of customer acceptance. This deliverable deals with those dimensions that affect the operation of this new concept of MDS systems.

The objective of this deliverable is to carry out a comprehensive study of the possible operating procedures for each selected MDS configuration, including operations and maintenance for the MDS, considering, where applicable, both pure MDS services and hybrid services (coexistence of conventional rail + MDS).

Starting from the MDS configurations selected in D6.1 (Made4Rail D6.1, 2024), this deliverable will identify and evaluate the design methodology and constraints for the operational procedures in typical and perturbed regimes. In this document, under the umbrella of operational procedures we will include considerations about capacity planning & timetabling, CCS, TMS, station design, management and maintenance, and customer acceptance assessments of a new way of travelling, also including miscellaneous aspects such as access control and buckling up, control of luggage arrangement, consequent dwell times, etc.

As a result of these studies, an evaluation framework and methodology has been established, including a benchmarking technique and indicators.

The workflow of the studies performed in this document is shown in **Figure 1**.

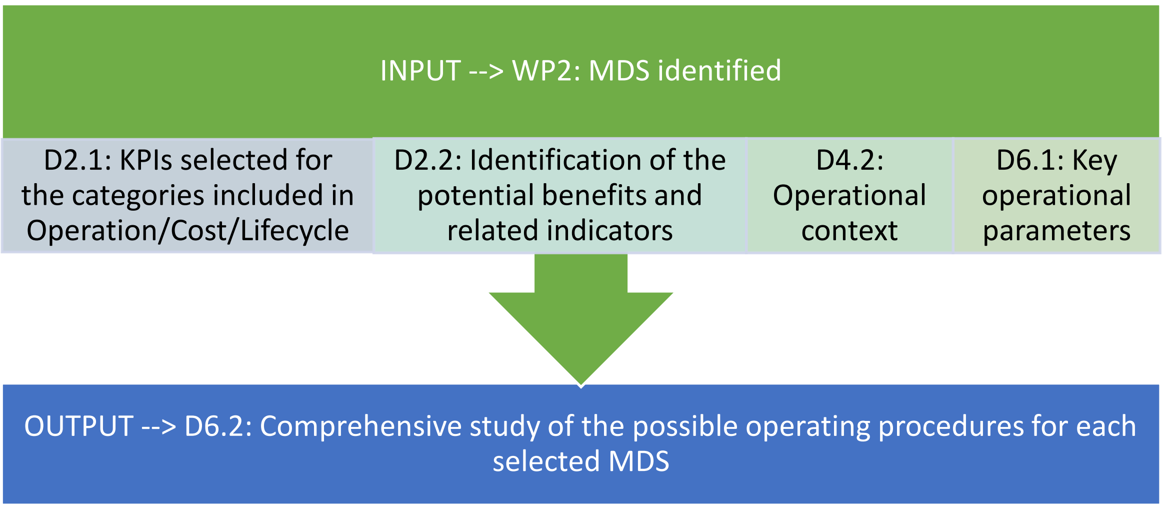

Figure 1. D6.2 workflow.

5 State of the art about operational aspects for existing pure maglev systems

This section provides a preliminary analysis of the state of the art for the different aspects that are considered and analysed in the present deliverable. More specific state of the art and additional references are included in the corresponding specific chapters.

In this way, in spring 2018, the non-profit International Maglev Board conducted a primary study among maglev specialists and transport experts with the aim of tracking current trends in the market prospects of magnetic levitation or maglev technologies (Wenk et al., 2018). Questions comparing the suitability of conventional wheel-on-rail and maglev technologies for different applications are the main focus of the study. Predicted opportunities and developments in maglev technology, acceptance issues and research needs are analysed. The results are broken down by expertise and nationality of the participants.

The primary study was conducted in the spring of 2018, using an internet-based online survey conducted among 1,058 maglev and transport experts (Wenk M. et al., 2018). The ratings vary considerably depending on the level of expertise and the country of origin of the respondents. In certain applications, wheel-rail remains the preferred transport technology. However, most transport professionals prefer maglev technology to conventional steel wheel-rail systems in certain other applications. This is particularly the case for high-speed magnetic levitation and the new application of magnetic levitation in buildings.

The first studies related to the operation of high-speed rail systems deal with comparisons with conventional high-speed rail (HSR) systems. In this way, the paper (Najafi and Nassar, 1996) focuses on the characteristics and conditions for which existing European and Japanese systems were designed, comparing the characteristics of existing HSR systems with magnetic levitation systems. The technologies considered are the French train a grand vitesse (TGV), the Swedish X2000, the German Intercity Express (ICE) and Transrapid, and the Japanese Shinkansen, MLU, and High-Speed Surface Train (HSST), which provides a general comparison of the key operating parameters of these HSR systems.

Also related to the need for high-speed ground transportation (HSGT) systems, the reference (Liu and Deng, 2004) compared the two distinguished technologies under the general HSGT umbrella: HSR and Maglev, and their potential implementation in the Beijing-Shanghai corridor, by analysing not only the technology, but also a comparison of the operating characteristics of HSR and Maglev, and the implications of their potential application in a 1,300-km-long corridor from Beijing to Shanghai - the top economic, population, and cultural engine in China. The study compared speed, acceleration, deceleration, capacity, safety and reliability, energy consumption and noise. The maglev is able to quickly reach its maximum speed once the limitations of the curve are overcome. Both the deceleration time and distance are shorter, so it can maintain the ideal speed much longer. It is not surprising, therefore, that the final travel time through HSR can double that of Maglev, although the ideal analysis showed only about a

50% difference. That is, the actual travel time for HSR may be closer to 8 h vs. 4 h, vs. our preliminary estimate of 5 h vs. 3.5 h. Nevertheless, HSR offers great advantages in accommodating the existing rail network with interchangeable operations. However, Maglev rail is exclusive and would be isolated.

The paper (Stephan and Fritz, 2006) described the methods and results of the operating planning and the system design of both Maglev and Railway system in the pan-European Corridor IV from Berlin (Germany) to Budapest considering the number and location of intermediate stops, the track alignment, the traffic prognosis, and the technical system parameters. The varying system characteristics of Maglev and Railway required different operating programs and technical layout of both systems. Finally, the study evaluated the feasibility and economic efficiency of high-speed urban passenger transport in the pan-European Corridor IV.

Reference (Mao et al., 2008) summarizes the advantages and disadvantages of the world's maglev technologies in the possible development of China and presented their technological and economic feasibility of different types of maglev systems and their current technical maturity from the viewpoint of engineering construction.

The paper (Barbosa, 2019) presented a review of the maglev transport technology, emphasizing its potential and risks of the low and high speed (urban and intercity) market, followed by a summary of some case studies.

In the field of capacity planning and timetabling, there are many publications in relation to the topic, although most of them are aimed at conventional rail. However, some publications that analyse the topic for magnetic levitation systems were found.

The paper (Kunimatsu et al., 2009) introduced a train timetabling algorithm which organizes train timetables directly from passengers' demands. The algorithm takes passengers' demands as its input and outputs a near optimal timetable from the viewpoints of different criteria.

Reference (Cheng et al., 2018) studied the timetable optimization of the ATO system of medium-speed maglev trains. The optimization goal was considering minimizing the total travel time of passengers, establishing a mathematical model based an improved novel global harmony search (INGHS).

The paper (Fritz et al., 2018) compared the secondary energy demand of different wheel-rail systems, such as ICE, TGV and Shinkansen, and maglev systems, such as Transrapid and Chuo Shinkansen. As conclusion, the paper stated that, up to the design speed of wheel-rail systems, there are slight advantages in terms of energy consumption for maglev. From the point of view of energy consumption to reduce travel time, high-speed maglev systems represent a promising option for new rail projects. However, the decision on a specific system for a project should be based on a full life-cycle cost analysis, including the investment cost.

In the reference (Huo et al., 2018) a study on the timetabling of medium-speed maglev train considering passenger demands was conducted. The timetabling problem was formulated as a

0-1 integer programming model based on cumulative flow variables with the objective of minimizing the total travel time for passengers, and the Lagrange relaxation algorithm was used to solve the model. Similarly, (Wang et al., 2018) proposed a method for calculating capacity of a medium-speed maglev line.

The reference (Canca et al., 2019) presented a mathematical programming model that simultaneously determines the infrastructure network as well as the line configuration and selects the train model to operate each line. Transit allocation, frequency and capacity issues need to be solved in an interrelated way.

The paper (Zhong et al., 2020) considered the time-optimal control problem for medium-speed maglev trains with operational and safety constraints. By expressing the basic resistance of the medium-speed maglev train as a piecewise-quadratic function of the train's speed, they formulated the time-optimal control problem as an optimal switching control problem with free terminal time and state-dependent switching conditions. A numerical example using data for a real line was given to demonstrate the effectiveness of the proposed approach.

Recently, considering both propulsion and suspension energy consumption, the paper (Lai et al., 2023) addressed the problem of energy efficiency of medium speed magnetic levitation train schedules. The problem of timetable design was modelled as a two-level model for a complete bi-directional magnetic levitation train line. The upper level, which makes the train operation more convenient for passengers, determines the departure time of the train at the first station. The lower level builds an energy efficient timetable optimisation model using an empirical description of train energy consumption as a function of segment running times. For this purpose, all the services in both directions over a given planning horizon that serve a known passenger demand were considered. Experiments showed that the proposed framework can generate energy-efficient medium speed magnetic levitation schedules including time, space, speed, and electrical variables.

The field of CCS & TMS has also been widely addressed in the railway sector. However, there are not many references specifically dedicated to maglev systems. Among the most relevant ones, the following one is worth mentioning. In (Wu et al., 2019), an Operation Control System (OCS) of 600 km/h high-speed magnetic levitated transport system was designed by the team of CRRC without any international standards for high-speed maglev. Based on principle of IEEE1474 CBTC (Communication Based Train Control) standard and Shanghai Maglev Commercial Line, a new operation control system of 600 km/h high-speed maglev named 600-OCS was successfully designed. After the prototype is completed, the simulation was carried out in the laboratory. The simulation results showed that 600-OCS has advantages of simplified system structure, safer traction power cut-off and integration of OCS and traction system compared with OCS of Shanghai Maglev Commercial Line.

In the field of station management and design, the main related publications focus on the field of integration of different transport modes. Thus, the reference (Marscholek-Uecker and Huhn, 2006) proposed a holistic design concept is for vehicles and stations with vehicles, stations, and the environs co-ordinated with one another.

The paper (Chen and Wei, 2013) reviewed the background and highlights the features commonly shared by most newly developed HSR stations. A case study of Hangzhou East Rail station (HERS) was presented to reveal four key issues: intercity accessibility, intra-urban accessibility, new town development, and social segregation.

In (Ma et al., 2018), a Transit-oriented development (TOD) planning model was developed to provide references for the rapid development of the rail transit in China. Based on the conditions of China, this TOD model was established on a multi-objective program model. A case study was used in this study to test the effectiveness of the proposed TOD model and solution method.

The paper (Coppola and Silvestri, 2020) proposed a method to assess the safety and security perceived by travellers in the railway stations and an application to the case study of the (medium size) station of Frosinone, Italy, was presented. Main findings confirmed that security issues are perceived as more threatening than safety ones. Models estimated shown that thefts, harassments, aggressions are the most relevant variable affecting the perception of safety and security in the station. Moreover, the levels of perception vary also with the socio-economic characteristics and the personal attitudes, meaning that not all the measures for effective safety and security are equally perceived.

In (Bychkov et al., 2021) authors proposed an approach to transport hub modelling using multiphase queuing systems with a batch Markovian arrival process as an incoming flow. In this paper, a method was developed by applying more complex models based on queuing networks that allow us to describe in detail the route of requests within an object with a non-linear hierarchical structure. The proposed method is suitable for describing a wide range of cargo and passenger transport systems, including river ports, seaports, airports, and multimodal transport hubs. It allowed a primary analysis of the hub operation and does not need large statistical information for parametric identification.

Finally, (Sundling and Ceccato, 2022) presented a systematic review the international evidence in rail-bound environments regarding characteristics impacting safety perceptions and behavioural consequences of unsafety, using the databases ScienceDirect, Scopus, PsycInfo, and Google Scholar. A social-ecological framework was adopted to categorize the findings in which place, social, individual, and temporal characteristics were identified along with short-term and long-term behavioural consequences of unsafety. Among the most important characteristics affecting passengers' safety were lighting, surveillance, other persons' behaviour, time of day, and one's own gender.

Finally, in the field of management and maintenance, although there are numerous publications in the field of railways, specifically in the field of maglev systems, only a few of them are published. The paper (Sawilla and Otto, 2006) described the Assessment Approach by using applicable standards, State of the Art and contractual. The application and differences of available German Guidelines (e.g. so-called "Mü8004") and European Railway Standards (EN 5012x) as well as the relationship between the Operation Control System (OCS) Assessment and the Overall System Safety Acceptance Process was presented in detail.

6 MaDe4Rail previous Work Packages considerations about operational aspects

Some aspects related to KPIs, operation, operational context and key operational parameters have been covered in previous deliverables. This chapter provides a summary of these previous analyses related to the analysis of the MDS railway operation.

6.1 WP2: Identification and design concept of technical enablers and basic technologies supporting MDS

In relation to WP2, the deliverable “D2.1: Functional, technical, operational and economical overview of conventional rail systems, traditional maglev systems and innovative maglev-derived systems” (MaDe4Rail D2.1, 2023) in section 5.5 “Operational principles” provided a first analysis on MDS, mainly with reference to operational aspects, including a classification according to commercial operation of the identified systems in different geographical locations, their Technology Readiness Levels (TRL), the declared maximum speed, declared maximum acceleration and declared transport capacity according to the operation planning.

Furthermore (MaDe4Rail D2.1, 2023) provided in section 6 a preliminary comparison of the functional, technical, operational, and economic aspects of conventional rail systems, traditional maglev systems and innovative MDS, as well as an operational overview of the conventional railway system, addressing terms such as scheduling and timetabling, dispatching and control centres, train operations, loading and unloading, integration with other modes and environmental issues.

In addition, in section "6.2 Systematic comparison of MDS", relevant qualitative KPIs were identified for the areas of Technology and of Operation/Cost/Lifecycle. For the categories included in the area of Operation/Cost/Lifecycle, all selected KPIs are quantitative.

On the other hand, Deliverable “D2.2: Potential benefits to the railway system derived from maglev and maglev-derived systems” (MaDe4Rail D2.2, 2024) included the identification of the potential benefits and related indicators for the assessment of the application of maglev and maglev derived systems, subsystems, technologies or components in synergy and integration with conventional rail systems, as well as the methodology for their integration for technical and economic assessment in accordance with the European guidelines for cost-benefit analysis.

The benefits of each subsystem (structure, propulsion vehicle, suspension, guidance, braking, vehicle control system, electrical system, etc.) have been reported in the document, obtaining that the macro expected benefits would be vehicle operating cost savings, variation in noise emissions, variation in air pollution, variation in GHG emissions, travel time savings, Infrastructure operating costs savings, and reduction of transport related accidents.

The possible indicators to measure the expected benefits are Maintenance Costs, Passenger Willingness Surveys, Noise Level Measurements, Speed and Time Efficiency, Operational Cost Analysis.

Deliverable 2.2 also identified potential synergies and related benefits for railway systems from the perspectives of economics, environment, customer attractiveness and performance that may arise from the potential adoption of importable technologies.

6.2 WP4: Design concept of the vehicle with a maglev-derived system including vehicle equipment

In relation to WP4, the deliverable "D4.2: Project requirements and technical specifications for MDS bogies/vehicles" (MaDe4Rail D4.2, 2024) provided the requirements and technical specifications necessary for a vehicle system referred to the use cases selected in the WP7.1, therefore it defines operation context of the lines covered by the use cases.

In this document, "Chapter 5. System definitions and operational context" provided a description of the operational context, operational aspects, safety considerations and business and strategic perspective of the different types of MDS that have been considered: hybrid MDS on magnetic suspension, hybrid MDS on air suspension, and upgraded conventional vehicle with MDS technologies on wheels. Also, "Chapter 6 MDS vehicle subsystem requirements" includes a set of requirements described in four different clusters of operational aspects, economic considerations, safety protocols, and the broader business perspective, including aspects such are: ensure smooth integration with urban infrastructure, including stations, terminals, and transit hubs; ensure compatibility with existing rail infrastructure, including track gauges, signalling systems, and electrification methods; guarantee to meet or exceed the minimum performance requirements for acceleration and deceleration in TSI; system control compliant with ETCS L2+; and constraints related to loading gauge, track gauge, minimum curve radius – on wheels maximum axle load, level noise, and maintenance.

With regard to security considerations, document D4.2 indicates that all security features required by applicable regulations will be employed and all mitigation measures resulting from a future comprehensive risk analysis of the system will be put in place.

All these considerations have been proposed with the aim of allowing seamless integration with conventional trains.

6.3 WP6: Technological maturity assessment for passenger and freight applications of the MDS & Evaluation of possible operating procedures

In D6.1 (Made4Rail D6.1, 2024), after the selection of MDS configurations based on the selected criteria, a set of possible use cases for the application of MDS was defined. From these different use cases, a set of six was selected considering the three types of MDS configurations and the type of service (passengers, freight, mixed operations, urban, conventional, high-speed, etc). The criteria used to select the different potential use cases include key operational parameters such as infrastructure cost, speed, vehicle dynamics, travel or journey time, frequency and flexibility, on-demand services, line capacity and quality of service.

7 Operating procedures

This chapter identifies and evaluates the design methodology and constraints for the operational procedures in typical and perturbed regimes. These operational procedures include operational modes, capacity planning & timetabling, CCS & TMS, station design, management and maintenance, customer acceptance assessments of a new way of travelling, also including several miscellaneous aspects such as access control, luggage arrangement control, consequent dwell times, etc. In the following sections, various considerations are made concerning all these aspects.

7.1 Operational models

The Operational Models should define the scenarios in which it is possible to use the technology in complete safety and those in which, instead, mitigating actions are necessary to ensure the correct management of railway traffic in every circumstance.

Generally, the implementation of the new MDS technology should comply with what is written in (Commission Implementing Regulation (EU) 2019/773, 2019), operational principles and rules to be applied throughout the European Union railway system are specified in Appendixes A (ERTMS operational principles and rules) and B (common operational principles and rules).

It is possible to define three different scenarios:

- **Normal conditions:**
    - Rail services are operated according to a detailed off-line operations plan, which specifies for each train its path through the network and its arrival and departure times at its scheduled stops. This operation could be referred to as operation under normal conditions. Traffic management shall ensure the safe, efficient, and punctual operation of the railway, including effective recovery from service disruption (Commission Implementing Regulation (EU) 2019/773, 2019), Annex, 4.2.3.4.1)
- **Perturbed conditions:**
    - During day-to-day operations, disturbances may affect the plan and dispatchers shall take measures in order to keep operations feasible and to limit the propagation of delays. The infrastructure manager shall define, publish, and make available appropriate contingency measures ad assign responsibilities based on the requirement to reduce any negative impact as a result of degraded operation (Commission Implementing Regulation (EU) 2019/773, 2019), Annex, 4.2.3.6.3). The planning requirements and the response to such events shall be proportional to the nature and potential severity of the degradation. These

measures, which shall as a minimum include plans for recovering the network to 'normal' status, may also address:

  - Rolling stock failures
  - Infrastructure failures
  - Extreme weather conditions.

- **Disruptions:**
  - The management of a disruption (such as train delays, reduced operating speeds, bad weather, temporary unavailability of some routes, a train malfunction, or an infrastructure failure), requires the modification of train services, making alterations to the train travel times and routes due to the temporary unavailability of one or more block sections. The infrastructure manager shall define, publish and make available appropriate measures to manage emergency situations and restore the line to normal operation (Commission Implementing Regulation (EU) 2019/773, 2019), Annex, 4.2.3.7.

    Such measures shall typically cover collisions, fires on train, evacuation of trains, accidents in tunnels, incidents involving dangerous goods, derailments.

In addition to complying with what is written in (Commission Implementing Regulation (EU) 2019/773, 2019), some procedures should be specifically identified for each type of MDS infrastructure (dedicated, upgraded, or existing) and for each type of propulsion to ensure operational safety in the event of malfunctions. It must be identified how the new technology fit into the context of the established procedures, which additional criticalities does it present that could impact the safety of circulation and which repercussion has on what is already planned.

It's important to consider that the risk analysis done in WP3, which is still under development at the time of completion of this deliverable, will identify the hazards for MDS, assess the potential risks and risk control measures and define technical solutions as well as technical acceptance processes for the different identified hazards.

However, this chapter presents some examples of requirements that may arise for operational procedures related to risks that would likely not be possible to control with technical solutions. For a better understanding it is possible to refer to the three use cases defined in WP 7.1.

The Use Case #1: Incline Pusher is identified for segments of the route where short but steep inclines affect the maximum load of a complete freight relation. So, in normal condition, MDS solution can be a punctual solution for additional traction. However, failures of this technology could potentially pose safety risks. For instance, a procedure should be established in case of power failure to prevent the vehicle to potentially sliding backwards. It also needs to be determined whether it is possible to send an assisting train on the rear of the train, or it must be sent just on the front of it for safety reasons.

The Use Case #2: Air Levitation configuration is identified for specific route with the aim of increasing rail capacity, reducing shuttle time and minimizing maintenance work disrupting line usage. This MDS solution involves both upgraded trainset with installed air fenders to carry part of loads with wheel-rail as propulsion and new trainset with complete train levitation by air fender and electro-dynamic wheels for propulsion. In normal condition this solution can be a punctual solution for increasing speed and capacity. However, failures of this technology could potentially pose safety risks. For instance, procedures should be specifically established for both cases: upgraded or full AirLev train failures. It also needs to be determined whether it is possible to send a traditional or upgraded assisting train to assist a full AirLev train.

The principle of air levitation is based on creating a pressure differential between the air inside and outside an air chamber, generating sufficient mechanical force to lift a vehicle off the ground. Specific procedures must be determined for air chamber failures and insufficient mechanical force to lift the vehicle. The procedures should explain if it is possible to move the vehicle under a failure and the modalities involved.

Finally, the Use Case #3: Magnetic Levitation configuration is identified to study if it is more convenient to upgrade existent secondary line with Maglev derived technology instead of built brand new high-speed infrastructure. This MDS solution involves upgraded trainset installing new propulsion system and/or magnetic suspension system on maglev corridors. In normal condition this solution can be a punctual solution for increasing speed, capacity and reduce maintenance necessity. However, failures of this technology could potentially pose safety risks. For instance, procedures should be specifically established for both propulsion and/or suspension failures cases. It also needs to be determined whether it is possible to send a traditional or upgraded assisting train to assist a Maglev derived train.

In any case, the infrastructure manager shall determine (in agreement with the driver when it is needed) whether the failure of equipment, including the new MDS solution, affects the safe and/or effective operation of vehicles.

7.2 Capacity planning & timetabling

As a general principle, rail infrastructural capacity is increasingly saturating, as clearly recognized by European legislation in directive 2012/34/EU, recital 58. According to this legislation, infrastructure capacity is meant as the potential to schedule train paths requested for an element of infrastructure on a certain period of time. Strict criteria are provided to ensure that Infrastructure Managers carry out capacity allocation and capacity management through equitable and non-discriminatory processes. Each Member State has established a Regulatory Body, legally distinct and independent from any other public or private entity, to supervise this process, with the power to request information and issue penalties.

Therefore, the operation of maglev derived systems on hybrid infrastructure, must be compatible with the path-based approach at the basis of the current legislation and practice. Technologically, paths are programmed by infrastructure managers with headways around 5 minutes on mainlines down to 2.5÷3 minutes on congested sections. This requires programming timetables with a resolution of 30÷60 seconds. Therefore, any operational procedure thought for the maglev derived systems must be able to ensure, under normal conditions, such a scheduling resolution.

7.2.1 Capacity definition

The capacity concept has been largely discussed in the rail operation literature (Hansen and Pachl, 2014) but the common shared vision confirms its dependence upon functional characteristic of lines and stations.

7.2.2 Theoretical and practical capacity

The first important distinction is between

- Theoretical Capacity: maximum number of trains movement manageable in a specific period;
- Practical Capacity: Maximum number of trains manageable under specified levels of operational quality (normally considered as regularity or punctuality) corresponding to the Minimum Headway (time spacing between trains compatible with safe stop of the following train).

7.2.3 Factors affecting capacity

The declination of the parameters affecting the capacity of a line or a station, in addition to their layout, includes, at least:

- Reference period,
- Train typologies and their sequence,
- Operational regimes,
- Signalling systems,
- Regularity requirements.

7.2.4 Capacity calculations methods

The capacity estimation can be based on various approaches, largely described in the literature (Abril et al., 2008; Kontaxi and Ricci, 2009). Apart the deterministic methods, based on simple algorithms normally not considering the disturbances to traffic and the corresponding effects on the operation, the methods commonly used can be summarised in two families:

- Analytical (stochastic) methods, normally based on probabilistic formulas including parameters representing the affecting factors listed above,

- Analogical methods, normally based on traffic simulations, which can indirectly provide with capacity assessments according to the description of the operational context and the fixed punctuality requirements.
- Among Analytical methods the most consolidated, largely used and recognized is the one issued by UIC in the Leaflets UIC 405-1 R (1978) and UIC 406 R (2004), characterized by user-friendliness and sensibility to parameters, such as the number and the typologies of trains running online, the operation quality requirements (tackled by the queuing theory application) and the infrastructural and technological features of lines (Wahlborg, 2004).

Another comprehensive consolidated probabilistic method is the one proposed by German Railways (DB), based principles like UIC method, though proposing a simplified minimum headway calculation a more sophisticated and articulated link with punctuality data and requirements (Navajas-Cawood et al., 2016).

7.2.5 Assessment of capacity of rail services operated by MDS: study cases

A fist classification could derive for the classification of operational regime based on the level of operational perturbations considered, measured by standard punctuality indicators.

The analysis will be carried out with reference to 3 types of regimes: Normal, Perturbed and Disrupted, as defined in the previous chapter.

In Table 1 the typologies of regimes have been qualified according to preliminary assumptions.

Table 1.- Definition of operational regimes

Type of regime	Level of expected perturbation	Expected delay
Normal	No perturbation	Delay ≤ 3 min [1]
Perturbed	Average perturbation	Delay ≤ 30 min
Disrupted	Peak perturbation	Delay > 30 min

The selection of the most appropriate methodology for the capacity assessment will be strictly depending on the data available from the study cases, which will be the input of the assessment.

According to the information collected and organized for each case study in WP7, we can expect that the available information and related formats, that describe in what form the information will be provided, will be those summarized in **Table 2.**

[1] Delay =0 is the ideal case. In practice, in the normal regime without perturbations, there may be a threshold of a few minutes that is not considered critical for service.

Table 2: Expected datasets from case studies

Information	Format
Goal of optimization with new technology (e.g. more trains, heavier trains, reduced travel time)	Decision
General information (e.g. traffic mode, category of the line, stations)	Description
Operational hours and distribution of trains	Timetable
Number of trains per day by category	Timetable
Complete timetables of all train using the line section (e.g. origin, destination, partial and total runtime on line, length of sections)	Timetable
Maximum allowed speed	Description
Maximum allowed freight trains length	Description
Maximum allowed freight train weights	Technical studies
Starting loads for used loco in different Gradients	Technical studies
Reached speeds (e.g. heavy trains in steep inclines)	Timetable studies
Capacity constraints (e.g. bottlenecks, quality of traffic, maximum possible train runs)	Timetable studies
Stations, terminals and yards along the line	Description layout
Level crossings	Description and layout
Signalling system	Description
Signal locations	Signalling plan
Categories of national signals	Description and rules
Communication system	Description
Elevation profile of the line (e.g. gradient)	Layout
Curve radius	Layout
Built in cant and cant deficiency in curves	Description, layout
Type of rails (e.g. welded, profile)	Description
Type of sleepers (e.g. material, distance, length)	Description
Type of switches	Description and layout
Track geometry and failures	Measuring protocol
Gauge (e.g. by category and restrictions under the vehicle)	Description and rules
Catenary system	Description and layout
Energy system (e.g. power supply, peak power, peak current)	Description and layout

Information	Format
Location of energy substations	Description and layout
Information of bridges and tunnels (e.g. specific conditions)	Description and layout
Special trackside related assets	Description and layout

The comparative calculation of the capacity will be referred to 3 case studies (identified and defined in WP7) x 3 regimes (Normal, Perturbed and Disrupted) x 2 system configurations (Traditional and Integrated with MDS) (**Table 3**).

Table 3: Scenarios overview

Case studies	Traditional configuration	Configuration integrated with MDS
1	Normal	Normal
	Perturbed	Perturbed
	Disrupted	Disrupted
2	Normal	Normal
	Perturbed	Perturbed
	Disrupted	Disrupted
3	Normal	Normal
	Perturbed	Perturbed
	Disrupted	Disrupted

Furthermore, deliverable "D7.2 Technical feasibility study of the maglev-derived system in the use cases selected" also considers two scenarios for each MDS configuration corresponding to MDS with minimum requirements, and MDS with the necessary adaptations to fully exploit the maximum performance.

WP7 will calculate the Normal regime and will give high-level indications for the other cases (perturbed, disturbed, etc.) on a qualitative rather than quantitative level and the final assessment will be conducted in the Cost/Benefit Analysis.

7.2.6 Calculation Key Performance indicators

In the IMPACT-2 Shift2Rail project (IMPACT-2, 2021), comprehensive models have been developed to quantify the Key Performance Indicators (KPIs) identified in the previous IMPACT-1 project (IMPACT-1, 2018).

Three separated models have been developed to display the influence of the Technical Demonstrators of Shift2Rail on the KPIs

- Punctuality

- Life-Cycle Costs (LCC)
- Capacity

The estimations were referred to four different market segments: High Speed, Regional, Urban (metro) and Freight.

Made4Rail proposes to use the same KPIs.

Punctuality assessment

The punctuality considers the distribution of delay across causes as well as the average delay minutes for each cause. These values can be obtained from empirical data provided by the Infrastructure Managers (IM). The MDS introduced in MaDe4Rail could introduce modifications of these values if they affect the causal factors of the delays, such as reliability of components, systems and subsystems of vehicles, superstructure, signalling and control systems, electrification systems, operational planning (timetable structures). Moreover, MDS will introduce new components and subsystems, as well as the interfaces between them and the traditional one, that could produce new cause of unreliability and consequent delays.

The measuring units for the punctuality can be referred to a certain line or network as:

- Number of delayed (over a defined tolerance) trains over the total number of trains,
- Average delay per train.

Life Cycle Cost assessment

There is an extensive literature on the impact of railway traffic on the deterioration of the infrastructure and on its maintenance costs. The approaches can be top-down, using empirical models to establish a direct relationship between traffic and costs; and a bottom-up approach that uses mechanistic models to establish relationships between traffic and deterioration of the infrastructure and then links the estimated deterioration to the maintenance costs. The mechanistic models can also be used to estimate how a deteriorated infrastructure may damage the railway vehicles.

The weight of the vehicles is an important aspect in the deterioration of the infrastructure. Increasing the weight of the trains will cause more wear and tear of the infrastructure and thus increase maintenance costs to keep the service level constant. The KPI model includes the impact of axle loads on maintenance costs, using estimates from an empirical top-down approach. The introduction of MDS could bring additional or decremental effects on infrastructure LCC.

Capacity assessment

The capacity concept introduced in IMPACT-2 includes, in addition to the line and station capacity defined above and measured in [trains/time], the concept of transport capacity, measured in [passengers/time] = [passengers/train] x [train/time] (IMPACT-2, 2021). The introduction of MDS can modify the transport capacity by acting on both components. The same approach can be used for all passenger market segments: High Speed, Regional and Metro.

7.3 Control, Command and Signalling, and Traffic Management System

Control, Command and Signalling (CCS) refers to the on-board and trackside structures and equipment designed to ensure the safe operation and movement of trains, directing rail traffic, and keeping trains clear of each other. Traffic Management System (TMS) is an integrated real-time system that offers monitoring and control of train movements.

TMS imports the status of signals, track circuits and points etc. from the station interlocking system on a real time basis. The Traffic Management System (TMS) implements the current timetable by requesting the assignment of the appropriate track section in a timely manner.

Starting from these generic definitions, it is necessary to address how systems that have been designed mainly for the railway world can also be used in the management of MDS vehicles.

The reference for the first considerations is the ERTMS area and therefore for ETCS signalling (European Union Agency for Railways, 2024).

As a first step it is necessary to highlight the potential areas that can be "compromised" in adopting MDS vehicles in a use that could also be mixed. That is, both traditional trains and MDS vehicles could fit on the same line.

Starting from a top-down approach, the TMS needs to know where the vehicles are present along the line, the status of the point machine switches, the fundamental points of the line, the priorities to be attributed to each vehicle and the timetable for all trains.

So, if we consider that all this information is provided to the TMS by other systems such as Interlocking RBC and ATO, the TMS for the railway world must also be used with the presence or management of MDS vehicles.

This means that there are no constraints introduced by the TMS towards the MDS vehicle. In general, there may be possible operating modes if the MDS vehicle, when traveling along a line, introduces changes to the management of the line itself. This eventuality may produce specific operating modes to be adopted.

Starting from the analyses carried out in the previous phases of the project, potential risks for the complete reuse of CCS systems were highlighted. In the ERTMS/ETCS CCS, the ETCS system cooperates closely with the interlocking present on the line, the ETCS system provides different levels of operation which require or do not require train detection systems installed along the line. Another important aspect to consider is the interoperability of the new MDS system with respect to lines in commercial operation; any repercussions must be evaluated.

Compared to the ETCS system and its installation, consistency with the subsystems used for signalling must be verified. These can be explained in:

- BTM-BALISE

- Radio Communication System
- On-board Train Interface
- Train Detection System
- Localization System (for the future)

7.3.1 Balise Transmission system

In this case it is necessary to verify that the new vehicle does not introduce spurious frequencies around the 27 MHz frequency for the balise energization functions and around the 4.2 MHz frequency for the data transfer functions, as indicated in the UNISIG 036 subset contained in the TSI. Moreover, the UNISIG 085 subset reports the types of tests that must be carried out to guarantee operation.

All these types of tests for interoperability verification should be included in the activities carried out for MDS vehicles. If the signalling is ETCS for each type of line on which the MDS vehicle runs in all its operating conditions, it means that the tests must be performed to cover all cases of vehicle operation.

If the vehicle is perfectly compliant with the use of Eurobalises, then there are no additional requirements to consider. If this does not happen, i.e. the MDS vehicle is not able to read the Eurobalises or introduces disturbances that could cause malfunctions to nearby trains. In this case it is necessary to operate the MDS vehicle and, depending on the side effect produced also on the other trains, in a mode of operation that also requires visual circulation, and this would be extremely intrusive and not acceptable, also due to the repercussions on the traffic of all the trains involved. Therefore, the MDS vehicle must comply with the Eurobalises, as indicated above.

7.3.2 Radio Communication System

The current ERTMS/ETCS system involves the use of GSM-R, but at the European level the FRMCS system specification is about to be published, which will include the use of multiple radio networks. Obviously, there will be backward compatibility with the GSM-R which will be decommissioned starting from 2035. The MDS vehicle is therefore required to comply with current radio communication specifications and future FRMCS specifications. In this context the MDS vehicle will not have to be compatible with a wide range of communication media. Theoretically, this should not be a problem because for non-ETCS applications, compatibility has been verified between the technology applied in MDS vehicles and different types of communication networks. In any case, for each specific MDS solution it is necessary to identify the band of radio frequencies that can be influenced, and the level of any noise produced on the radio bandwidth. This will allow us to better define the operational areas for communications.

All modern signalling systems use radio communications to manage the movement authority for the different trains running on the lines. The ETCS complies with this approach.

7.3.3 On-board Train Interface

One area of intervention that, especially in the past, has produced secondary effects on on-board systems is the introduction and interconnection of the on-board signalling system. For the ETCS world, this type of system includes the OBU (On-Board Unit) for train protection functions and ATO (Automatic Train Operation) for automation functions. Both systems interface with the vehicle and can be affected by side effects produced by the vehicle, or even produce unexpected effects. In accordance with railway regulations, it is necessary to carry out all checks of the operating conditions and therefore of the applicable standards referred to in EN 50155. This involves a series of checks of the site where the systems are hosted and of the use of the MDS vehicle in all possible ways operational so that the checks are exhaustive.

The new electronic systems used for on-board equipment are developed according to European regulations, these are designed to be unaffected by a wide band of disturbances. In the railway sector, the disturbance mask was designed for the technologies adopted up to that point. With the introduction of the new MDS systems it is necessary to check whether the masks are still valid. If it is found that the MDS vehicles introduce signals of an amplitude not permitted in the masks currently in force, it is necessary to evaluate how to mitigate this fact.

Therefore, as mentioned for the radio communication part, it is necessary to have a clear image of the signals emitted by the MDS vehicles to evaluate any areas of intervention.

Carrying out these investigations is however a step required by regulations, therefore a nominal path for vehicle certification. For now, no additional operations have been highlighted, but only exploratory ones.

7.3.4 Train Detection System

Train Detection System (TDS) may or may not exist both depending on the ETCS level adopted and any backup actions chosen by the Infrastructure Manager. If the signalling system provided on the specific line uses TDS, then it is necessary to evaluate the coexistence of the MDS vehicles with the TDS systems adopted.

It must be ensured that the present TDS system is able to safely recognize the presence of the MDS vehicle, otherwise there will be serious impacts on the safety of the line.

There are two main families of TDS adopted: track circuits and axle counters. Both systems can in principle have non-detections and/or false detections in the presence of MDS vehicles operating in their full functionality and may not be operational when the system is levitating. This fact certainly has an impact on the sure determination of the presence of the rolling stock on the rail. This means that levitation cannot be implemented if this type of TDS the only one present on the line travelled.

If there is not a correct coupling between the wheels and the tracks the systems currently in use could fail to recognize the vehicle, further investigations must be made in this direction to guarantee interoperability between the TDS systems used and the MDS vehicles. It is also necessary to carry out cross tests between the different technologies adopted to develop the MDS vehicles and the TDS systems in use.

This series of checks is essential to allow the circulation of MDS vehicles in operational service on the lines also travelled by traditional vehicles.

A possible mitigation at the adoption of TDS is the use of localization systems that implement the safe localization of the train using other sensors, like for example on-board sensors that detects digitally encoded location flags on the guideway. The Train Localization is addressed in the following paragraph.

This type of approach, however, requires that there is a signalling system that safely identifies the presence of the train without the use of TDS. In this case we are talking about ETCS moving blocks without TDS.

7.3.5 On-Board Train Localization

The safe location of the train is a very important function which has the objective, on the one hand, to simplify the architecture of the railway line while reducing maintenance costs and, on the other hand, to achieve increasing accuracy in order to be able to discriminate exactly where the rolling stock is always located.

This ambitious project, also underway in FP2-R2DATO (EURAIL R2DATO, n.d.), must resolve some aspects of the use of certain sensors in the open field and the fact that some of these are influenced by the surrounding environment such as the GNSS receiver.

In the case of MDS vehicles, it is necessary to investigate whether the sensors used to obtain the safe localization of the train can coexist with the technologies and systems used to create the MDS vehicle. These studies have partly been carried out providing good results, but further investigations still need to be carried out, verifying all possible interactions.

Since the Train Localization isn't part to the current TSI, the tests that must be performed to guarantee interoperability are not officially indicated. This is still a relatively young area that needs further investigation.

7.3.6 Final considerations

In general, the TSI currently in use will be updated especially following the results from ongoing projects, for example for the introduction of the ATO GoA 3/4.

This evolution also involves the introduction of the "standardized" use of other sensors for which compatibility with MDS vehicles will have to be verified.

For the CCS field, it is therefore necessary to identify a roadmap for MDS vehicles and define in this process how to adhere to and interact with the ongoing evolution. This way you can anticipate any problems and find solutions that eliminate them.

One point in favour of this evolutionary path concerns the simplification of the lines with the reduction of the installed elements, and the movement of most of the intelligence on board the train. Once all aspects of EMC on board the MDS vehicle have been analysed and resolved, the path should proceed quickly towards the use of combined vehicles on the same lines.

For all other functional aspects, no functional incompatibility problems emerged. MDS vehicles will have to be added as other possible circulating vehicles, and the braking curves, therefore the spacing between trains, will have to be considered. But this is part of how to configure the control system.

7.4 Station management and design

This chapter addresses the main considerations about station management and its design regarding the identified configurations for MDS and their possible interaction with the existing railway system.

7.4.1 Railway stations

Today railway stations are places for transit, for the arrival and departure of travellers. Train stations are designed and built according to specific norms, guidelines, and objectives. The operation of railway stations directly impacts the sustainability of the transportation process and the overall capacity of the railway network, which shows the importance of well-planned stations.

The categorisation of the station is generally done according to the volume of passengers or number of trains per time period, the type of service or the arrangement of the rails.

If the stations are classified based on the volume, they are generally defined by national offices or departments of transport based on a national scale, from main hubs to small secondary stations.

If the stations are classified on the type of service, it can be classified as stations for long distance services or regional stations. Nowadays there are no freight services in passenger stations, as freight operations are separated in specific areas like terminals or yards, which are usually not accessible to the public.

If the stations are classified based on the position of the rail, they can be pass through stations (a.), terminus (b.) or mixed (c.) as shown in **Figure 2**. The terminus architecture indicates that the trains always must invert direction, which causes operational efforts especially by operating classic trains with a locomotive and wagons.

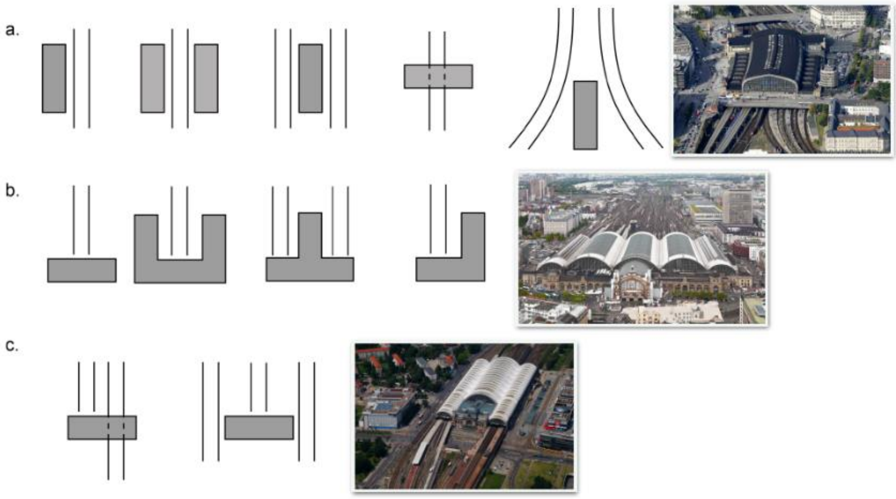

Figure 2. Different types of stations classified by position of the rails.

The guidelines to design passenger friendly stations are based on the central role of passengers and their needs, while maximising structure capacity by designing efficient and safe passenger flows. There is often an increased attention to the passenger experience, by providing additional and community-oriented services. Modern stations are more integrated and consistent with the surrounding community, connected between each other and accessible for everyone.

Platforms are the areas alongside the railway tracks that provide access to the trains. They are generally designed and classified according to the relative height of the train floor. The platform heights and gaps between vehicle and platform are defined in TSI INF (section 4.2.9.2) to guarantee maximum interoperability. The nominal platform height for platforms with high-speed train services shall generally be 550 mm or 760 mm above the running surface. For platforms where only passenger trains for regional services are intended to stop in normal service, different provisions for the nominal platform height might apply. As TSI INF is not completely realized in today's operations the platform height in Europe varies between 200 mm and 1.300 mm. The gap in height and width and possible measures to reduce or overcome the gap are regulated in TSI PRM.

In the future railway stations will be the heart of the smart cities, thanks to accessibility and multi-modal designs. They will be multi-service hubs, places of integrated and sustainable mobility. The new visions, which focuses on people's needs, aim to make stations and surrounding areas safer and more enjoyable, having various objectives including:

- increasing the level of connectivity between long distance and local public transport, sharing mobility and active mobility, to better respond to people's needs;
- improve accessibility within the stations through an inclusive and barrier-free design;
- enhance availability of information and better wayfinding both inside and outside the station.

7.4.2 Platform design for MDS vehicles

The implementation of MDS services in existing stations means that stations will be created in a transport environment which is been developed since decades. To bring together two different transport systems as MDS and conventional railways in one building some major criteria must be considered:

- Integration in existing transport infrastructure and the building structure to connect the systems as good as possible but keeping the innovative character of MDS
- Differences in regulations of MDS and conventional transport, as for example different GoA levels
- Specific and sometimes contrary requirements of customers and operators

Focussing on the platform design it is strictly related to the type of MDS adoption and interoperability needs. Three different approaches must be considered. The first is to have dedicated platform for each transport system, the second is to design platforms for a mixed operation of MDS and conventional trains. And also, a combination of both approaches by sectioning the platforms can be a third solution to be considered.

In case of MDS vehicle floor heights that substantially differs from traditional train floor height, platform height and width design should be targeted to the new system to maximise loading and unloading operations while maintaining a high level of service for passengers. This design of separated traffic platforms streamlines operations by minimizing congestion and ensuring efficient boarding and disembarking processes. Pleasant passengers experience and minimal delays will result in enhanced overall satisfaction. A such separated design should also be used if different GoA levels will be realized. If Maglev pods in a hybrid MDS will operate without drivers, safety measures must be implemented at the platforms, where those vehicles will arrive. In such cases, conventional trains may no longer fit properly on the dedicated platforms (**Figure 3**).

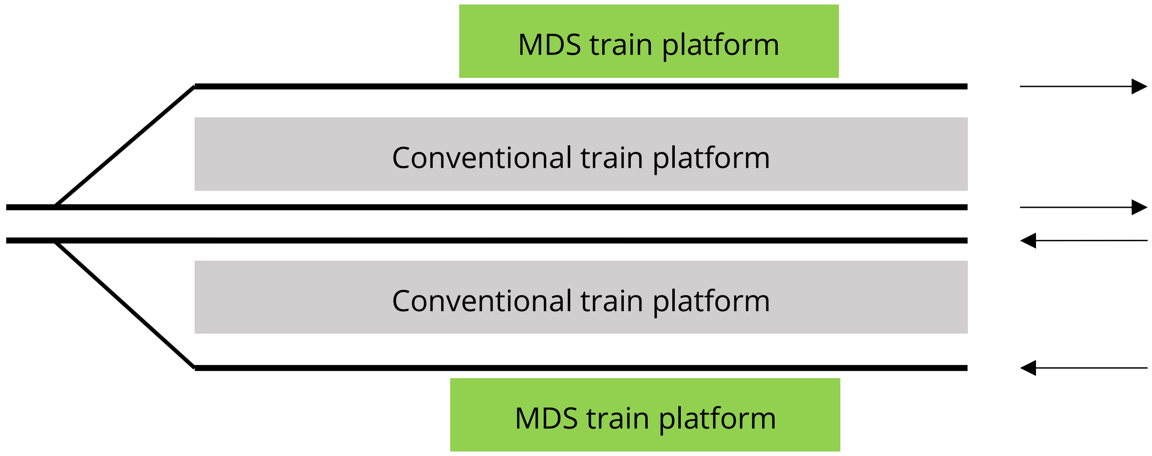

Figure 3. Separated traffic platform schematics.

Contrary to the separated model, mixed traffic platforms (**Figure 4**) accommodate both MDS and traditional trains on the same platform. While this design offers increased flexibility in scheduling, it poses challenges in managing a higher complexity of the flow of passengers and trains. This solution might be feasible for use cases with upgraded vehicles, where the dimensions of the train cars stay the same and only the propulsion system changes.

Figure 4. Mixed traffic platform schematics.

The combined model integrates elements of both dedicated and mixed platform designs. By strategically allocating platform sections for specific trains while allowing flexibility for mixed traffic in other sections, this approach optimizes space utilization and passenger flow, achieving a balance between efficiency and flexibility.

Depending on the configuration of the MDS trading system, the necessary platform adaptations may vary considerably. If the MDS trains are updated vehicles operating with drivers as the conventional trains, the regulations might be comparable, and both types of trains can use the same platform easily (**Figure 5**). In case of integrating a hybrid MDS with driverless pods, the needed measurements will be complex. Variable mechanisms at the edge of the platform are needed to bridge the gap between the platform and the pod in height and width. The platform might also be prepared for GoA 4 operations to ensure passenger safety.

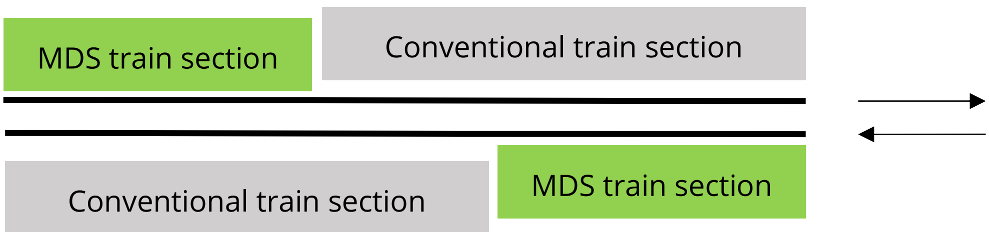

Figure 5. Combined traffic platform schematics.

The decision of the platform design is strongly depending on circumstances. The existing station infrastructure, the specific concept of MDS implementation and the traffic demand of the different traffic systems, all are influencing the station design. The aim must be to fulfil the regulations and find an optimum of all different operational requirements.

The three approaches above are all focussing on the integration of MDS services in existing stations, with as less adaptations as possible. Thinking about future scenarios where lines and stations might be rebuilt and optimised to the new traffic system with both conventional and MDS services, station layouts can look much different and new ideas to guarantee optimized traffic flows can take place. **Figure 6** shows an optimal example of a possible configuration.

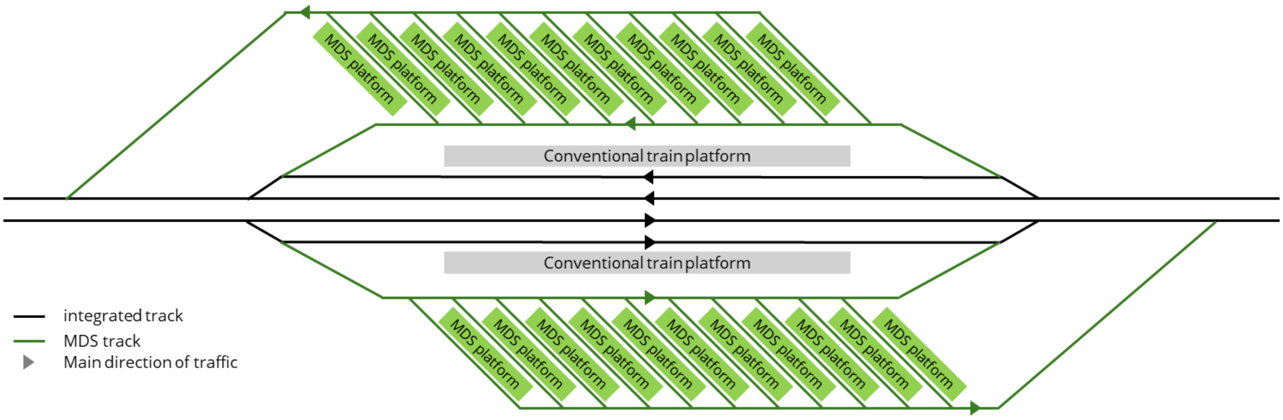

Figure 6. Visionary optimized station layout

Such design can bring the advantages in flexibility of smaller MDS pods into operation. The parked MDS pods can stay at the platforms without disturbing the traffic on the main lines. Arrival and departure times of the pods can be planned individually without caring about the vehicle order at a shared platform. If a real time information system is implemented and the distances between the platforms are short, it might also be feasible to use the platforms individually depending on the operational situation. Passengers will be informed about the next train arrivals and departures and can always choose the next pod.

Another advantage of this design will be the scalability if the space would be there. The MDS platforms can be built as it is needed from the traffic demand. Starting with the first few platforms and extending it stepwise might be a useful approach to implement.

7.4.3 Station planning and management

Transitioning from conventional traffic systems to MDS will bring notable differences in station management and capacity. Stations with high speed MDS transport might prioritize rapid transit and optimized scheduling, deviating from the conventional approach of accommodating diverse traffic types on shared platforms.

This shift necessitates a re-evaluation of station layouts to maximize capacity and efficiency. Through meticulous planning and innovative design, stations can be optimized to efficiently accommodate passenger influxes and minimize congestion. Capacity calculations and simulations for both trains and also passenger flows through the proposed station design have to be considered. The number of trains and passengers per platform will be an indicator for the capacity and quality of a tested station layout. Effective planning parameters for MDS stations encompass factors such as passenger flow analysis, platform allocation strategies, and integration with other modes of transportation into existing infrastructure. By considering these parameters holistically, planners can optimize station design to meet the demands of modern transit systems.

A valid planning needs always effective service control of operations. Service control refers to the management and optimization of resources to ensure efficient operation while meeting demand. This station management should involve monitoring and controlling the movement of trains and people in real-time to maintain efficient operations.

It includes various strategies and techniques to balance supply (available infrastructure and trains) with demand (passengers) in order to prevent congestion, minimize delays, and maximize the utilization of planned and built infrastructure.

It is particularly important for this task to define common KPIs to ensure effective station management. Potential KPIs for evaluation and decision-making in station management can be the following:

- Train and Passenger Throughput: Evaluate the number of trains (MDS and conventional) and passengers processed through the station per hour or per day. This KPI indicates the station's capacity to handle train and passenger traffic efficiently.
- Dwell Time: Measure the average time a train (comparable MDS and conventional) spends at the station for boarding and disembarking passengers. Lower dwell times indicate faster turnaround and improved efficiency.
- On-Time Performance: Track the percentage of trains (divided in MDS and conventional trains) that arrive and depart from the station according to the schedule. This KPI reflects the system's reliability in adhering to timetables.
- Platform Occupancy Rate: Monitor the percentage of platform space occupied by trains during peak and off-peak hours. Optimizing platform occupancy ensures efficient space utilization and minimizes congestion. Which is important especially for mixed or combined use of platforms by MDS and conventional trains.
- Customer Satisfaction Score: Gather feedback from passengers regarding their experience at the station, including aspects like cleanliness, signage, ease of navigation, and overall satisfaction. This KPI reflects the quality of service provided and can be integrated with specific score about MDS systems.

A regular assessment of station capacity is essential to identify potential bottlenecks and areas where improvements are needed. This involves analysing many different factors such as train frequencies, journey times, and platform capacities to determine the maximum throughput of the station.

7.5 Asset management and maintenance

This chapter includes aspects and considerations related to asset management and maintenance procedures and what will be changed by implementing MDS technologies and operations into the existing railway system.

7.5.1 Asset Management and Maintenance strategy

The asset management must consider the entire impact of a railway asset, from investment to the end of its operational lifespan. Impacts in this context include both technical and economic aspects.

For the railway track, this means demonstrating the cost-effectiveness of new investment and maintenance strategies, including the need to address the life cycle costs of the assets. In the case of railway assets with a usage period of 30 years or more especially in infrastructure, maintenance becomes a significant factor that cannot be neglected.

As an example for railway tracks, beyond these economic requirements, there is also a fundamental technical correlation that emphasizes the necessity of a valid maintenance strategy. A general observation for railway tracks states that a qualitatively good track performs better and leads to less wear and tear, than a lower-quality one. This implies that the current deterioration rate of a railway track is largely determined by its current quality.

This simple correlation can be transferred and forms the basis for the technical behaviour of a railway assets throughout their entire life cycle. Since the goal of proving the economic viability of asset management or investment and maintenance strategies is to monetarily evaluate the technical impacts of the asset, the consideration of new maintenance strategies requires the development of suitable paths, especially for new and previously unknown technologies. The definition of standard situations can be helpful in those cases:

- Definition of standard situations
- Identification of relevant costs
- Development of work cycles for standard situations
- Verification of work cycles
- Analysis of comparable actual data
- Development of fundamental maintenance strategies and alternative work cycles
- Economic evaluation based on life cycle costs.

In the context of asset management, it is essential to understand that various maintenance strategies are available, which can be tailored to the specific needs and operational conditions (**Figure 7**). Each of these strategies features a unique set of practices, objectives, and methodologies aimed at optimizing performance, reliability, and safety of assets while minimizing operational and maintenance costs.

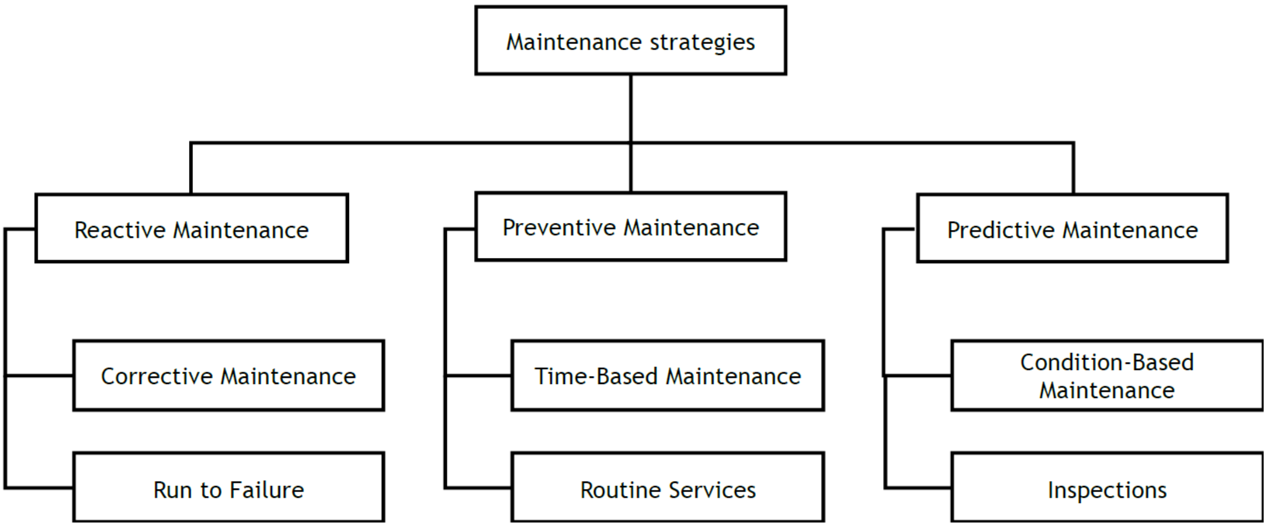

Figure 7. Different Maintenance strategies (Bhebhe and Zincume, 2020).

In general maintenance strategies can be categorized in 3 different approaches as shown in **Figure 7**. Reactive maintenance strategies such as RFT (Run To Failure) involve intervention only when a failure occurs, which may be suitable for less critical system components where unplanned downtimes do not significantly impact overall operations.

In contrast, preventive maintenance strategies rely on regular inspections and maintenance routines conducted according to a predetermined schedule, regardless of the current condition of the equipment.

A more advanced approach, predictive maintenance, leverages condition monitoring technologies and data analysis to predict potential failures before they occur, allowing for maintenance activities to be scheduled at the most optimal time. The Total Productive Maintenance (TPM) methodology for example extends the responsibility for maintenance to involve all employees, from operators to management, fostering a culture of continuous improvement and maximizing production efficiency.

Additionally, there are many methods in use to priories the maintenance works in the whole system. Risk-based approaches, such as Risk-Based Maintenance (RBM), emphasize identifying and prioritizing maintenance activities based on the risk assessment of potential failure, considering both the likelihood of its occurrence and the potential consequences for the operation. Reliability Centred Maintenance (RCM) represents a systematic approach aimed at determining the most effective maintenance practices focused on preserving the system's function in its current operational context.

Most important in asset management and maintenance operations is continuous improvement of the processes. Most common examples might be the PDCA (Plan, Do, Check, Act) cycle and the 5S methodology (Sort, Set in Order, Shine, Standardize, Sustain). These are additional tools that support maintenance processes through systematic planning, implementation, evaluation, and improvement of maintenance activities and workplace organization, which directly translates to enhanced efficiency and safety of operations.

A framework regarding all components like business objectives, regulations, health, safety, and environment demands and interaction between different maintenance tasks, can help to define the right strategy as show in **Figure 8**.

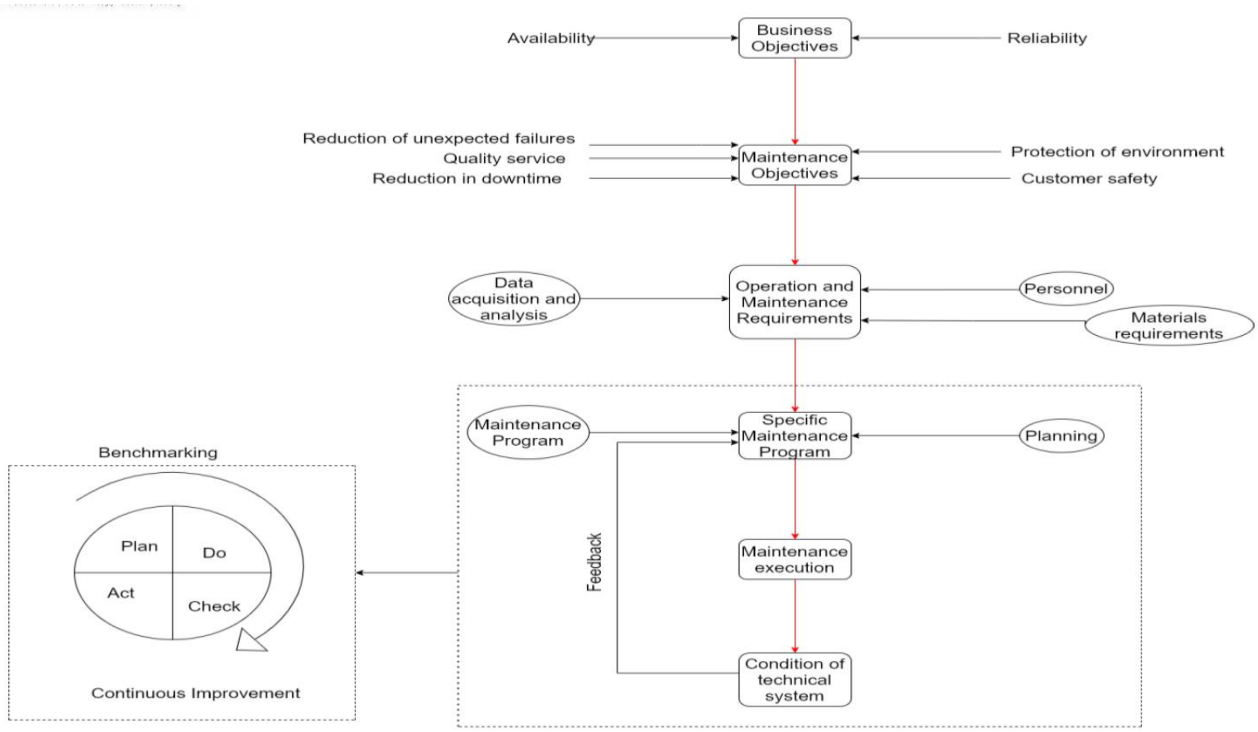

Figure 8. Maintenance Strategy Framework (Bhebhe and Zincume, 2020)

7.5.2 Maintenance Management

Maintenance means all activities and processes carried out to ensure the maximum safety, availability, and reliability of the system, as well as its proper functioning. It is important that all service activities last as short as possible and that they are optimized in terms of finances. For new MDS the following maintenance processes might be considered.

The proper operation of vehicles should be ensured by a global maintenance management system. The set of procedures, instructions and maintenance cycles is concluded in technical documentation. The next source of information needed for the planning process could be the counters generated from IoT schedule application. Real-time vehicle monitoring by diagnostic system with the possibility of predictive maintenance can be implemented.

The proper operation of infrastructure shall be ensured by instructions concerning the technical conditions of maintenance of MDS infrastructure. The next source of information needed for the infrastructure maintenance process could be the data from sensors installed in the infrastructure and a diagnostic device on the vehicle. Real-time infrastructure monitoring by diagnostic system with the possibility of predictive maintenance of wearing components and prediction for degradation of MDS infrastructure can be implemented.

Table 4 shows the possible change in the maintenance approaches from conventional traffic to the different stages of MDS technology. Assuming, that the information of the sensors in the vehicles, which will be needed to control the movements can be used for data analytics, maintenance regime will change to sensor driven predictive maintenance at least for the new components of the MDS. But especially for the infrastructure subsystem, the generated data from the sensors might be used for quality control of the existing infrastructure elements.

Table 4: Different maintenance strategies by implementing MDS stages

Subsystem	Component	Conventional system	Upgraded vehicles	Hybrid MDS
Vehicle	Structure	Preventive maintenance	Preventive maintenance	Sensor driven predictive maintenance
	Propulsion vehicle part	Preventive maintenance	Preventive maintenance	Sensor driven predictive maintenance
	Suspension	Preventive maintenance	Preventive maintenance	Sensor driven predictive maintenance
	Guidance	Preventive maintenance	Preventive maintenance	Sensor driven predictive maintenance
	Braking	Preventive maintenance	Preventive maintenance	Sensor driven predictive maintenance
	Vehicle Control System	Preventive maintenance	Preventive maintenance	Preventive maintenance
	Electrical system	Preventive maintenance	Preventive maintenance	Preventive maintenance
	Monitoring & Safety	Preventive maintenance	Sensor driven predictive maintenance	Sensor driven predictive maintenance

Subsystem	Component	Conventional system	Upgraded vehicles	Hybrid MDS
Infrastructure	Propulsion infrastructure part	n.a.	Sensor driven predictive maintenance	Sensor driven predictive maintenance
	Guideway	Preventive inspections Maintenance works as needed after inspections	Preventive inspections Maintenance works as needed after inspections	Preventive inspections Maintenance works as needed after inspections
	Switches	Preventive inspections Maintenance works as needed after inspections, also sensor driven predictive maintenance	Preventive inspections Maintenance works as needed after inspections, also sensor driven predictive maintenance	Preventive inspections Maintenance works as needed after inspections, also sensor driven predictive maintenance
	Substructure	Preventive inspections Maintenance works as needed after inspections	Preventive inspections Maintenance works as needed after inspections	Sensor driven predictive maintenance
Energy	Power supply station	Preventive inspections Maintenance works as needed after inspections	Sensor driven predictive maintenance	Sensor driven predictive maintenance
	Electrical system	Preventive inspections Maintenance works as needed after inspections	Sensor driven predictive maintenance	Sensor driven predictive maintenance
	Sensing and communication	n.a.	Sensor driven predictive maintenance	Sensor driven predictive maintenance

Subsystem	Component	Conventional system	Upgraded vehicles	Hybrid MDS
	Segment switches	n.a.	Sensor driven predictive maintenance	Sensor driven predictive maintenance
Command and Control	TMS	Preventive maintenance by periodic software updates	Preventive maintenance by periodic software updates	Preventive maintenance by periodic software updates
	Control Centre	Preventive maintenance by periodic software updates	Preventive maintenance by periodic software updates	Preventive maintenance by periodic software updates
	Monitoring & Safety	Preventive inspections Maintenance works as needed after inspections	Preventive inspections Maintenance works as needed after inspections	Sensor driven predictive maintenance
	Communication	Preventive inspections Maintenance works as needed after inspections	Preventive inspections Maintenance works as needed after inspections	Preventive inspections Maintenance works as needed after inspections
	Positioning	Preventive inspections Maintenance works as needed after inspections	Sensor driven predictive maintenance	Sensor driven predictive maintenance

7.5.3 Maintenance planning and procedures

Usually, vehicle and infrastructure maintenance planning are divided into different functions and different companies. The responsibilities for vehicle maintenance are clearly defined in the Article 14 of Directive (EU) 2016/798 on railway safety and in the Regulation (EU) No 445/2011 on ECM as four different "entities in charge of maintenance" (ECM).

ECM 1 (the ECM management function) bears overall responsibility for the structure and effectiveness of the maintenance management system. This function is always the one in charge tasking and monitoring the other ECM functions.

ECM 2 (the ECM maintenance development function) defines the maintenance specifications and is also responsible for monitoring rolling stock and continuously developing maintenance specifications based on this monitoring.

ECM 3 (the fleet maintenance management function) is responsible for ensuring that rolling stock is taken out of operation in good time and maintained. Once maintenance has been completed and confirmed, it hands the rolling stock back over to operations.

ECM 4 is the executive function. It is the entity that is responsible for delivering maintenance. At the depot, the maintenance order must be processed, documented, and archived.

In order to plan a maintenance cycle, the operator (ECM 3) will use a maintenance schedule system, which will be based on the maintenance documentation and regulation in given country. An IoT and data analytics system can also include real data and prediction to adjust and optimize the maintenance plan to ensure the highest availability and reliability of vehicles and infrastructure.

The responsibility for infrastructure maintenance in Europe is given to the infrastructure managers (IM). They are in charge of planning, financing and execution. For the IM one of the biggest challenges will be to combine conventional and MDS infrastructure maintenance without having big changes on planning and execution processes but also on the machines or their configurations. Nonetheless some adaptations can be needed and must be taken into account when implementing MDS operations.

The new kind of vehicles for both of the hybrid MDS configurations will need several sensors or cameras to ensure the save guidance and movements in levitation mode. These sensors will produce data, which could also be used for the vehicle and infrastructure surveillance to support predictive maintenance strategies. The sensors on the vehicles will not substitute the periodic runs of the specific measuring trains, but can bring a very dense data driven view on infrastructure as the pods collect data with every trainrun.

In **Table 5**, the main maintenance activities are listed and the expected changes between classic railway and the different MDS solutions (updated vehicles and hybrid MDS) are mapped. The list of infrastructure maintenance activities come from reference (Liden, 2014), and vehicle maintenance activities.

Table 5: Expected changes in maintenance between classic railway and the different MDS solutions

Subsystem	**Name**	**Category**	**Updated vehicle and infrastructure**	**Hybrid MDS with magnetic levitation**	**Hybrid MDS with air levitation**
Infrastructure	Catenary wire replacement	Maintenance	No differences – linear motors will be used for additional power supply (traction booster), so catenary use is maintained	Linear motors with track-side energy feed means less catenary use, and thus longer catenary wire life and replacement time.	No differences

Subsystem	Name	Category	Updated vehicle and infrastructure	Hybrid MDS with magnetic levitation	Hybrid MDS with air levitation
Infrastructure	Track/turnout replacement	Maintenance	Before the track replacement, it is necessary to disconnect, lift and move the propulsion system elements installed in the track, and then reattach them to the new section of track, based on the modular design of the stator	Before the track replacement, it is necessary to disconnect, lift and move the propulsion and levitation system elements installed in the track, and then reattach them to the new section of track, based on the modular design of the stator	The prefabricated stator (concrete slab with aluminium strip) is made to replace the old track.
Infrastructure	Tamping of tracks	Maintenance	No differences if tamping machines can be reconfigured to take the space of the stator into account; if this is not possible before the tracks tamping, it is necessary to disconnect, lift, and move the propulsion system elements installed at this location on the track, and after tamping, reattach them to this section of the track	No differences if tamping machines can be reconfigured to take the space of the stator into account; if this is not possible, before the tracks tamping, it is necessary to disconnect, lift, and move the propulsion and levitation system elements installed at this location on the track, and after tamping, reattach them to this section of the track	Heavier track is lifted (because the insertion of concrete slab and aluminium strip), and the rest of the procedures are the same.
Infrastructure	Grinding	Maintenance	No differences	No differences	No differences
Infrastructure	Switch replacement	Maintenance	Before the switch replacement, it is necessary to quickly disconnect, lift, and move the propulsion system elements installed at this location on the track, and after the switch replacement, reattach them to this section of the track, based on the modular design of the stator	Before the switch replacement, it is necessary to quickly disconnect, lift, and move the propulsion and levitation system elements installed at this location on the track, and after the switch replacement, reattach them to this section of the track, based on the modular design of the stator	The prefabricated stator (concrete slab with aluminium strip) is made to replace the old track.

Subsystem	Name	Category	Updated vehicle and infrastructure	Hybrid MDS with magnetic levitation	Hybrid MDS with air levitation
Infrastructure	Catenary inspection and maintenance	Diagnostic	No differences – linear motors will be used for additional power supply (traction booster), so catenary use is maintained	Linear motors with track-side energy feed means less catenary use, and thus longer catenary wire life and replacement time.	No differences
Infrastructure	Tamping of turnouts	Maintenance	No differences if tamping machines can be reconfigured to take the space of the stator into account if this is not possible before the turnouts tamping, It is necessary to quickly disconnect, lift, and move the propulsion system elements installed at this location on the track, and after tamping, reattach them to this section of the track	No differences if tamping machines can be reconfigured to take the space of the stator into account if this is not possible before the turnouts tamping, It is necessary to quickly disconnect, lift, and move the propulsion and levitation system elements installed at this location on the track, and after tamping, reattach them to this section of the track	New type of turnout should be developed, and the maintenance means are made accordingly.
Infrastructure	Rails inspection	Diagnostic	No differences	Data from sensors and cameras installed on the pods for operations can also be used to support predictive maintenance strategies	Data from sensors and cameras installed on the pods for operations can also be used to support predictive maintenance strategies
Infrastructure	Fastener- joint- rail-repairs	Maintenance	No differences	No differences	No differences
Infrastructure	Periodic measurement	Diagnostic	No differences	Periodic measurements of the propulsion and levitation system using sensors located on the pods. Regularly collecting additional data from the sensors will ensure even greater reliability of the system and significantly improve the quality of the infrastructure	No differences

Subsystem	**Name**	**Category**	**Updated vehicle and infrastructure**	**Hybrid MDS with magnetic levitation**	**Hybrid MDS with air levitation**
Infrastructure	Fast grinding	Maintenance	Fast grinding can generate metallic scales with extreme temperatures, the sensitivity of the traction components in the tracks to these metallic shards should be assessed.	Fast grinding can generate metallic scales with extreme temperatures, the sensitivity of the levitation and traction components in the tracks to these metallic shards should be assessed.	Fast grinding can generate metallic scales with extreme temperatures, the sensitivity of the levitation and traction components in the tracks to these metallic shards should be assessed.
Infrastructure	Inspection	Diagnostic	Inspection of the propulsion system components installed in the track	Inspection of the propulsion and levitation system components installed in the track	Inspection of the aluminium and concrete slab health laid on the sleepers between two rails
Infrastructure	Signal repair, vegetation, etc.	Maintenance	No differences	No differences	No differences
Infrastructure	Slippery rail, snow removal	Maintenance	No differences	No differences	No differences
Infrastructure	Accidents, urgent repairs	Maintenance	No differences	The risk of urgent repairs can decrease due to the evaluable data from sensors on the pods, which can help to monitor the condition of the infrastructure with higher frequency.	No differences
Vehicle	Wheel reprofiling	Maintenance	Linear motors for traction and braking means reduced damage due to traction and braking issues, such as wheel flats and hot spots.	During magnetic levitation, friction between the rail and the wheel is limited, so there is less overall damage. Therefore, wheel reprofiling may be done less often	No differences
Vehicle	Wheel profile	Diagnostic	No differences – however there is reduced wear, RCF, and local damages, as the wheelsets are not used for accelerating & breaking, as this is done by the linear motor drive	During magnetic levitation, friction between the rail and the wheel is limited, so the wheel profile maintains its desired shape for a longer period of time	No differences
Vehicle	Axle bearing replacement	Maintenance	No differences	No differences	No differences

Subsystem	Name	Category	Updated vehicle and infrastructure	Hybrid MDS with magnetic levitation	Hybrid MDS with air levitation
Vehicle	Axle bearing temperature	Diagnostic	No differences	No differences	No differences
Vehicle	Braking pad replacement	Maintenance	Braking is performed using a linear motor, therefore, brake pads can be used less, increasing their useful life and decreasing the pad replacement frequency.	Not needed	Not needed
Vehicle	Braking pad wear volume	Diagnostic	Braking is performed using a linear motor, therefore there is less wear volume of braking pads. Due to this, braking pads can be replaced less often compared to conventional usage	Not needed	Not needed
Vehicle	Braking disc replacement	Maintenance	Braking is performed using a linear motor, therefore there is a longer period of braking discs usage. Due to this, braking discs can be replaced less often compared to conventional usage	Not needed	Not needed
Vehicle	Braking disc wear volume	Diagnostic	Braking is performed using a linear motor, therefore there is less wear volume of braking discs. Due to this, braking discs can be replaced less often compared to conventional usage	Not needed	Not needed
Vehicle	Pantograph Carbon strip replacement	Maintenance	Linear motors with track-side energy feed means less pantograph use, and thus longer carbon strip life and replacement time.	Not needed	No differences

Subsystem	Name	Category	Updated vehicle and infrastructure	Hybrid MDS with magnetic levitation	Hybrid MDS with air levitation
Vehicle	Pantograph carbon strip wear volume	Diagnostic	No difference. However, linear motors with track-side energy feed means less pantograph use, and thus longer carbon strip life and replacement time.	Not needed	No differences
Vehicle	Gearbox lubrication oil	Maintenance	No differences	Not needed	No differences
Vehicle	Sanding system - sand refilling	Maintenance	Not needed	Not needed	Not needed
Vehicle	Dampers	Maintenance	No differences	No differences	No differences
Vehicle	Air Spring	Maintenance	No differences	Not needed	Not needed
Vehicle	Axle flaw detection	Diagnostic	No differences	No differences	No difference
Vehicle	Buffing draw gears	Maintenance	Less wear of draw gears, because of distributed traction force in the train. As a result, draw gears can be buffing less often compared to conventional usage	Not needed	Not needed
Vehicle	Examination of all safety-critical components	Diagnostic	No differences	No differences	No differences
Vehicle	Measurement of vehicle geometry	Diagnostic	No differences	No differences	No differences

In the context of maintaining a new kind of rail vehicles, logistics requires the coordination of various activities and resources to support the upkeep and operation of the rolling stock. This encompasses the procurement and distribution of spare parts, tools, and specialized equipment required for maintenance tasks such as inspections, repairs, and component replacements. But logistics in maintenance of specialized rail vehicles also includes managing the in- and outflow of those vehicles. For the updated vehicles it will be like today's procedures because they can run on every standard track like a classic wagon, as long as the components of the MDS are disabled. For the pods in a hybrid MDS stage it must be secured, that maintenance facilities are reachable. That means, tracks must be updated and equipped with linear motors. If pods must be maintained in other facilities not connected to the MDS network, they can also run on wheels but need an external traction unit to be moved on non-equipped tracks. Also, here it must be secured, that all MDS components on the vehicle are disabled. In summary it can be stated that effective logistics practices are essential for ensuring the reliability, safety, and longevity of rail vehicles while minimizing disruptions to service.

7.5.4 Potential benefits of MDS in maintenance issues

As it has been described in the last chapters, the MDS technologies will bring changes to the procedures of vehicle and infrastructure maintenance. More complexity in planning processes and new configurations of machinery may need additional efforts. On the other side, the implementation of MDS technologies can also bring benefits:

- Propulsion by a linear motor is a direct drive without any wear and tear of rails and wheels caused by traction forces.
- In levitation mode wear and tear is at best reduced to zero as long as there is no physical contact between rail and wheel.
- Distributed traction along an updated train (when some wagons are equipped with mover magnets) optimize the longitudinal forces in a trainset, what can reduce wear and tear especially at the couplings.
- Using operational data from the vehicle sensors or the linear motor to build up a predictive and condition-based maintenance strategy can save efforts and help to increase reliability and operational quality.
- Leveraging data analytics and IoT (Internet of Things) sensors to predict when parts might fail or when maintenance is needed, thus preventing accidents caused by unexpected failures.
- Braking by a linear motor is no longer dependent on rail-wheel adhesion and friction between brake disc and brake pad. Relevant inspection and maintenance costs (brake disc, brake pads, etc.) can be much reduced.
- Propulsion by linear motor can make the traction chain simpler. There is no gearbox and no rotational part in the motor. The traction systems have longer service life, and less inspection is required.
- Wireless power supply can directly transmit power without physical sliding between current collectors and power supply infrastructure. Relevant inspection and maintenance costs (catenary, contact strips, etc.) can be much reduced.

Even, when this might be only a selection of potential benefits, the new technology will have the ability to reduce wear and tear on many points which leads to longer lifetimes of the components and less but purposeful maintenance activities. Well-maintained railways and vehicles are less likely to suffer from unexpected breakdowns, leading to fewer delays and more reliable service.

Additionally, no maintenance procedure was found that would completely invalidate the application of MDS technologies in conventional railways, but there are however some maintenance procedures that will need to be adapted and updated when additional subsystems are introduced. In particular, ballast tamping and switch-related maintenance processes will be heavily impacted when introducing new subsystems close to track and rails in hybrid conventional-MDS tracks.

7.6 Assessments about the acceptability to customers of a new way of traveling

This chapter includes aspects and considerations related to assessments about the acceptability to customers of a new way of traveling and definition/redefinition of related elements.

7.6.1 Passenger services

The new technology under assessment could either be perceived by travellers as a completely new mode of travel or a technological enhancement of the existing rail travelling. As the superposition of maglev derived system on existing infrastructure is being investigated, the traveller will be accessing the system in the existing rail station and therefore a straightforward comparison with the existing rail travelling is very likely to be expected. Therefore, it is quite important to state the underlying travel facets that drive customers nowadays to choose rail travelling when other modes are available; their preservation should be seen preferably as a constraint to the development of the new maglev-based modes, or else a careful trade-off evaluation should be carried out whether the new technologies require necessarily for them to be jeopardized.

Moreover, applying the new system to the existing railway infrastructure will have as a straightforward consequence that typical rail mindsets, e.g. on safety aspects, and cultural / regulatory framework, such as the ones concerning infrastructural capacity usage, are expected to be applied.

In the following points a series of requisites commonly assumed by the rail passenger travellers are listed, as well as some points on their fulfilment with the new technologies:

- Any additional physical discomfort during travels imposed to passengers should be considered unacceptable, as counter-productive to the objective to divert travels from air and road modes to rail.

  Therefore, the maglev derived system performance evaluation should take into account lateral accelerations and variations of lateral acceleration per time unit applied to the traveller, that must be compatible with the traveller's comfort, considering the cant and the length of transition curves on existing lines in shared infrastructure. Studies and practice on tilting trains about limiting those parameters could be used as a reference. Some references can be found in (Förstberg et al., 1998; Milchevskaya, 2023; Persson and Kufver, 2010).

- The possibility to walk in safety along a train during the journey should be considered not negotiable for comfort reasons, being connected with some of the basics expectations from customers choosing rail mode: possibility to use a toilet, possibility to use cafeteria / catering services (both by a walking to a specific carriage or by at-seat services), possibility to relieve leg stress. It should be noted that walking restrictions in air travel are usually limited to specific and brief moments (take-off and landing), while journeys with weather conditions that impose prolonged limitations are often perceived as very uncomfortable. Regarding maglev-derived systems, in the case that the walking constraints were to be related to the infrastructure layout, if these constraints were to be active throughout the journey, this would put rail services at a significant disadvantage in terms of comfort compared to the air sector.

  Therefore, the maglev derived system performance evaluation should take into account lateral accelerations and variations of lateral acceleration per time unit applied to the traveller, that must be compatible with safe walking, considering cant and length of transition curves on existing lines.

- Customers require that short and medium distance trains, especially PSO (Public Service Obligations – e.g. regional trains) services, must be accessible without reservation, as the possibility to adapt one's daily programming has shown to be a basic requisite for service appeal. High frequency services are considered to give a quantum leap in service quality, as the traveller often accesses the rail system without even knowing the scheduled timetable. Compulsory reservation on short and medium distance PSO service could also arise legal issues. Therefore, travellers should be admitted on short and medium distance maglev derived trains also without reservation, hence a safe ride for standing passengers must be ensured.

  About long-distance services, should a reservation be compulsory, performance benefits could be weighted versus customer loss by railway undertakings nowadays admitting standing passengers.

- Typically, rail travel does not entail any limitation to luggage transport, giving a significant competitive advantage to rail compared to air travel. Also, large luggage is usually admitted, without any previous luggage reservation. Luggage handling is left to the traveller, with significant benefit on luggage security. Also, bike transport is expected on short and medium distance services and on most lost distance services.

  Therefore, maglev-derived system should allow the possibility to carry large luggage, preferably but non compulsorily on dedicated spaces, with luggage handling under the traveller's responsibility and without any compulsory luggage reservation. Also bike transport with traveller's handling should be possible.

- Punctuality expected from the rail mode is significantly higher than in any other transport mode. Passenger punctuality performance is assessed relating to different thresholds for passenger trains, that differ country by country but usually range from 3 to 5 minutes for short-distance PSO services and High-Speed trains and from 3 to 15 minutes for Long Distance trains.

  Therefore, any operational procedure thought for the maglev derived systems must be able to ensure, in normal conditions, such a scheduling and operational resolution.

- Kinematic conditions should not put constraints to operational procedures:

  Passengers should be able to sit without wearing seatbelt and occasionally stand to access services such as restrooms, bistro car, restaurant, etc.

  Onboard safety check procedures in station must not affect normal operations in terms of dwell time as this would result in a considerable loss of capacity for the system. Existing terminal and stations could not support a systematic extended dwell time.

  The onboard passenger safety is demanded to Railway Undertakings (RUs). Responsibility handover to the traveller can hardly be considered admissible considering the railway regulation mindset. RUs must ensure that all passengers are travelling under safe conditions. The monitoring of these conditions must not affect the normal operations. However, if the safety control is supposed to be automated, with a system that detects whether all seat belts are fastened, the connection to emergency braking systems or procedures should be considered unacceptable.

- Both the punctuality requirements and the path-based capacity usage require trains to depart when their time is scheduled, with very limited tolerances. An airplane-like model, where the cabin crew checks seatbelt fastening and luggage-compartment locking before authorizing take-off, is utterly incompatible with the rail system. Moreover, the presence in each carriage of safety staff to insist with reluctant travellers to sit and fasten seatbelts, or to lock luggage compartments, is not compatible with actual train staffing and its economic impact on operation.

7.6.2 Freight services

About the adoption of the new technologies to the freight transport, in the following points a series of requisites commonly assumed by the freight operators are listed:

- Typically, rail freight market works with tight economical margins, that require a strong effort to cut costs for any system element. Therefore, it is very important that maglev derived system require limited additional construction cost to vehicles.

- Maintenance of freight wagons is carried out for the most part with limited equipment usually transported by a van, directly in freight yards, without taking the wagon out of its trainset. Only major maintenance works require the wagon to be treated in a workshop. It is important that light maintenance for wagons equipped with maglev derived system could be carried out in compliance with this maintenance setting, without requiring more frequent workshop treatment.

- Weight constraints on MDS vehicles must not make the freight services inviable due to economical margins.

- MDS technology must not interfere with goods transported and ensure electromagnetic compatibility with it.
- Freight operations in terminal must be compatible with MDS technology, in terms of safety of yard operators and handling vehicle.
- Specific procedures that require additional holding system should not affect normal operations. Intermodal Container should be carried without additional precautions.

7.7 Evaluation framework and methodology, including benchmarking technique and indicators' definition

The object of this chapter is to propose an evaluation framework and methodology, including benchmarking technique and indicators' definition to evaluate the constraints and design methodology for the operational procedures in typical and perturbed regimes identified in the previous chapters, including capacity planning & timetabling, CCS & TMS, station design, management and maintenance and customer acceptance assessments.

IMPACT-2 proposed to assess the achievements of the S2R objectives towards three independent models developed for quantitative KPI as well as a model for the indicators related to customer experience. The KPI model evaluates the economic sustainability of Shift2Rail using the three KPIs: Reliability, Capacity, and Life-Cycle Cost, the Customer Experience Model evaluates which barriers to travel by train the Shift2Rail innovations will remove for passengers, and the Modal Shift Model evaluates the impact of both on the actual shift of passengers and goods to rail.

The evaluation framework proposed by MaDe4Rail is based on the KPI models developed in(IMPACT-2, 2021). The following sections show a qualitative assessment of how and to what extent MDS innovations can have an effect on the different KPIs defined in the proposed model.

Due to the scope of the MaDe4Rail project, only the first two models will be considered, i.e. the KPIs model and the Customer Experience model.

7.7.1 KPIs model

The KPI model developed in IMPACT-2 was based on the general structure of the KPI model, developed in (IMPACT-1, 2018). The developed KPI model was based on S2R's five key Innovation Programmes (IPs) encompassing relevant technical and functional technology subsystems structured in Rolling Stock (IP1), Command, Control and Signalling (IP2), Optimized Infrastructure (IP3), Digital Services (IP4) and Rail Freight (IP5).

The three separated sub-models display the effects of S2R-innovations on the respective KPIs Life-Cycle Costs (LCC), Reliability & Punctuality and Capacity. Following this scheme, **Table 6** provides different considerations and constraints specific to MDS systems for each one of the three KPIs.

In relation to the model presented in (IMPACT-2, 2021), MaDe4Rail provides different considerations and constraints specific to MDS systems, which are outlined in **Table 6**.

Table 6: Considerations and constraints to MDS systems for the KPIs Model

Cathegory of KPIs	General description	MaDe4Rail Considerations and constraints
Life- Cycle Costs	Calculates the effects of the developed technical innovations on the total cost of the railway system. The measuring unit chosen is EUR/passenger-km and for the freight transport scenarios respectively EUR/ton-km. To account for the different lengths of life cycles of the assessed components of the railway system, an assessment period of 30 years and a discount rate of 3% have been chosen. The developed LCC model does not only capture direct cost effects of individual components but also system effects	The weight of the vehicles is an important aspect in the deterioration of the infrastructure. Increasing the weight of the trains will cause more wear and tear of the infrastructure and thus increase maintenance costs to keep the service level constant. The KPI model includes the impact of axle loads on maintenance costs, using estimates from an empirical top-down approach. The introduction of MDS could bring additional or decremental effects on infrastructure LCC. Propulsion by linear motor can make the traction chain simpler. There is no gearbox and no rotational part in the motor. The traction systems have longer service life, and less inspection is required. In addition, propulsion by a linear motor, distributed traction, and levitation are direct drives without any wear and tear of rails and wheels caused by traction forces, producing also additional or decremental effects on infrastructure LCC. There need for new inspection and maintenance processes of the traction components installed on the track that will also affect the LCC. Also using operational data from the vehicle sensors or the linear motor, leveraging data analytics and IoT (Internet of Things) sensors to predict when parts might fail or when maintenance is needed can save efforts and help to increase reliability and operational quality and reduce maintenance cost. Wireless power supply can directly transmit power without physical sliding between current collectors and power supply infrastructure. Relevant inspection and maintenance costs (catenary, contact strips, etc.) can be much reduced. Efficiency of the energy transmission will also be different. For the CCS field in Europe, even if not in the immediate future, the trend is to bring more and more intelligence on board the train. This change started with the introduction of ATO and soon with Train Integrity and Train Localization. In this scenario, the use of MDS vehicles benefits

Cathegory of KPIs	General description	MaDe4Rail Considerations and constraints
		because the architecture of the infrastructure is simplified and many of the devices currently in use on the lines are eliminated or reduced. In this way, in addition to reducing infrastructure costs, it facilitates the introduction of MDS vehicles which will reduce the number of certifications to be produced and maintained. Furthermore, with the use of the new TMS and ATO, energy consumption and the management of braking curves are optimized as well as an increase in punctuality. When the degree of automation reaches GoA4 then it will be possible to replace the machinists, further reducing costs. this scenario is projected towards a not-too-distant future in which MDS vehicles will also have the advantages. An advantage of new station designs using dedicated MDS platforms will be the scalability. The MDS platforms can be built as it is needed from the traffic demand. This reduces CAPEX costs by only investing the amount which is needed. New stations can also be designed and renewed with modern technologies and to save OPEX costs. When considering end-of-life costs, components that are to be recovered, recycled, or reused after complete lifetime need to be considered. The carbody contributes most significantly to reducing dismantling costs, which is not a differential feature of the presented MDS concepts. There is however an increased usage of sensors and electronic components in MDS systems with respect to conventional rail which will have an impact in these end-of-life processes and costs, especially for integrated electronics or embedded systems. Special attention should be paid to the dismantling and handling processes of materials with high environmental impact such as Batteries, or scarce materials such as permanent magnets or rare earth metals. Recycled or reused materials will have a positive impact in the form of carry-on embedded carbon emissions.
Capacity	The calculation of the capacity KPI is a multiplication of the three aspects: track capacity, train capacity and coupling ability. The track capacity calculates the number of trains per time and corridor. For passenger transport scenarios, the track capacity is calculated for a peak hour, whereas for freight transport, it is calculated per day. The train capacity captures the increase of passengers per train or respectively tons per train. Coupling ability, hence the coupling of different units of different manufacturers, classes and series is the third factor.	Due to the distributed power provision the driving performance of the trains can be scaled and hence trains running closer together. This leads to higher capacity which is especially on saturated lines relevant. The capacity concept introduced in IMPACT-2 includes, in addition to line ad stations capacity defined above and measured in [trains/time] the concept of transport capacity, measured in [passengers/time] = [passengers/train] x [train/time]. The introduction of the MDS can modify the transport capacity by acting on both the components. Moreover, as the total capacity depend on the coupling ability, the information provided for the case study in the configuration of integrated traditional railway with MDS system should allow calculating the capacity with the concerned methods. The same approach can be used for all the passenger market segments: High-Speed, Regional and Metro In Europe we are increasingly moving towards signalling systems based on radio communication. systems that manage and optimize the distance between trains in real time. This allows us to increase the number of trains and travel time. These two factors increase the profitability of the line for both passenger and freight lines. Often the lines are the same and used intensively at different times. MDS vehicles are designed to be perfectly aligned with the new ETCS systems (Moving Block ATO GoA4) together with an efficient TMS and are therefore ready for the next challenges.

Cathegory of KPIs	General description	MaDe4Rail Considerations and constraints
		New station designs can be optimized to the traffic needs and timetable concepts to assist the capacity increase of the lines and not being the bottlenecks.
Reliability & Punctuality	The punctuality model calculates the number of delay minutes caused by a specific failure as well as the frequency of its occurrence. The delay threshold chosen to include trains into the delay statistic is different for each system. The delay minutes are then all added up to the sum of delay minutes within the network.	The punctuality considers the distribution of delay across causes as well as the average delay minutes for each cause. These values can be obtained from empirical data provided by the Infrastructure Managers. The MDS introduced in MaDe4Rail could introduce modifications of these values if they affect the causal factors of the delays, such as reliability of components, systems and subsystems of vehicles, superstructure, signalling and control systems, electrification systems, operational planning (timetable structures). Moreover, MDS will introduce new components and subsystems, as well as the interfaces between them and the traditional one, that could produce new cause of unreliability and consequent delays. The power transmission outside of the wheel-rail contact leads to reduced wear and tear and hence reduced cost for maintenance and higher capacity, too, as less time for maintenance is needed. Also using operational data from the vehicle sensors or the linear motor, leveraging data analytics and IoT (Internet of Things) sensors to predict when parts might fail or when maintenance is needed can save efforts and help to increase reliability and operational quality. The new ETCS systems (Moving Block ATO GoA4) together with an efficient TMS capable of resolving conflicts in real time, allow IMs to optimize even cases of non-linear operation, when unexpected events occur. all this leads to an increase in the capacity of the entire system. Furthermore, the simplification of the line allows for an increase in its availability. Furthermore, the new systems have been designed to increase reliability as well as the recognition of any potential problems. Therefore, the probability that a vehicle that may have problems can circulate is significantly reduced. MDS vehicles are designed to be perfectly aligned with these developments and are therefore ready for the next challenges. New stations can be designed to the traffic needs and timetable concepts to optimize the track section for arrival and departure of the platforms. Speeds and precise stopping can be optimized, travel times reduced, and disturbances avoided which will lead to better punctualities. The better adhesion management due to the introduction of linear motors will increase the stopping precision in signals, reducing disturbances due to SPADs (Signal Passed at Danger) due to e.g. rain, ice, or crushed leaves at the top of the rail.

Accordingly, and based on the above considerations and constraints for the MDS, **Table 7Errore. L'origine riferimento non è stata trovata.** describes the effects of MDS innovations on the different KPIs.

Qualitative expected effects must be addressed and assessed in each particular MDS configuration.

Table 7: Effect of MDS innovations on the different KPIs

Category	KPI	Effect on the KPI
Life- Cycle Costs	CAPEX	Less infrastructure investments to increase capacity compared to building new tracks Variation in size for power supply and substations More intelligence on board the train. More vehicle investment. Costs of modifying maintenance operations, procedures and equipment for the new hybrid tracks. Cost reduction by being able to substitute pushing locomotives, their parking tracks, etc. when these are necessary due to the characteristics of the infrastructure.
	OPEX	Reduced cost for shunting operations Variation on onboard personnel costs linked to travel times and automations Variation in energy consumption costs Variation in costs related emergency response systems and safety and security operations compared to those used in traditional railway operations Depreciation costs may be different for specific MDS infrastructure and vehicles
	Maintenance cost	Less maintenance due to several aspects, e.g. less wheel and rail damages, reduced brake usage, or wireless power supply. Increased maintenance for the new components introduced for the hybrid systems.
	Energy cost	Lower energy consumption mainly because of their lower rolling and mechanical resistance. Higher energy consumption for incline pushers
	Dismantling cost	Cost due to dismantling the vehicle and processing, repurposing, and recycling of components or materials. Benefits from material recycling gains, scarce materials recovery, component reselling for repurposing.
	Environmental aspects	Variation in noise emissions Variation in air pollution Variation in GHG emissions Variation in usage of high-impact materials such as batteries or rare earth metals.

Category	KPI	Effect on the KPI
Capacity	Trains per hour & Passengers per train	Less track occupation by better train dynamics / acceleration and deceleration (e.g. inclines or passing tracks) More exact operation following precisely the planned speed & time profiles and hence, smaller headways Travel time savings
	Operating hours * trains per hour	More trains per day
	Train and Passenger Throughput	Evaluate the number of trains (MDS and conventional) and passengers processed through the station per hour or per day.
Reliability & Punctuality	On-Time Performance:	Number of delayed trains over the total number of Track the percentage of trains (divided in MDS and conventional trains) that arrive and depart from the station according to the schedule. This KPI reflects the system's reliability in adhering to timetables
	Maintenance cycle	Variation in track maintenance windows needed Variation in ad-hoc maintenance needs caused by accidents
	Quality of service	Precise stopping and less disturbance due to less SPADs (Signal Passed at Danger) due to low braking adhesion. More continuous and less peaks in both acceleration and deceleration. Predictive Maintenance strategies can be supported by the collected data of the guidance sensors on the pods for hybrid MDS use cases, less immediate asset defects

7.7.2 Customer experience model

The Customer Experience (CE) Model was developed in (IMPACT-1, 2018; IMPACT-2, 2021) to highlight Shift2Rail's projects outcomes on the demand side (i.e. improving customer experience). Whereas the KPI model focuses on improvements on the supply side (Infrastructure Manager, Railway Undertaking), the CE model focuses on improvements associated with customers (i.e. individual persons).

The CE Model was based on a "project portfolio approach" which assesses additionality effects between barriers to improve customer experience and improvements in customer experience. The model mainly was based on the IP4 projects ("IT Solutions for Attractive Railway Services") and to a lesser extent, on IP1 (as for train layout and train noise) and IP3 (as for station design and station services). The structure of the CE model was based on isolating each single item impacting customer experience which entails breaking down a package of items into the most basic possible units ("AMPIs" and "Elementary Barriers"). This activity was performed making use of previous surveys related to Customer experience when travelling by train: (FairStations, 2019; FINE1, 2019; GoF4R, 2018; IMPACT-1, 2018; NEAR2050, 2018; SMaRTE, 2019)

Turning now to the outputs from the Customer Experience Model, the large set of Customer Experience variables were aggregated into three categories: Booking & ticketing, Information, and Comfort & services.

MaDe4Rail only addresses different considerations and constraints specific to MDS systems, related to the Comfort & services category, as the other two are out of the scope of the project. These considerations are outlined in **Table 8**.

Table 8: Customer Experience Model

MaDe4Rail Considerations and constraints about Comfort & services category
Faster trains due to faster and more exact acceleration leads to shorter travels. Reduced cost by value of time i.e. less cost.
Better punctuality due to less slip and slide of trains during acceleration.
More comfortable acceleration. Any additional physical discomfort during travels imposed to passengers should be considered unacceptable.
The possibility to walk in safety along a train during the journey should be considered not negotiable for comfort reasons.
Train journeys should not entail any limitation on the transport of luggage.
Any operating procedure designed for the MDS must be capable of ensuring, under normal conditions, the expected scheduling and operational resolution.
The use of seat belt type measures is strongly discouraged for MDS as it would decrease passenger comfort offered by the existing railway system.
New station designs and real-time passenger information system along the walkways and platforms will lead to better travel experiences.

Accordingly, and based on the above considerations and constraints for the MDS, the indicators included in **Table 9** are proposed to be considered for the assessment of customer experience, including also the effects of MDS innovations on these indicators..

Table 9: Customer experience indicators proposed by MaDe4Rail

Category	**Indicator**	**Effect on the indicator**
Comfort & services	Travel time (longitudinal acceleration higher and/or more continuous)	Faster trains due to faster and more exact acceleration leads to shorter travels. Reduced cost by value of time i.e. less cost.
	Ride comfort	Changes in vehicle dynamics: expected improvement in vertical comfort for levitating systems, decrease in longitudinal comfort due to higher vehicle acceleration and retardation, and decreased lateral comfort due to the increase of average speeds in curved sections.

	Noise	Less noise and vibration Electromagnetic noise needs to be analysed
	Customer Satisfaction Score	Feedback from passengers regarding their experience at the journey. This KPI reflects the quality of service provided and can be integrated with specific score about MDS systems.

8 Conclusions

This deliverable has identified and evaluated the design methodology and constraints for MDS operation in typical and perturbed regimes, taking into account capacity planning & timetabling, CCS, TMS, station design, management and maintenance, and customer acceptance assessments of a new way of travelling, including miscellaneous aspects such as access control and seatbelt enforcement, baggage control, consequent dwell times, etc.

Initially, three operational models were considered: Normal, Disturbed and Disrupted. In addition to complying with what is written in (Commission Implementing Regulation (EU) 2019/773, 2019), some procedures have been specifically identified for each type of MDS infrastructure (dedicated, upgraded or existing) and for each type of propulsion to ensure operational safety in case of disruptions. Some examples of requirements that may arise for operational procedures related to risks that are unlikely to be controlled by technical solutions are presented for the three use cases defined in WP 7.1.

In the context of capacity planning and timetabling, parameters affecting the capacity of a line or station were identified, in addition to its layout, such as reference period, train typologies and their sequence, operational regimes, signalling systems and regularity requirements. A first classification of the operational regime was made based on the level of operational disturbances considered, measured by standard punctuality indicators. Finally, an assessment of the calculation of key performance indicators for the MDS was also provided.

With regard to CCS & TMS, based on the analyses carried out in the previous phases of the project, potential risks for the complete reuse of CCS systems were highlighted, taking into account the interoperability of the new MDS system with respect to lines in commercial operation and possible repercussions.

For the CCS field, it is therefore necessary to establish in the industrial roadmap that will be developed in WP7 specific considerations for MDS vehicles and to define how to comply and interact with the ongoing developments. In this way, any problems can be anticipated and solutions found to mitigate them.

One of the arguments in favour of this evolutionary path is the simplification of the lines by reducing the number of installed elements and moving most of the intelligence on board the train. Once all the aspects of EMC on board the MDS vehicle have been analysed and resolved, the path should move quickly towards the use of hybrid operations of trains and MDS vehicles on the same lines.

For all other functional aspects, no functional incompatibility problems have been identified. MDS vehicles will have to be added to the list of possible circulating vehicles, and the braking curves, and therefore the distance between trains, will have to be taken into account. But this is part of the configuration of the control system.

In terms of station management and its design in relation to the identified configurations for MDS and their possible interaction with the existing railway system, the new station visions are similar to the ones of traditional railway systems, which focus on people's needs, proposing stations and their surroundings as safer and more pleasant areas, with various objectives including: increasing the level of connectivity between long distance and local public transport, shared mobility and active mobility to better respond to people's needs; improving accessibility within stations through inclusive and barrier-free design; and improving the availability of information and better wayfinding both inside and outside the station. The main difference regarding the introduction of MDS hybrid configuration remains on the platform design, and the station management and capacity considerations.

The focus on platform design is strictly related to the type of MDS implementation and interoperability requirements. If the MDS vehicle floor height is significantly different from the traditional train floor height, the platform height and width should be designed to accommodate the new system in order to maximise loading and unloading operations while maintaining a high level of passenger service. The choice of platform design is highly context dependent. The existing station infrastructure, the specific concept of the MDS implementation and the traffic demand of the different transport systems will all influence the station design. The aim must be to comply with the regulations and to find an optimum between all the different operational requirements.

In the context of station planning and management, it is particularly important to define common KPIs to ensure effective station management. Potential KPIs for evaluation and decision making in station management can be the following Train and passenger throughput, dwell time, punctuality, platform utilisation and customer satisfaction.

Regular assessment of station capacity is essential to identify potential bottlenecks and areas for improvement. This involves analysing many different factors such as train frequencies, journey times and platform capacity to determine the maximum throughput of the station.

In terms of asset management and maintenance, an analysis of the possible changes in maintenance approaches from conventional traffic to the operations of the system considering different MDS configurations has been provided. Assuming that the information from the sensors in the vehicles can be used for data analysis, the maintenance regime will change to sensor based predictive maintenance, at least for the new components of the MDS. But especially for the infrastructure subsystem, the data generated by the sensors could be used for quality control of the existing infrastructure elements.

In addition, the main maintenance activities have been listed and the expected changes between the classic railway and the different MDS solutions (upgraded railway vehicles and hybrid MDS) have been mapped.

In the context of the maintenance of a new type of rolling stock, logistics requires the coordination of different activities and resources to support the maintenance and operation of the rolling stock. For the upgraded vehicles, this will be similar to today's procedures, as they can run on any standard track like a conventional wagon, as long as the components of the MDS are deactivated. For the pods in a hybrid MDS stage, it will be necessary to ensure that maintenance facilities are accessible. This means that the tracks must be updated and fitted with linear motors. If the pods need to be maintained in other facilities not connected to the MDS network, they can also be wheeled, but require an external traction unit to move them on non-equipped tracks. Again, care must be taken to ensure that all MDS components on the vehicle are disabled. In summary, effective logistics practices are essential to ensure the reliability, safety and longevity of rolling stock while minimising service disruption.

In terms of customer acceptance of a new mode of travel, the new technology under consideration could be perceived by travellers either as a completely new mode of transport or as a technological enhancement of existing rail travel. As the superimposition of the maglev system on existing infrastructure is being investigated, the traveller will access the system in the existing railway station and therefore a direct comparison with existing rail travel is most likely to be expected. It is therefore very important to identify the underlying aspects of travel that today lead customers to choose rail travel when other modes are available; their preservation should preferably be seen as a constraint to the development of new MDS, or else a careful trade-off assessment should be made as to whether the new technologies necessarily require them to be compromised. A number of requirements commonly assumed by rail passengers have been listed, as well as some points on their fulfilment with the new technologies, considering both passenger and freight services.

The last part of the study was the proposal of an evaluation framework and methodology, including a benchmarking technique and the definition of indicators to evaluate the constraints and design methodology for operation in typical and perturbed regimes. The evaluation framework proposed by MaDe4Rail is based on the methodology proposed in (IMPACT-2, 2021), adapted to the specificities of the MDS.

In relation to the KPIs model, the three separate sub-models corresponding to Life-Cycle Costs (LCC), Reliability & Punctuality and Capacity have been taken into account, providing different considerations and constraints specific to MDS systems. Accordingly, and based on the above considerations and constraints for the MDS, several KPIs have been proposed to be considered in the general KPI model. For MDS.

The second part of the evaluation framework and methodology included the Customer Experience Model, also based on the one proposed in (IMPACT-2, 2021), adapted to the specificities of the MDS. In this case, MaDe4Rail has only addressed various considerations and constraints specific to MDS systems, related to the Comfort & Services category, as the other two considered in the general model are outside the scope of the project.

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