Deliverable D 10.1

High-Level System Architecture

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1 EXECUTIVE SUMMARY

This document, D10.1 in FP3-IAM4RAIL, outlines high-level system architecture aligned with EU-RAIL Multi-Annual Work Programme (MAWP). It is the initial output of work package 10, focusing on Intelligent Asset Management Strategies (IAMS) application refinement. Work packages 10 and 11 are vital components, addressing infrastructure asset management in FP3-IAM4RAIL. The document details the approach, use cases, and architecture for WP10/11.

The Multi-Source Multi-Purpose (MSMP) IAMS integrates diverse stakeholder data for informed decisions by maintenance experts and asset managers. It monitors asset conditions, maintenance, by using real-time (through embedded sensors) and historically data during railway operations. User-friendly decision tools provide reliable diagnostic and prognostic data. The core uses self-learning anomaly detection and applying AI technology, including unsupervised, supervised, and reinforcement learning. The high-level system architecture encompasses critical elements like onboard and wayside systems, diverse data sources, integrated analytics, decision support, planning, execution, and visualization. Onboard systems have vehicle-installed components, wayside systems involve trackside infrastructure, and data integration aggregates and harmonizes data for analysis. It is applicable to complex systems like railway or transportation management, aiding decision-making for efficient operation planning and execution. The approach emphasizes a modular methodology, enabling effective collaboration among partners in different locations, resulting in a cohesive and integrated system.

Achieving high Technology Readiness Levels (TRLs) presents challenges when implementing novel technologies, necessitating a balance between immediate applications and research exploration, especially with diverse data integration. Access to operational usage is key to advancing TRLs, while involving researchers enhances problem-solving for greater innovation. Combining practical application with research-driven exploration fuels progress and innovation. This deliverable demonstrates substantial progress within Work Package 10, aligning with predetermined objectives and grant agreement requirements. It encapsulates successful task completion for the first ten months, following project guidelines. Future steps involve data acquisition, comprehensive analysis, and application development using various technologies. The project will explore latent opportunities within integrated data to address real-world maintenance challenges. This interactive synergy integrates research and practical aspects, emphasizing the dynamic interplay between theoretical investigation and real-world infrastructure maintenance demands.

2 ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Description
ABA	Axle Box Accelerometers
AI	Artificial Intelligence
API	Application Programming Interfaces
ATO	Autonomous Train Operation
BIM	Building Information Modelling
CAD	Computer Aided Design
CCS	Control Command and Signalling subsystem
CDM	Conceptual Data Model
CNN	Convolutional Neuronal Network
CSM	Common Safety Method
DC	Direct Current
DMI	Directional Movement Indicator
DSP	digital signal processing
DT	Digital Twin
DTM	Digital Track Management
DXF	Drawing Interchange Format
DWG	AutoCAD Drawing Database (file extension)
ENE	Energy (subsystem)
ERJU	Europe's Rail Joint Undertaking
ERTMS	European Railway Trafic Management System
EU	European Union
FA	Flagship Area
FEM	Finite Element Modelling
FME	Feature Manipulation Engine
FMU	Functional Mock-up Unit
FP	Flagship Project
GAN	generative adversarial neural network
GIS	Geographic Information System
GNSS	Global Navitation Satellite Systems
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HMI	Human Machine Interface
HS	High Speed
IAMS	Intelligent Asset Management Strategies
IM	Infrastructure Manager
IMU	Inertial Measurement Unit
INF	Infrastructure

Abbreviation / Acronym	Description
InteDemo	Integrated Demonstrator
JU	Joint Undertaking
KER	Key Exploitable Results
KML	Keyhole Markup Language
KPI	Key Performance Indicator
LCC	Life Cycle Cost
MAP	Modelica Association Project
MAWP	Multi-Annual Work Programme
MBM	Multi Body Modelling
MBS	Multi Body Simulation
MCA	Model Consortium Agreement
MEMS	Micro-electromechanical system
ML	Machine Learning
MSMP	Multi-Source Multi-Purpose
OPEX	Operational Expense
PCB	Printed Circuit Board
R&I	Research and Innovation
RAMS	Reliability, Availability, Maintainability, Safety
RCF	Rolling Contact Fatigue
RF	Radio Frequency
RST	Rolling Stock
RU	Railway Undertaking
S2R	Shift2Rail
S&C	Switches and Crossings
SP	System Pillar
TMS	Trafic Management System
TRL	Technology Readyness Level
TT	Transversal Topic
UAV	Unmanned Autonomous Vehicle / Unmanned Aerial Vehicle
UXO	UneXplode Ordnances
WP	Work Package
XML	Extensible Markup Language

3 BACKGROUND

This document represents Deliverable D10.1, titled "High-Level System Architecture", within Flagship Project 3 FP3–IAM4RAIL. It is aligned with the EU-RAIL Multi-Annual Work Programme (MAWP) as detailed in the FP3-IAM4RAIL Grant Agreement. D10.1 is the initial output of work package 10, "Multi-Source/Multi-purpose IAMS application: scope refinement & quick wins," of FP3-IAM4RAIL.

Work packages 10 and 11 are crucial components of FP3-IAM4RAIL cluster D, "Infrastructure Asset Management." Cluster D addresses long-term maintenance and costs (WP8), track systems (WP9), innovative multi-purpose IAMS infrastructure applications (WP10 and WP11), and civil assets (WP12 and WP13).

WP10 and WP11 complement each other, forming a cohesive block within cluster D. Work package 11 is dedicated to the main development tasks, including the demonstration of applications conceptualised and initiated in WP10, specifically for the multi-source/multi-purpose (MSMP) asset management platform.

The document's purpose is to outline and describe in more detail the idea behind the work in the two work packages (WP10/11), the approach, the use cases as well as the high-level architecture of the connected entirety being developed within WP10/11.

FP3-IAM4RAIL is part of the broader EU-RAIL Multi-Annual Work Programme (MAWP), aligning with the EU's strategic goals and objectives for the railway sector.

WP10/11 also collaborates with other Flagship Projects, focusing on different aspects within the railway sector to collectively enhance and modernize the industry. Specifically, for FP1-MOTIONAL, the contributions relate to federated data space and digital twins (refer paragraph 6.1).

This collaborative approach allows WP10/11 FP3-IAM4RAIL to foster synergies, share knowledge, and promote innovation, leading to a more comprehensive and effective transformation of the railway sector, primarily centred on the technologies at hand.

4 OBJECTIVE/AIM

The deliverable at hand presents a preliminary High-Level Architecture outlining the approach of WP10. Task 10.1, "Requirements and System Architecture for MSMP initial developments," is responsible for refining requirements and scope. This task aligns with end-user expectations and leverages the findings of previous Shift2Rail projects like In2Smart and In2Smart2.

Work package 10 aims to deploy innovative rail infrastructure asset management solutions in an operational environment. These solutions build upon previous EU projects like IN2SMART and IN2SMART2 but elevate their application to a higher level of maturity. The focus is on ’short-term asset management’ and off-site work preparation, integrated as a multi-source/multi-purpose (MSMP) asset management platform.

To achieve this objective, the emphasis is on providing continuous traceable diagnostic and prognostic information. This data is obtained from embedded wayside and onboard sensors, empowering maintenance experts and asset managers to make day-to-day decisions efficiently.

The scope of the rail infrastructure subsystem covers data acquisition processes, particularly for assets along the railway line within a range of 360 degrees and approximately 5 meters around each asset (Figure 1). The goal is to gain valuable information, potentially even observing underground issues. Special attention is dedicated to Switches and Crossings (S&Cs) as vital assets in this subsystem.

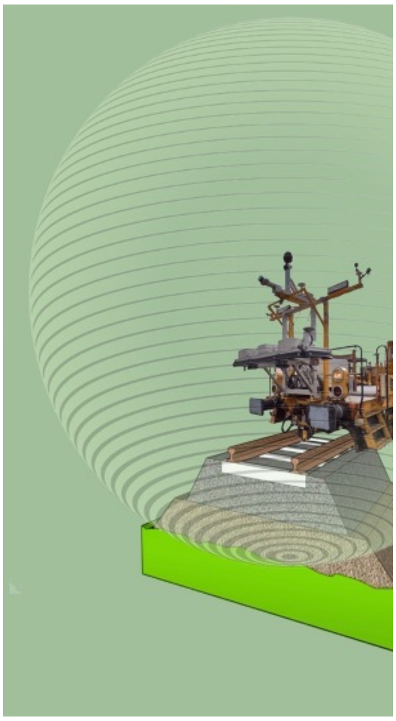

Figure 1: Scope rail infrastructure monitoring, range of 360 degrees

Furthermore, Task 10.1 collaborates with WP2 to establish a common view and system architecture. This sets the foundation for collaboration with other work packages, fostering combined activities, exploring synergies, and sharing experiences and best practices in the utilization of similar technologies.

5 MULTI-SOURCE/MULTI-PURPOSE INTEGRATED ASSET MANAGEMENT SYSTEM

Maintaining smooth operation of the railway infrastructure is the primary objective of short-term (operational) asset management. It brings together the execution of long-term overhaul and mid-term preventive maintenance activities with short-term repairs due to unexpected failures or external damaging events. The spatially widely distributed rail infrastructure in Europe is a historically grown and heterogeneous system consisting of many technically sophisticated individual systems with several decades of lifetime provided by international set of suppliers. Normal asset behaviour as well as degradation are driven by harsh environmental conditions and heavy static as well as dynamic loadings. In summary, successful short-term asset management is a complex team challenge (see stakeholders' description, paragraph 5.1). Nowadays, it furthermore relies largely on the comprehensive technical expertise and especially many years of experience of the individual operators and asset managers, who decide which actions to take next based on sparse available data and information.

The Multi-Source / Multi-Purpose (MSMP) Integrated Asset Management System (IAMS) shall provide a framework which enables the fusion of all relevant information provided by all involved stakeholders, to support the day-by-day decisions of the maintenance experts and asset managers. This comprises information about actual and historic asset condition, maintenance activities and loading. Basis of the MSMP IAMS is the continuous, automatic condition monitoring during ongoing railway operations based on embedded vehicle-borne and wayside sensors. Easy-to-use decision support tools fed with reliable and traceable diagnostic and prognostic information are the interface to the individual asset managers. In between, at the heart of an MSMP IAMS are self-learning anomaly detection, diagnostic and prognostic models, based on sophisticated algorithms and artificial intelligence including unsupervised and supervised machine learning as well as reinforcement learning.

The implementation of such a MSMP IAMS is considered as a federated MSMP asset management platform providing a set of key technical and digital enablers as well as digital models and standards to realize operational interfaces between the involved stakeholders.

Main objective of FP3-IAM4RAIL WP 10 and 11 is the prototype implementation and evaluation of such a MSMP asset management platform (see paragraph 5.3) in the operational environment of two pilot sites in the Netherlands and Spain (see section 8). This prototype is part of the FP3-IAM4RAIL integrated demonstrator #4 and addresses two over-arching use cases (see both paragraphs 5.2.1 and 5.2.1) The prototype will enable in-depth research and development on a high TRL for a various set of specific technical applications (section 9) in FP3-IAM4RAIL and the upcoming FP3-projects.

5.1 Stakeholders

Main purpose of a federated MSMP asset management platform as realization of a MSMP IAMS is to provide the technical, legal, and organizational foundation to connect and enable all actors contributing to the short-term asset management of a specific set of railway infrastructure assets. The platform will facilitate seamless collaboration and data exchange among these interconnected actors, roles, and entities, optimizing the rail industry's overall efficiency and effectiveness.

Relevant actors, roles, and entities for the short-term asset management are:

- Actors
  - Infrastructure Manager
  - Engineering companies
  - Suppliers
  - (Sub)-contractors
- Roles
  - Data analysts
  - Maintenance staff
    - Senior decision maker (strategy)
    - Maintenance professionals and managers (tactics)
    - Maintenance technicians and operational staff (operations)
- Entities
  - Infrastructure
  - On-board and wayside monitoring platforms and the technologies
  - Other IT applications

In the context of MSMP IAMS, the three interrelated components as listed above are defined as:

Actors refer to the organisations engaged in the management of rail infrastructure assets. These actors assume *roles*, which denote distinct functions with specific responsibilities. While a particular role might be undertaken by a single actor, these functions could also be carried out by multiple actors based on their unique viewpoints and duties. *Entities* encompass the tangible elements of the rail infrastructure, encompassing primary assets integrated into the rail system, as well as auxiliary assets that provide support.

5.1.1 Actors

Actors within the rail infrastructure ecosystem encompass a range of organizations contributing to its functioning, as an example:

Infrastructure Manager: The Infrastructure Manager is a pivotal actor responsible for the overall coordination, maintenance, and operation of the rail infrastructure. This includes managing tracks, stations, and other core components of the rail network. Their role involves ensuring safe and efficient rail operations, overseeing maintenance activities, and optimizing the utilization of resources to enhance the performance of the rail system.

Engineering Companies: Engineering companies are pivotal in rail system lifecycles, contributing from design to maintenance. They create designs, supervise construction, optimize operations, and develop maintenance strategies, ensuring reliable, efficient, and safe rail infrastructure. Collaboration with various stakeholders is key, highlighting their expertise, innovation, and dedication to rail network functionality and enhancement.

Suppliers: Suppliers are entities that provide various materials, equipment, and resources necessary for the construction, operation, and maintenance of rail infrastructure. These can include suppliers of rails, signalling equipment, rolling stock components, maintenance machinery, and other essential resources. Suppliers play a crucial role in ensuring that the rail system is equipped with the necessary elements to operate reliably and efficiently.

(Sub)contractors: (sub) contractors are organizations hired by primary contractors or infrastructure managers to perform specific tasks within the rail infrastructure ecosystem. They are often specialists in certain fields such as construction, maintenance, or technology deployment. Subcontractors collaborate closely with the primary actors to execute tasks such as track maintenance, station upgrades, or signalling system installations. Their role contributes to the overall development and upkeep of the rail network.

5.1.2 Roles

Roles refer to the functions performed by an actor in specific situations and can be linked to one or more actors depending on their position within the supply chain. The following examples (list is not exhaustive/comprehensive):

Data Analysts: Data analysts are individuals responsible for collecting, processing, and interpreting data related to various aspects of the rail infrastructure. They utilize analytical tools and techniques to identify trends, patterns, and insights from the data. Their role involves generating reports, visualizations, and recommendations that aid in making informed decisions for optimizing rail operations, enhancing safety, and improving overall efficiency.

Maintenance Staff: Maintenance staff are personnel dedicated to ensuring the proper functioning and upkeep of the rail infrastructure. They perform routine inspections, repairs, and preventive maintenance on tracks, signalling systems, stations, rolling stock, and other rail components. Their role is vital in maintaining safety, reliability, and the overall operational quality of the rail network.

Senior Decision Maker (Strategy): Senior decision makers in a strategic capacity are individuals at the higher levels of management responsible for setting long-term goals and direction for the rail infrastructure ecosystem. They make decisions that shape the overall strategy of the rail network, which can include expansion plans, technological upgrades, and policy implementations. Their role involves considering broader industry trends, financial considerations, and regulatory aspects to guide the future development of the rail system.

Maintenance Professionals and Managers (Tactics): Maintenance professionals and managers in tactical roles are responsible for planning and executing maintenance activities within specific areas of the rail infrastructure. They oversee maintenance schedules, allocate resources, and coordinate with maintenance staff to ensure that routine and corrective maintenance tasks are carried out efficiently. Their role focuses on translating strategic goals into practical maintenance plans to guarantee the smooth operation of the rail system.

Maintenance Technicians and Operational Staff (Operations): Maintenance technicians and operational staff in operational roles are hands-on workers responsible for carrying out maintenance tasks on a day-to-day basis. They perform inspections, repairs, and maintenance procedures on rail assets, responding to immediate maintenance needs and addressing unexpected issues. Their role is critical in maintaining the operational readiness of the rail infrastructure and promptly addressing any maintenance-related concerns.

5.1.3 Entities

Entities encompass a spectrum of resources within the rail infrastructure domain, encompassing both the distinct physical infrastructure exclusive to the rail sector and complementary components like on-board and wayside monitoring platforms, technological systems, and various IT applications. The following paragraphs explain these entities in more detail:

Infrastructure Entities: Infrastructure entities refer to the integral physical components constituting the rail network. These incorporate the essential elements of rail operations, encompassing tracks, stations, bridges, tunnels, signalling systems, electrification mechanisms, and other structures pivotal to effective rail functioning.

Monitoring Platforms & other Technologies Entities: On-board and wayside monitoring platforms and technologies entities comprise systems and apparatuses employed for continuous surveillance and seamless operation of the rail infrastructure. On-board mechanisms are situated within train carriages, offering real-time data on train performance, condition assessment, and passenger safety. Wayside systems, positioned alongside tracks, provide insights into track conditions, train positioning, and potential hazards. These technologies include sensors, cameras, communication setups, and analytical tools that contribute to heightening rail safety, maintenance, and overall operational efficiency.

Other Entities, such as IT Applications: Other entities, encompassing IT applications and analogous solutions, serve as software tools that bolster diverse aspects of rail infrastructure administration. These encompass ticketing systems, scheduling software, maintenance management platforms, asset tracking solutions, and communication interfaces. IT applications streamline administrative procedures, facilitate data analysis for operational optimization, and enhance passenger experiences by facilitating tasks like ticket booking and real-time updates.

5.2 Integrated Demonstrator and Use Cases

Within FP3-IAM4RAIL, a total of seven integrated demonstrators have been defined to bring together the individual developments in the various work packages to a coherent and holistic approach (see FP3-IAM4RAIL concept, Figure 2). The MSMP asset management platform prototype of WP10/11 (see paragraph 5.3) contributes to the FP3-IAM4RAIL concept and the integrated demonstrator #4 *"Asset Management & Infrastructure" (*see Appendix 1 for full definition of this integrated demonstrator).

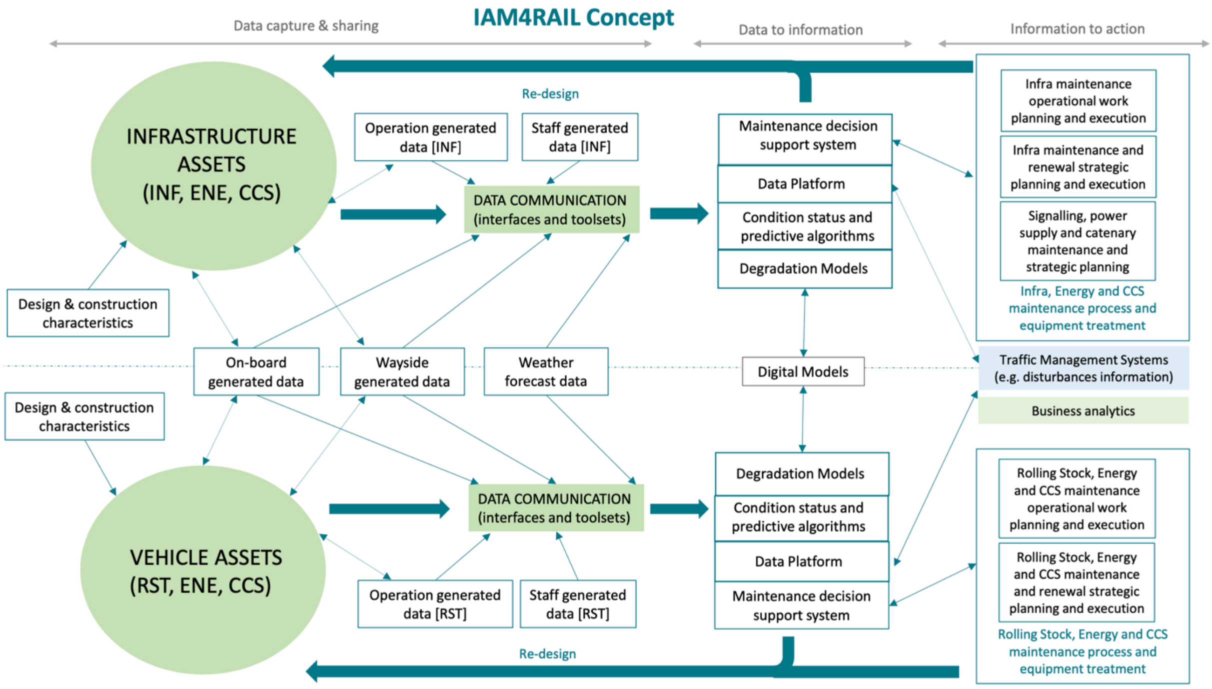

Figure 2: FP3-IAM4RAIL Concept

Within WP10/11, furthermore two basic use cases to guide the implementation of our specific MSMP asset management platform prototype is defined:

- Use Case 1: Linking (new) monitoring technologies to asset management issues
- Use Case 2: Fusion of monitoring data for an enhanced fault detection and diagnosis

Short summaries of the two use cases are given in paragraphs 5.2.1 and 5.2.1, the full descriptions are given in Appendix 2 and Appendix 3 respectively.

The use cases can be seen as consisting of two distinct steps:

- In the first step, we focus on the direct utilization of technology and its data, linking it to specific rail infrastructure issues. This phase aims to quickly address and tackle targeted problems, potentially leading to immediate benefits and quick wins.
- In the second step, we adopt a more scientific and comprehensive approach. We explore the integration of data from different technologies to achieve more accurate and insightful results. This stage involves a deeper analysis of the data to uncover additional information about the infrastructure's behaviour and potential issues. While this step requires more effort and resources, it promises to provide a more thorough understanding of the railway system and its performance.

In essence, the first step is geared towards immediate gains, while the second step seeks to unlock a more profound and informed perspective, laying the groundwork for long-term improvements and advancements in rail infrastructure management.

In summary, we will follow a layered approach, by developing a set of applications by using different technologies, that will leverage the high-level architecture of the prototype platform in two different Use Cases, contributing to the high-level demonstrator (#4) in three different pilot demonstration sites.

5.2.1 Use Case 1: Linking (new) monitoring technologies to asset management issues

This use case is serving as the first step in implementing new sensor technologies in an operational rail environment. It aims to assess the feasibility and effectiveness of integrating these technologies into the existing asset management framework.

It involves deploying the sensors on the rail infrastructure subsystems, including wayside and onboard sensors, to gather sensor data relevant to extract diagnostic and prognostic information. By utilizing these sensors, the project aims to provide traceable data for continuous asset condition monitoring, enabling maintenance experts and asset managers to make informed decisions. By conducting experiments and data analysis, the use case helps identify potential challenges that may arise from the deployment of new (embedded) monitoring systems. It serves as a crucial groundwork to identify specific asset issues, possibly at an early stage and being able to predict its evolvement so as to plan timely interventions.

By exploring and analysing the data collected from the new sensor technologies, the use case aims to identify relevant patterns and insights that can address specific asset management issues. This helps bridge the gap between the potential of the modern technologies and their practical implementation in the rail industry. The use case also demonstrates the interoperability and cross-border applicability of the solutions by conducting early demonstrations in different operational scenarios across EU member states.

Overall, this use case plays a crucial role in the demonstrator of the project by laying the foundation for the integration of new sensor technologies in the rail infrastructure. It helps assess the compatibility, effectiveness, and potential challenges of these technologies in an operational environment. The insights gained from this use case will inform subsequent steps and developments in the project, leading to further advancements in asset management practices and ultimately improving the performance and reliability of the rail infrastructure subsystem.

5.2.1 Use Case 2: Fusion Monitoring Data for Enhanced Fault Detection & Diagnosis

This use case aims to improve fault detection and diagnosis in the rail infrastructure subsystem by integrating onboard and wayside monitoring data (see use case 1), along with potential other sources of relevant information (e. g. meteorological conditions, railway operations, etc.). The main objective is to develop a comprehensive monitoring environment that utilizes multi-sensor and multi-vehicle modular architectures, combined with advanced algorithms and models, to enhance fault detection capabilities and enable better maintenance decision-making.

The problem currently faced in the rail industry is the limited effectiveness of existing fault detection and diagnosis methods, which rely on partial data from either onboard or wayside sensors. This leads to delayed fault detection, increased maintenance costs, operational disruptions, and safety risks. To address this, the use case focuses on fusing data from different monitoring sources to improve fault detection and diagnosis.

By combining data findings and employing advanced algorithms, the use case aims to create effective solutions for maintenance decision-making. This requires handling diverse data sets using new data analytics techniques, leading to improved maintenance strategies and the readiness of the technology for real-world implementation in the rail industry.

The rail industry's current position relies heavily on manual inspections, periodic maintenance, and limited sensor data, resulting in time-consuming and labour-intensive processes that may miss subtle or intermittent faults. The lack of integration between onboard and wayside monitoring data further limits fault detection effectiveness. By embracing data integration and modern analytics, the industry can significantly enhance fault detection capabilities, leading to improved maintenance practices, better resource allocation, and safer and more reliable rail operations.

The use case addresses the subproblem of fusing onboard and wayside monitoring data and sets measurable objectives, including developing monitoring systems with multi-sensor architectures, implementing advanced algorithms for fault detection, assessing turnout health through anomaly detection and early prediction, and developing decision support tools based on learning approaches.

The proposed innovation of fusing data from onboard and wayside monitoring improves the ability to identify and address faults accurately and in a timely manner. This comprehensive approach allows for proactive maintenance interventions, reducing the risk of asset failures, minimizing disruptions, and improving safety. The use of advanced algorithms further enhances the accuracy and reliability of fault detection, enabling informed maintenance decisions and optimized planning. Ultimately, this innovation improves asset reliability, reduces maintenance costs, and enhances the operational performance of the rail infrastructure subsystem.

5.3 MSMP: general system architecture

FP3-IAM4RAIL plays a significant role in fostering enhanced integration and collaboration among various stakeholders both within and outside the rail ecosystem. This vision is encapsulated in the project concept displayed in **Error! Reference source not found.**. The project recognizes that substantial cross-border integrated advancements, and demonstrations yield a greater impact on the entire railway system, particularly from a maintenance perspective.

Consequently, FP3-IAM4RAIL's underlying concept outlines its dynamic approach to interlinking different components: the railway infrastructure (INF), the energy subsystem (ENE), the control command and signalling subsystem (CCS), and the rolling stock (RST). This is accomplished through a phased process comprising three main steps:

Data Capturing & Sharing: This phase involves the acquisition and sharing of new data, facilitated by innovative means like wayside and on-board systems, as well as external sources.

Transferring Data into Information: Innovative digital models are employed to convert the collected data into actionable information and valuable insights, thereby transforming raw data into knowledge.

Setting Information into Actions: The actionable insights derived from the previous step guide decisions and actions, driving improvements in various aspects of the rail ecosystem.

FP3-IAM4RAIL's strategy encompasses:

- Introducing novel data acquisition and sharing capabilities, integrating information from both wayside and on-board systems along with external data sources.

- Creating advanced digital models that transform raw data into meaningful information and valuable knowledge.
- Implementing cutting-edge technologies and methodologies that empower decision-making and operational enhancements.

By following this framework, FP3-IAM4RAIL seeks to realise its vision of seamless integration, informed decision-making, and overall progress within the rail domain. This holistic and integrated asset management approach is illustrated in the previously mentioned Figure 2.

Aligned with the overarching vision of FP3-IAM4RAIL, it is important to note that not all components pertain to WP10/11. Figure 3 in section 5.3.1 highlights the pertinent elements with a distinct red marking. Section 5.3.1 elaborates on the chosen elements, offering insight into their relevance. Concurrently, section 5.3.2 presents the high-level architecture of the platform prototype for WP10/11. Lastly, in section 5.3.3, the correlation between these elements and the broader context is expounded upon.

5.3.1 WP10/11 platform prototype within the FP3-IAM4RAIL concept

The general ideas differentiate between Infrastructure Assets and Vehicle Assets. Within the category of Infrastructure Assets, we can identify Infra Assets (INF), Energy (ENE), and Control, Command, and Signalling assets (CCS). Among the Vehicle Assets, we find Rolling Stock (RST), Energy (ENE), and Control, Command, and Signalling assets (CCS).

Our platform prototype focusses on the Infrastructure Assets, meaning that the elements of the overall concept are visualised in the upper part of the visualisation, highlighted in red in Figure 3. That said, and due to the holistic approach to asset management, some elements that are common to both infrastructure and rolling stock (e.g. Digital Models) and even exclusive to vehicles (e.g. Design & construction characteristics) will be addressed in this Work Package.

A brief explanation about each of these relevant elements in relation to the ambition of our work is provided below.

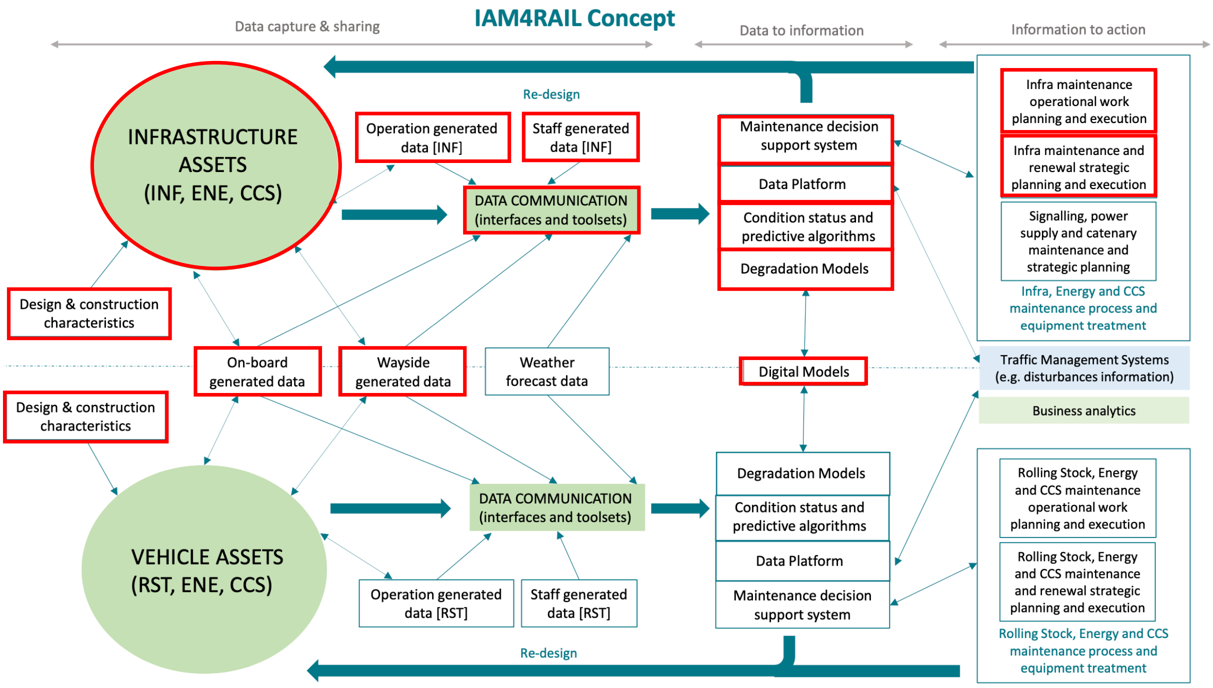

Figure 3: FP3-IAM4RAIL general concept and the relevant parts for WP10/11

INFRASTRUCTURE ASSETS (INF, ENE, CCS): focus will be in infrastructure assets, particularly for assets along the railway line within a range of 360 degrees and approximately 5 meters around each asset. Main examples of potential target assets are switches & crossings, track, catenary, signals, etc.

Design & construction characteristics: design and construction characteristics of assets are necessary to parametrise algorithms and models. These characteristics include materials, geometries, installation & assembly, etc. The focus will not only be in characterising infrastructure assets: the design & construction characteristics of vehicles operating along the pilot lines are necessary too, as assessing their interaction with the infrastructure (e.g. wheel-rail interaction) is key to evaluate their impact in the degradation of infrastructure assets.

On-board generated data: data generated by sensors and systems installed on-board Leonardo platform (see section 7.1), either raw or processed. Some examples of this data are 2D images, 3D point-clouds (LiDar, laser-scaner), inertial (accelerations & gyros, displacements, etc.), GPR, etc.

Wayside generated data: data generated by sensors and systems installed in the track and in the vicinity of switches and crossings, either raw or processed. Some examples of this data are inertial (accelerations, displacements, forces, etc.), electrical (e.g. currents and voltages), temperature, acoustic emission, etc.

Operation generated data (INF): data generated during operations may include information about the status of assets (e.g. track geometry inspection data), services operating along the line (including the characteristics of vehicles, speeds, loads, etc.)

Staff generated data (INF): data generated by maintenance staff may include information about the status of assets (e.g. visual/manual inspections), history of reparations and replacements, maintenance plans, etc.

DATA COMMUNICATION (interfaces and toolsets): sensors and systems (both on-board and wayside) will include some means to transmit relevant information to back-office applications. Focus will be in the interoperability of systems; for that reason, a common data model approach will be followed for the different interfaces.

Maintenance decision support system: set of tools and functionalities that will assist decision-makers in making informed choices for maintenance work planning and execution based on the analytics and insights generated by the system. Example of these functionalities include the detection of anomalies and the diagnostic of failures, as well as the comparison and benchmarking of health condition data and its projected evolution. These tools and functionalities include the integration and visualization of data (including multiple type and historical information data analysis) in IAMS.

Data platform: Implementation of the Rail Data Space to provide exchange and sharing of digital resources across rail operators, infrastructure managers, suppliers and service providers involved in the maintenance activities and processes. The data platform is based on data federation services for building a trusted, reliable, cybersecure federated data space connecting all stake holders (see section).

Condition status and predictive algorithms: the health condition of target assets will be assessed by means of different data sources, models, and algorithms. Based on that, the future condition status will be assessed by means of predictive algorithms that will be based on physical degradation modelling, machine learning techniques, and a combination of both (hybrid modelling).

Degradation models: development of digital models (see below) will allow assessing the degradation of infrastructure assets, taking into account the interaction between assets and the characteristics of their lifecycle. Degradation models can be theoretical and/or based on the experience (analytical approach), but they can also make use of historical data to enable approaches based on machine learning. Both approaches will be used for the development of predictive algorithms (see above).

Digital models: models of assets (of both vehicles and infrastructure) are key to the development of condition status and predictive algorithms, as well as for assessing their degradation (see above). We will make use of different kind of modelling techniques: analytical, Finite Element Modelling (FEM), Multi Body Modelling (MBM), data-based (e.g. using machine learning techniques), etc.

Infra maintenance operational work planning and execution: The information provided by condition status and predictive algorithms and maintenance decision support system will enable a more effective planning of maintenance operational work in the short term. The goal is to transform the information into action (execution) by prioritising cost, safety, and availability.

Infra maintenance and renewal strategic planning execution: all the above will be fed back into the system to support better strategic decisions in the mid-long term.

5.3.2 High-Level Architecture Of WP10/11 Platform Prototype

The envisaged platform is multi-purpose. For this reason, it needs different data sources but also aspects to receive, process and combine the data. The total platform is therefore divided in different generic elements.

Figure 4 is a schematic representation of the high-level architecture we have in mind for the platform we envisage.

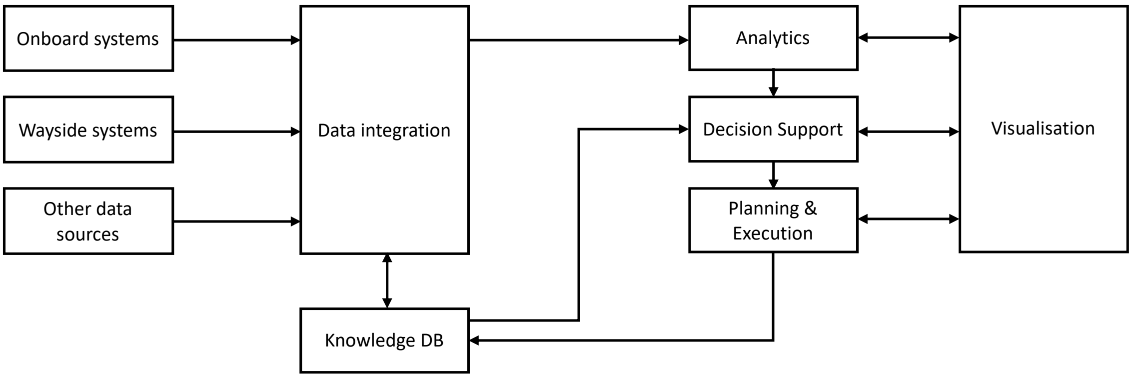

Figure 4: High-level architecture WP10/11

The high-level system architecture, as visualised in Figure 4, consists of the following elements:

1) *Onboard Systems:* Refers to the systems and components installed on the vehicles or equipment directly. These could include sensors, communication devices, and other relevant technologies.
2) *Wayside Systems:* Refers to the systems and infrastructure located along the track or wayside. These could include signals, switches, trackside sensors, and other equipment used to monitor and control the railway.
3) *Other Data Sources:* Encompasses additional sources of data that contribute to the overall system. These sources might include external databases, such as weather information, or third-party systems.
4) *Data Integration:* Involves the process of collecting, aggregating, and harmonizing data from various sources to create a unified and coherent dataset for analysis and decision-making.
5) *Analytics:* Involves the application of data analysis techniques to extract insights, patterns, and trends from the integrated dataset.
6) *Decision Support:* Provides tools and functionalities that assist decision-makers in making informed choices based on the analytics and insights generated by the system.
7) *Planning & Execution:* Encompasses functionalities related to the planning and execution of various tasks or operations within the system. This could include scheduling, resource allocation, and coordination.
8) *Visualisation:* Involves the presentation of data, analytics results, and other information in a visual format, making it easier for users to comprehend and interpret.

9) *Knowledge DB:* a structured repository that stores and organizes diverse information and knowledge, facilitating efficient retrieval and utilization for informed decision-making and problem-solving.

This high-level architecture likely describes a complex system, such as a railway management or transportation system, that integrates various data sources, applies analytics, and supports decision-making for planning and executing operations effectively.

5.3.3 Mapping of FP3-IAM4RAIL concept to Architecture

The FP3-IAM4RAIL concept represents the holistic and integrated management of railway assets. In subsection 5.3.1 we highlighted which of its elements will be tackled in the scope of work packages 10 and 11. On the other hand, the high-level architecture we envision for our platform prototype is illustrated in subsection 5.3.2.

Table 1 shows the correspondence between the different elements of both representations, describing how each building block of the high-level architecture maps into the FP3-IAM4RAIL concept.

Architecture WP10/11	FP3-IAM4RAIL concept
- Onboard systems	- On-board generated data
- Wayside systems	- Wayside generated data
- Other data sources	- Operation generated data (INF) - Staff generated data (INF) - Digital models
- Knowledge DDBB	- INFRASTRUCTURE ASSETS - Design & construction characteristics (INF) - Design & construction characteristics (RST) - Digital Models
- Data integration	- DATA COMMUNICATION (interfaces and toolsets) - Data Platform
- Analytics	- Condition status and predictive algorithms - Degradation models - Digital models
- Decision Support	- Maintenance decision support system
- Planning & Execution	- Infra maintenance operational work planning and execution - Infra maintenance and renewal strategic planning and execution

Architecture WP10/11	FP3-IAM4RAIL concept
- Visualisation	- Condition status and predictive algorithms - Degradation models - Digital models - Maintenance decision support system - Infra maintenance operational work planning and execution - Infra maintenance and renewal strategic planning and execution

Table 1: Mapping of FP3-IAM4RAIL concept to Architecture

6 RELATION WITH OTHER WORK PACKAGES & FLAGSHIP AREAS

This chapter outlines the connection between work packages 10 (and 11) within the broader context of the FP3-IAM4RAIL flagship project. It delves into the interplay with clusters and other work packages of FP3-IAM4RAIL (section 6.1), as well as the possible associations and significance concerning other Flagship Projects under the umbrella of Europe's Rail Joint Undertaking (sections 6.2., 6.3 and Figure 5).

6.1 Interaction within FP3-IAM4RAIL

The FP3-IAM4RAIL Flagship Project's developmental process encompasses a total of twenty distinct work packages. Given the project's scope and complexity, it becomes imperative to break down the work into manageable units. Interestingly, the size of each work package, or even the coupling of two related work packages, often resembles a self-contained project in terms of the sheer workload and the involvement of numerous partners and engineers. This compartmentalization of tasks is not just strategic; it's practically a necessity.

These work packages are thoughtfully organized into clusters, and this organizational structure is depicted in Figure 5. This visual representation is crucial in illustrating the coherent and logical groupings of these twenty work packages, aligning them according to shared themes and objectives.

Figure 5: Overview work packages within FP3-IAM4RAIL

Within the context of the FP3-IAM4RAIL Flagship Project, each cluster stands as a strategic combination of interconnected work packages. These clusters function as cohesive units, facilitating the management, coordination, and execution of diverse facets within the project. By grouping together work packages that share common goals, themes, or dependencies, these clusters significantly heighten the efficiency of project development and harmonise collaborative efforts across multiple teams. Importantly, this arrangement also strengthens the potential for collaboration among individual work packages within each cluster, fostering a natural flow of information and expertise that is both beneficial and essential for the project's success.

To provide a more comprehensive understanding, a brief description of the clusters in more detail:

Cluster A - Transversal Activities. This cluster unifies the common activities of the project including project coordination (WP1); system vision, architecture and validation (WP2); and dissemination, communication and exploitation activities (WP20).

Cluster B - Wayside Monitoring and Traffic Management System Link. The cluster focuses on the design, development, testing and validation of an Intelligent Asset Monitoring System capable of supporting the railway operators and infrastructure managers in maintaining smooth and uninterrupted operations (WP3 and WP4).

Cluster C - Rolling Stock Asset Management: On-board and Wayside Technologies. This cluster addresses both on-board (WP5 and WP6) and wayside (WP7) monitoring technologies for the design, testing and validation of intelligent rolling stock asset management solutions.

Cluster D - Infrastructure Asset Management. The infrastructure asset management cluster addresses (i) long term maintenance and costs (WP8); (ii) track systems (WP9); (iii) innovative multi-purpose IAMS infrastructure applications (WP10 and WP11); and (iv) civil assets including structures, earthworks and geotechnics (WP12 and WP13).

Cluster E - Railway Digital Twins. This group of developments focuses on the implementation of railway Digital Twins across the rail sector (WP14 and WP15).

Cluster F - Environment, User and Worker Friendly Railway Assets. Cluster F has the objective of creating environment, user and worker friendly railway assets addressing environmental and cost-effective lines (WP16), new additive manufacturing repair processes (WP17), robotic platforms for railway interventions (WP18) and Augmented Reality and exoskeletons to support railway maintenance (WP19).

For WP10 and 11, the most relevant work packages naturally fall within the boundaries of Cluster D itself – this rationale underscores their inclusion within the same cluster. Additionally, a logical connection exists with Cluster A owing to the cross-cutting nature of the work packages grouped in this particular cluster.

This does not imply that there are no feasible or potential connections with the work packages present in the remaining clusters.

In the next sections the links with these work packages are described in more detail.

6.1.1 Cluster D: relation with direct linked Work Packages

Collectively, Cluster D comprehensively tackles four dimensions of Infrastructure Asset Management (Figure 6), and this cluster is further subdivided into four distinct work streams based on those dimensions.

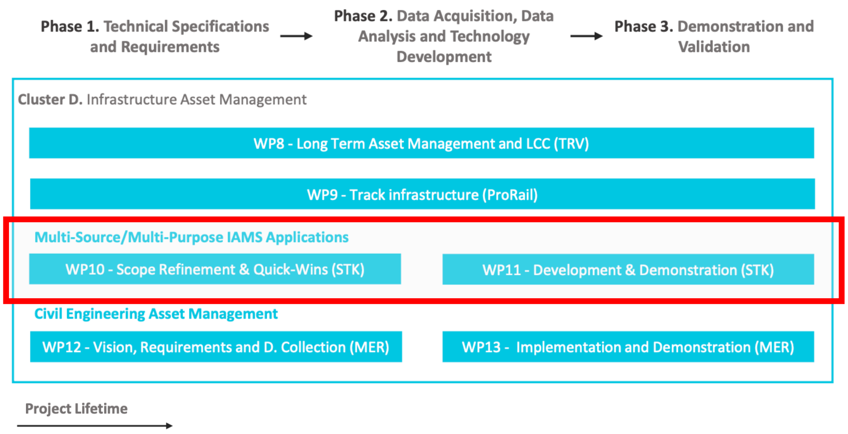

Figure 6: Overview Cluster D. Infrastructure Asset Management

Work Package 10 and 11 complement each other, forming a cohesive block within cluster D. Expressed as one work stream. The same for work packages 12 and 13. WP11 is dedicated to the main development tasks, including the demonstration of applications conceptualised and initiated in WP10, specifically for the multi-source/multi-purpose (MSMP) asset management platform.

The different work streams in cluster D are summarised in more detail:

1) *Long-Term Maintenance And Costs* (WP8), with main objectives:
    a. development of relevant decision support applications for long-term asset management and optimised life-cycle costs, following:
    b. Best practices, with origin in standardisation within asset management, dependability, RAMS, and maintenance, and
    c. Considering all the specific topics for long term asset management, this leads to the development of decision- support tools taking advantage of the close cooperation with infrastructure managers to assess the relevance of the developments.
2) *Track systems* (WP9), with as main objectives:
    a. To develop and evaluate new sensing methodologies for track structure condition state.
    b. To develop advanced and interpretable AI-based approaches for detecting and classifying track infrastructure
    c. anomalies, predicting geometry failures and degradation, and identifying extraordinary degradation rates.
    d. To design decision support tools for track infrastructure prescriptive maintenance.
    e. To showcase these innovative approaches in use cases and demonstrators.
3) *Innovative Multi-Purpose IAMS Infrastructure Applications* (WP10 and WP11), with as main objectives:
    a. To implement multi-sensor/multi-source modular systems for data acquisition including both wayside and onboard systems.

b. To use onboard solution test platforms with direct access to rail networks or existing measurement trains so as to offer the possibility to compare data with existing measurement equipment.
c. To explore new sources of information and the combination of data sources to tackle the challenges of short- term asset management and off-site work preparation.
d. To demonstrate the robustness of the developments through use cases in operational scenarios in Spain and the Netherlands making sure technologies are fit for purpose in different environments.

4) *Civil Assets* (WP12 and WP13), with as main objectives:
   a. To define use cases addressing common civil engineering needs and challenges.
   b. To develop the specifications of these systems addressing bridges, tunnels, earthworks, or geotechnics.
   c. To acquire asset inspection and monitoring data from the field.
   d. To plan the implementation and simulation.
   e. To implement and demonstrate the technologies as designed and specified
   f. To validate, through the demonstration, the robustness of these technologies by measuring KPIs and making recommendations for the future market uptake of the technologies.

Work Stream 3, encompassing Work Packages 10 and 11, takes a systemic approach with a strong emphasis on monitoring tools and translating data into practical daily applications. The central focus here revolves around tools, data utilization, and their resultant applications.

In contrast, Work Streams 2 and 4 concentrate on specific assets, namely track systems and civil assets, respectively. The connection between WP10/11 (Work Stream 3) lies in the fact that the tools, data utilization, and applications developed may also be relevant to the particular assets addressed by these two work streams. Conversely, the outcomes of Work Streams 2 and 4 may be integrated or applied within the framework of Work Stream 3.

Meanwhile, Work Stream 1 is centred on long-term asset management and cost considerations, as implied by its name. Here, data once again plays a critical role, and the technologies developed within Work Stream 3 can potentially contribute to the objectives of Work Stream 1. However, it's important to note that Work Stream 3 places a stronger emphasis on short-term Asset Management.

6.1.2 Cluster A: Transversal Activities

There is a logical and obvious link with Cluster A. All project hygienic activities are grouped together, as visualised in Figure 5:

- Project coordination
- Development of a system vision
- Dissemination

The next sections describe in more detail the link with these three work packages.

6.1.2.1 WP1: Project Coordination

The connection with Work Package 1 is quite straightforward, given its name and purpose, which is Project Coordination. This work package aims to provide the necessary tools and framework for efficiently managing the project. It follows regulations such as Horizon Europe regulation EU 2021/695, Council Regulation EU 2021/2085, and the Model Consortium Agreement (MCA). Additionally, it adheres to the recommendations of the Project Management Handbook approved by Europe's Rail Joint Undertaking (ER JU) Governing Board, offering detailed guidelines for various project roles and areas.

Work Package 1 encompasses tasks related to General Project Coordination, acting as an intermediary between project members and the Funding Authority to ensure efficient coordination. Its objectives include supporting Technical Coordination, managing consortium activities, aligning technical aspects among work packages, overseeing administrative and financial aspects, implementing quality assurance, establishing communication channels with ER JU, fostering cooperation with different ER JU destinations, and providing progress reports to ER JU through annual KPIs.

6.1.2.2 WP2: System Vision

WP2, known as "System Vision," has well-defined objectives aimed at ensuring a harmonized and coordinated approach across the technical aspects of the project. These objectives encompass maintaining consistency in architecture across work packages, establishing effective interaction with the future system pillar, aligning efforts with flagship areas 1 and 5, and orchestrating the formulation of safety and security requirements integral to efficient demonstrations.

The core goals of WP2 are as follows:

Sustaining Common Architecture Baseline: WP2's foremost objective is to uphold alignment among work packages' architectural foundations.

Facilitating Interaction with the System Pillar: WP2 seeks to create a seamless bridge for interaction between the project and the future system pillar.

Strengthening Cooperation with Flagship Areas: This involves ensuring close collaboration and alignment with flagship area 1 and flagship area 5, both of which are crucial for the project's success.

Coordinating Safety and Security Requirements: WP2 is responsible for coordinating the formulation and integration of safety and security requirements within the architectural framework and demonstration plans.

Within WP10, a specific task, 10.1, is designated to contribute to the definition of a unified view and system architecture. This task operates in close collaboration with WP2, "System Vision." Task 10.1 sets a foundation for collaborative efforts with other work packages, fostering activities that explore synergies and share experiences and best practices, particularly in the utilisation of similar technologies.

These collaborative endeavours extend not only to work packages within cluster D but also encompass connections to other work packages mentioned earlier in the introduction part of section 6.1. This aligns with the acknowledgment that potential links exist beyond the immediate cluster. WP2 serves as the cohesive element, fostering connections among all work packages. Over time, as relevance might require, these connections will be further developed to facilitate holistic project integration.

6.1.2.3 WP 20: Dissemination

The primary aim of Work Package 20 is to ensure the broad and effective dissemination of project results and outputs, making them accessible and valuable to their intended audience within Europe's Rail Joint Undertaking (ER JU), the rail sector, and beyond. Additionally, Work Package 10, along with its related Work Package 11, plays a role in supporting these essential project communication and dissemination activities.

Efficient communication and dissemination efforts initially revolve around building and engaging a community of stakeholders. Subsequently, they focus on widely distributing the outcomes of collaborative efforts to all target audiences in the most effective way possible. Furthermore, exploitation activities are instrumental in fully implementing and widely adopting the project results, thereby ensuring a lasting impact in the long term.

Work Package 10 will contribute to achieving these objectives through various means, including:

- Participation in events organised by WP 20
- Deploying integrated demonstrators for promoting and disseminating the results
- Contribute to the development of an exploitation strategy for the results of this work package
- Providing information on impact monitoring, including Key Performance Indicators (KPIs) and Key Exploitable Results (KERs).

Additionally, Work Package 10 plans to submit two papers for TRA 2024 in Dublin and anticipates making contributions to InnoTrans 2024 as well as other future conferences or events including scientific publications where reasonable.

6.2 Relation to FP1-MOTIONAL

The initial plans in Europe's Rail assumed a specific flagship project called Transversal Topic (TT), where research on digitalization, data and model exchange as well as associated infrastructure issues and enabling technologies in the railway field should be gathered. This way, these digital technologies were intended to be developed independently from specific applications where these technologies are to be exploited such as passenger information, automatic train operations or asset management.

However, when the call on FP1 was published, it included the research topics initially addressed by TT in Work Stream 2 entitled "Digital Enablers". In the FP1-MOTIONAL consortium, whose proposal was accepted, the Subgroup 4 constituted to cover these contents and organized them in a work package structure presented in Figure 6.

Despite of this organizational reallocation, the initial idea, namely to separate the development of the digitalization technologies in FP1-MOTIONAL from the applications in other FPs such as asset management use cases in FP3-IAM4RAIL is retained. On the one hand, the enabling technologies are supposed to be general enough to be exploited in as much applications fields as possible, some might even be unknown today. On the other hand, the consideration of specific use cases from other FPs is intended to facilitate the relevance and suitability of the developed digital tools and processes for given problems and issues in the railway field.

Of course, this concept relies on communication, exchange of requirements, coordination of development work etc. between FP1-MOTIONAL and FP3-IAM4RAIL or other FPs, respectively. This is why, the specific Work Package 26 was specified in FP1-MOTIONAL dedicated to “Process Scenarios from all FAs”, see Figure 7.

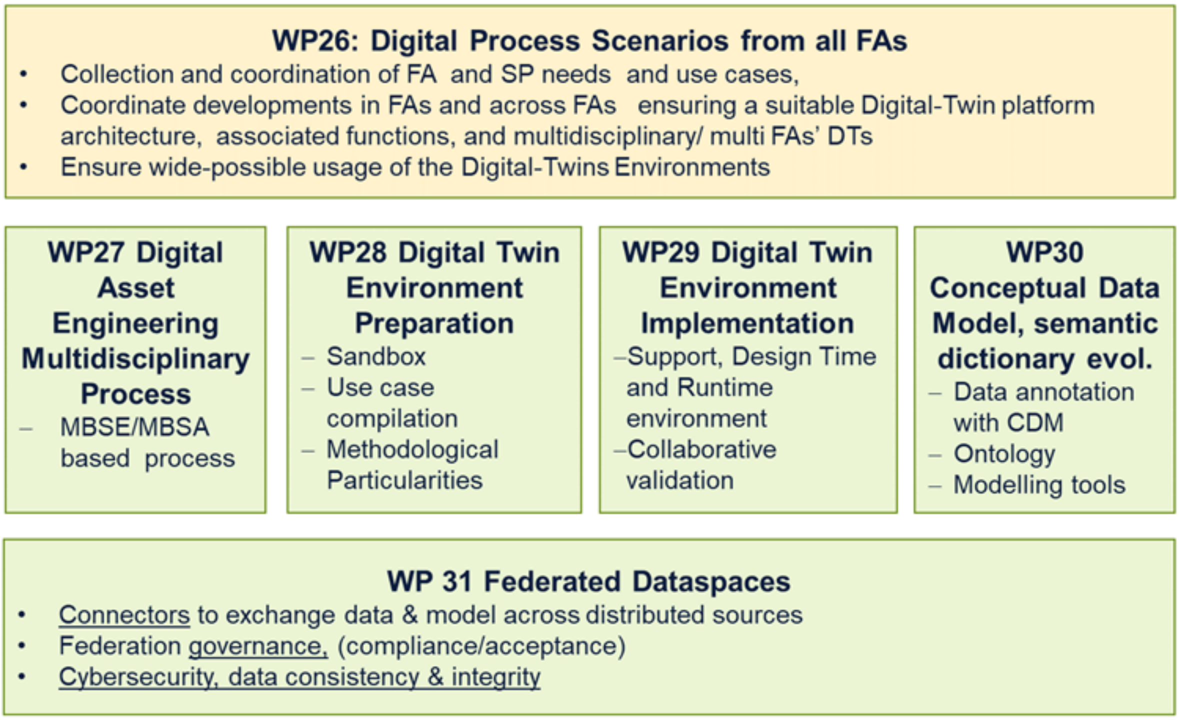

Figure 7: FP1-MOTIONAL, work packages associated with Digital Enablers work stream

6.2.1 Digital Twins

This section is intended to address the Digital Aspects as they are covered in FP1, initiated by the associated call. It is the objective to get away from the general question “what is a Digital Twin?” and come down to the point “what does FP1 want to do with it?”.

6.2.1.1 Background and Definition

Although, there is no lack of related papers and literature reviews, see e. g. van der Valk et al. [1] and their references, it is not possible to give a commonly accepted specification of Digital Twins. At contrary, the more the authors gain overview beyond their own application, the more likely they are to conclude: “There still is ambiguity regarding the term’s precise definition” [2]. This is one reason why the FP 1 call comes with its own definition:

„… a Digital Twin is a virtual representation able to imitate the behaviour of a physical system during the spans of its lifecycle…”.

Again, this is a very general statement that does not give many guidelines for its technical realization, e. g. if compared to the solution space dimensions presented by the 8D model of Stark et al. [3] shown in Figure 8, Here, only reference to one of these dimensions is given in order to demonstrate how set-ups may differ:

- For the purpose of load monitoring, it may be sufficient to record shunting impacts and only exchange data when certain threshold values are exceeded.
- For the monitoring and maintenance of yaw dampers in high-speed trains, it makes sense to organise a regular update-frequency of lateral running gear vibration data.
- In order to improve vehicle traction and braking operations, it may even helpful to exchange real-time data on the rail adhesion conditions..

This little introduction motivates the approach of the FP1-MOTIONAL project with respect to Digital Twins: Basically, a Digital Twin is a logical construct that incorporates data, models, algorithms, software etc. that can be associated to a physical system and accompanies it. But it is the specific use case and its objectives where the requirements for the realization and in turn the technical specification for the associated Digital Twin comes from. This is why use case collection plays an important role in the FP1-MOTIONAL project Subgroup 4and rules the relationship between FP1-MOTIONAL and the other flagship projects as regards Digital Twin aspects.

Figure 8: Overview of different Digital Twin realization dimensions, cp. Stark et al. [3]

In addition, there is another important task for the realisation of a Digital Twin which is given by the Enabler 31 definition, which reads:

“Provision of Digital Twin development and run-time simulation environment for creation of modular, interoperable, composable Digital Twins”

So, the organization of interoperability, modularity and composability are additional requirements of the Digital Twins in FP1-MOTIONAL.

In order to cope with this task, an approach successfully applied in the automotive field will be adopted. In 2006, Dempsey et al. [4] published a free modelling library for whole system automotive models. Its main purpose is the standardization of a vehicle model and interface architecture shown in Figure 9.

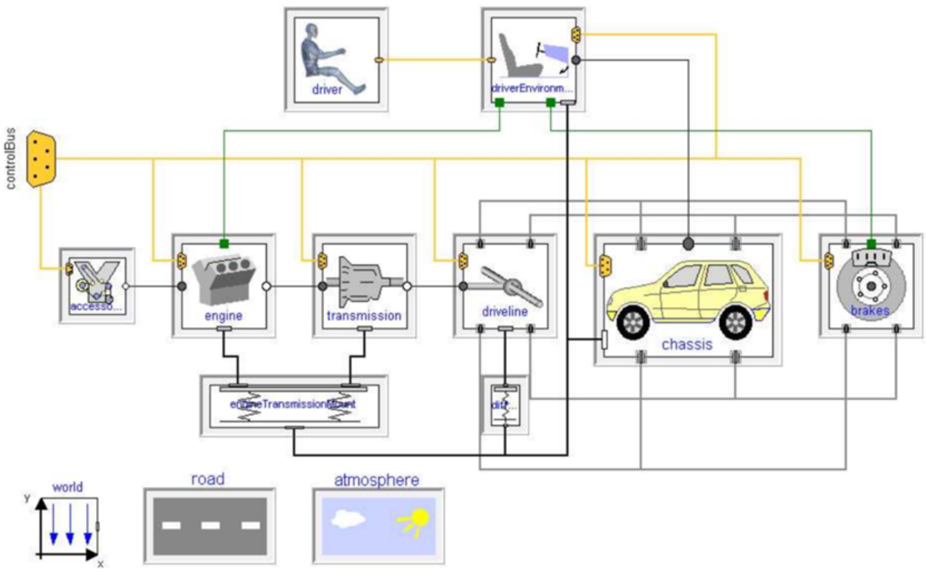

Figure 9: Modelica Vehicle Interfaces Library, see Dempsey et al. [4]

There, the subsystem, and component models are templates implemented with minimal physical model information. Each line that connects subsystems such as brakes, chassis, engine, driveline etc. represents an interface definition, which is the actual key issue of the library. It is the idea to standardize these interfaces in such a way that each component and subsystem may be easily replaced by more specific user models in practical applications. This concept complies with the requirements on modularity, interoperability and composability given in the Enabler 31 definition.

Therefore, it is the general work description of the FP1-MOTIONAL WPs 28 and 29 to compile the use case specifications in such a way that reference architectures with standard interface definitions are obtained. However, compared to the automotive field, the railway system as symbolized in Figure 10 contains much more subsystems and components such as tracks with rails, switches and catenaries, stations, control, command, signalling and traffic management systems and so on. The challenge is obvious and reflected by the Enabler 31 definition, which is targeted on the comparable low Technology Readiness Level 5.

Figure 10: Railway Vehicle Digital Twin Rendering, courtesy of DLR

6.2.1.2 Concept and Organization

Figure 11 presents the organization of Digital Twin (DT) environments as demanded by the FP1 call:

- The DT support environment is a repository of models that contain minimal physical model information and standardized interfaces. Consider e.g. a brake subsystem: it may need a brake demand as input, no matter whether it originates from the driver or an automatic control, and provides braking torques for each wheelset as an output. The minimal model may just contain algebraic relations between input and output or brake demand and torques, respectively.
- The DT design time environment uses these minimal models to design assemblies similar to the automotive example in Figure 9, but of course adopted for the railway field. In addition, exemplary algorithms and test data e.g. for analysis or prediction are to be included.
- The DT runtime environment is a collection of environments where these models, algorithms and data are evaluated.

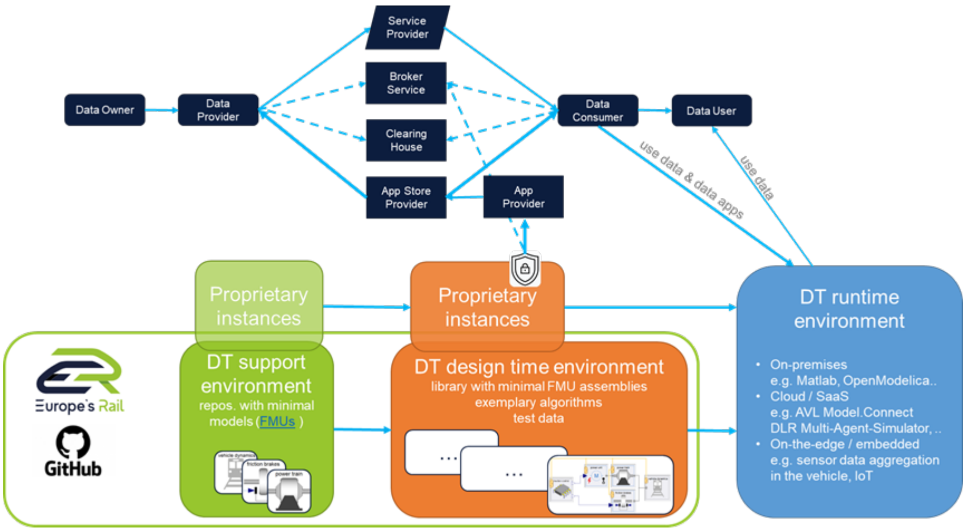

Figure 11: Digital Twin Environments

The DT support and design time environment will be organized by a GitHub repository hosted by the ERJU. In addition, it is expected and will be supported that FP project partners use the minimal models as templates and implement their own proprietary instances considering more elaborated physical descriptions. Since the model technology to be described in the next section allows for IP protection, these proprietary models may even be provided to other project partners as well by uploading them into the ERJU GitHub repository on a voluntary basis.

The DT business case to be adopted later is based on the Rail Federated Dataspace. Each stakeholder who wants to offer the usage of a specific DT model or algorithm may publish his offer using the Broker Service and may organize the access to the associated code using the App Store of the Rail Federated Dataspace.

6.2.1.3 Associated Technologies

As regards the basic modelling technology, the FP 1 call refers to a low-level standard interface for the exchange of dynamic models called Functional Mock-up Interface [5]. Figure 12 presents the general structure of a Functional Mock-up Unit (FMU) as a model component according to this standard is called. An FMU is distributed as a zip-file containing a combination of XML files for documentation purposes and binaries. C-source code may be included instead of binaries for open-source distributions.

FMI has been developed within the ITEA project MODELSAR [6] and is now maintained as a Modelica Association Project (MAP FMI). In the meantime, more than 170 commercial tool vendors including Mathworks, Maplesoft, Dassault Systemes, Modelon, dSpace, ETAS and so on support FMI and are in particular capable of exporting proprietary models as an FMU. This technology allows for reusing existing models e. g. from industry in a DT environment. If binaries are exported only, the Intellectual Property of the models are protected and may even be licensed.

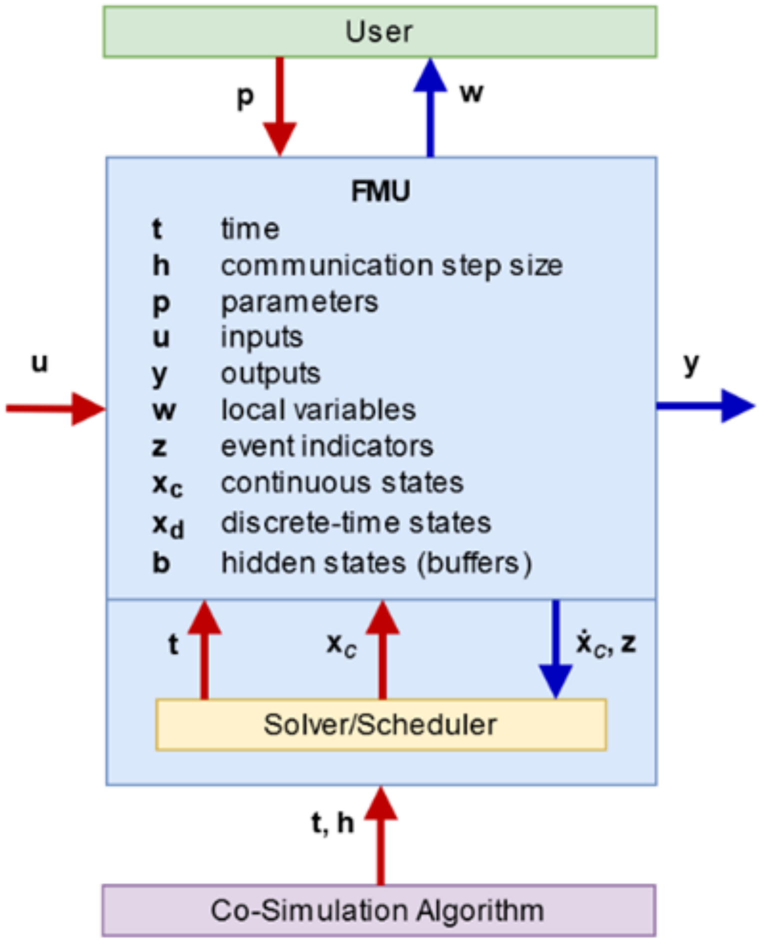

Figure 12: Schematic view of data flow between user, co-simulation algorithm and the FMU

Most of the commercial tool vendors given above as well allow for importing FMUs, which paves the way for the simulation of DTs on premises. Besides, several tools for cloud-based co-simulation are available such as AVL Model. Connect or under development such as DLR Multi-Agent Simulator, which are capable of organizing simulation jobs which distributed FMUs.

Containerization, i.e. organizing a computing environment surrounding the FMU will be applied and adopted within the FP1-MOTIONAL project in order to keep an FMU independent and portable as well as support fault isolation and security.

As regards the evaluation of data, it is pretty probable that a jungle of different data formats is to be processed and simple one-to-another data format conversions do not present a satisfying approach. This is why data with embedded semantics on basis of an ontology will be used for reasoning over data and operating with heterogeneous data sources [7].

6.2.2 Federated Data Spaces

The FP1-MOTIONAL WP31 aims to deliver data federation services for building a trusted, reliable, cybersecure federated data space for the rail ecosystem - the Rail Data Space. The Rail Data Space will provide exchange and sharing of digital resources across Rail operators, Infrastructure Managers and Suppliers as a contribution towards building the European Mobility Data Space.

In order to meet the twin requirements of delivery in time to Flagship Projects and consistency 'by design' with the European Data Strategy, the FP1-MOTIONAL project had deliberately chosen a strategy for development in which existing 'building blocks' already available from current large scale data space projects are assembled in a 'sandbox' for further development.

A simplified view of the Dataspace concept is provided in Figure 13.

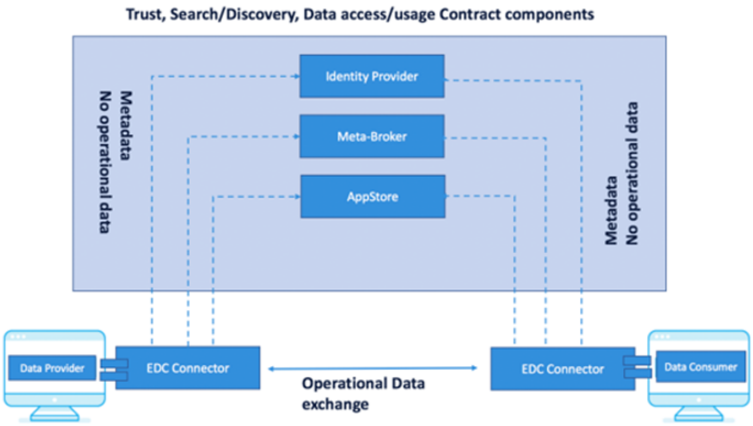

Figure 13: Essential elements of a Dataspace

The essential features of the pattern can be summarized as follows:

- The Dataspace is a *community* of autonomous Participants who play the roles of Data Provider and Data Consumers. They become Participants by identifying themselves to the community through the Identity Provider services and implementing/installing a DataSpaceConnector registered with the Dataspace through the Meta-Broker. Becoming a Participant or leaving the Dataspace is an autonomous decision of the Entity.
- The Dataspace common components provide trust and identity, search and discovery, and contract negotiation and enforcement (web) services. They do not collect, store or forward the actual digital assets, and they do not perform or are involved in the actual digital assets exchange.
- Actual data exchange is peer-to-peer between the mutually recognized participants in the mutually contracted exchange through a mutually agreed protocol implemented by the DataSpaceConnector. Data assets are stored *at the Participant nodes*.
- The architectural pattern is *distributed* and 'parametrized' in the sense that it can be implemented and deployed on any suitable computing and system software environment: other than being able to run a computing and operating-system agnostic open-source DataSpaceConnector, a Participant has no constraint on technology stacks or programming languages at its end of the exchange.

Since implementing and executing a DataSpaceConnector is the only technical requirement for an Entity to be a Participant in a Dataspace, the Entity can be a Participant of multiple sectorial dataspaces at the same time, e.g., Mobility Dataspace, Energy Dataspace, etc. In fact, a federation of sectorial dataspaces is possible and envisioned by the European Data Strategy and the GAIA-X Association, as depicted in Figure 14.

Figure 14: Federated Dataspaces

This is achieved through federation protocols that synchronize the individual Dataspace common components, i.e., Meta-broker, Identity Provider. This also means that individual, usually large, organization could create dataspaces 'private' to the organization that use the pattern to share data asset across the Organization's constituent Affiliated organizations, and then federate the 'private' dataspace with other dataspaces of one or more sectors.

Details on the design and architectural principles of dataspaces are available in the specialist documentation:

- GAIA-X Technical architecture [8]
- IDSA Reference Architecture Model [9]
- Design Principles for Dataspaces – Position Paper [10]

6.2.3 IAMS – TMS link

In FP1-MOTIONAL CEIT develops an interface (IAMS -> TMS) in view of the future autonomous inspection vehicle for the infrastructure) and its integration with the Intelligent Asset Management System (IAMS). To receive information about asset status and planned interventions and deliver allocated paths to execute inspections and interventions.

The information will be encapsulated using XML files, mainly containing three types of messages:

- *Asset's status:* Periodic report containing the status condition of assets that may demand a future intervention.
- *Planned interventions:* Periodic report containing a list including details about planned interventions in the line.

- *Alarms / Alerts:* Whenever a critical situation is diagnosed by the IAMS (either detected or predicted), asynchronous alarm/alert messages will be sent in order to inform about potential restrictions.

6.3 Relation to FP2-R2DATO

FP2-R2DATO (Rail to Digital automated up to autonomous train operation) is the flagship project 2 within Europe's Rail. Within FP2-R2DATO digitalization and automation of the railway are addressed, including ATO, ETCS Level 3 operation, 5G connectivity. Information on the participants and main goals can be found in the project websites[1,2].

Several FP2-R2DATO work packages are about the positioning of rail vehicles. This includes WP21 and WP22 for safe train positioning and WP48 for innovative operational solutions such as virtually coupled train sets. The term positioning can be interpreted in different ways. There are closely related terms such as navigation or localization. Here, positioning refers to the estimation of vehicle positions from streams of onboard sensor data. Other quantities of motion (velocities, accelerations) are understood to be estimated with the vehicle position. The employed sensors can be different and include inertial measurement units (IMU), antennas and receivers for satellite navigation (GNSS), wheel speed sensors, etc. Although novel sensor concepts based on electro-magnetic signals can be regarded. Because rail vehicles are constrained to move along the rails of a network, map data can be incorporated in different ways.

There is a relation to FP3-IAM4RAIL WP10 because position information can be vital for the condition monitoring of railway assets. One example is the analysis of onboard vibration data from repeated runs over the same track segment. Here, the monitoring data and positioning data are stored in a data base. Offline positioning algorithms (that are related to online positioning algorithms of FP2-R2DATO) access batches of sensor data (entire measurement sessions or days) and compute high-frequency position data (at constant 100 Hz rates, regardless of gaps and rate variations in the recorded sensor data). Map data can be included in a smart way to include the path-constrained vehicle motion. The batch processing allows for using offline estimation algorithms that improve the accuracy in comparison to online approaches ("smoothing" versus "filtering"). The entire process can be termed georeferencing because monitoring data are assigned accurate geographic position references (including on-track distances in the railway case). Another example is the transformation of time series to signals that depend on the distance. Here, accurate velocity information is vital. The velocity estimation is a sub-problem of positioning and can be performed using the same sensor setup and algorithms as positioning. Relevant references include [11] [12].

The developments of both online and offline approaches can yield insights for both FP2-R2DATO and FP3-IAM4RAIL. For example, "non-safety-critical" but highly accurate georeferencing applications are a rich test site for algorithms that have potential use in safety-critical positioning.

[1] https://projects.rail-research.europa.eu/eurail-fp2/
[2] https://doi.org/10.3030/101102001

7 UTILIZED TOOLS, SOLUTIONS AND SYSTEMS

Within this chapter, we'll outline the monitoring tools, solutions, systems, and various methods, approaches, algorithms, and implementations in use.

7.1 Multi-Sensor & Multi-Vehicle train borne onboard monitoring

New inspection & monitoring solutions (e.g., based vision systems, RF-microwave, inertia sensors, lidar, etc.) for the infrastructure subsystem will be developed based on modularity, exploring their potential integration in future concepts of autonomous inspection and monitoring vehicles of any kind. Existing data provided by current systems will also be used to speed up the evolution towards higher TRLs. This way, fusion of data and information provided by multi-sensor systems (multi-purpose vehicles) as well as by multiple vehicles (especially in-service monitoring fleets) will enable new approaches for inspection and monitoring of plain line track, switches and crossings, embankments, and their surroundings. The development of systems and the acquisition of data will be enabled using in-service vehicles and platforms, and the availability of tracks provided by Strukton and ADIF, in the Netherlands and Spain respectively.

7.1.1 Leonardo platform: introduction

Strukton developed an agile measurement vehicle, the "Leonardo" platform, to access operational rail assets and monitor rail infrastructure using both existing and new technologies. This initiative aims to gain better insight into rail infrastructure due to increased competition, stringent maintenance contracts, higher safety demands, more train traffic, and limited technical specialists. The focus was on gathering comprehensive digital track data in a single trip, processing and enhancing it with other available digital data for remote analysis.

The retrofitted tamping machine has been transformed from its original role into an advanced rail measurement train, named "Leonardo". The Leonardo has been reconfigured to conduct precise measurements using various sensor technologies. The “Trackscan” laser measurement system is employed to measure the railway tracks, while a Lidar sensor is utilized to map the surrounding environment alongside the tracks. Both the railway tracks and the surroundings are captured through the “Geoconda” optical camera system, which gathers detailed visual information.

The Leonardo also incorporates 3D ground radar to measure ballast and ground layers, providing valuable data regarding the stability and consistency of the rail infrastructure. Additionally, axle-mounted acceleration sensors are integrated to record vibration patterns, aiding in the assessment of overall rail performance and safety.

With these combined sensor technologies, the retrofitted machine can gather comprehensive and accurate data on both the rail condition and the environment.

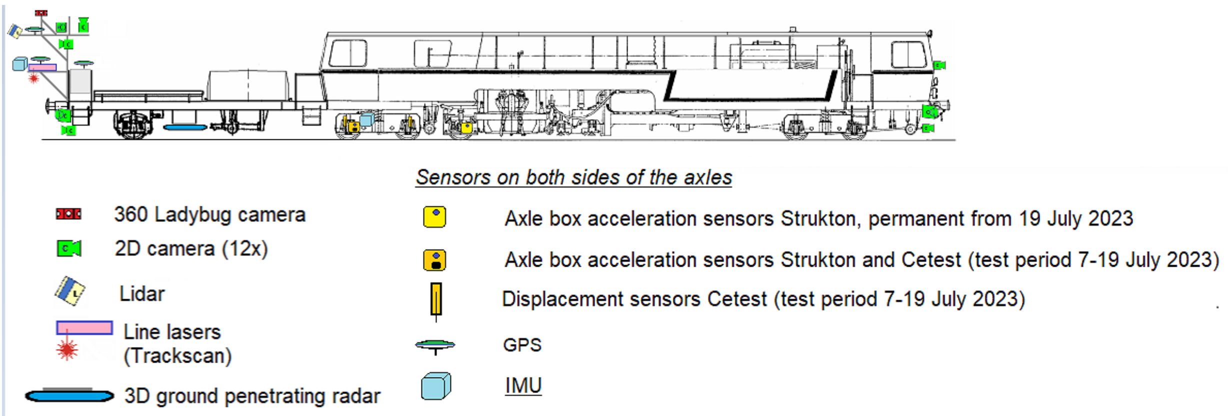

Figure 15: The Leonardo platform

The Leonardo platform proved highly beneficial, supporting maintenance and renewal contracts and offering potential for research activities due to its abundant and combinable data. Uniquely, the platform repurposes a retired tamping machine, incorporating various measurement systems like Lidar, radar, cameras, ABA, and track geometry tech. This assortment provides a holistic infrastructure snapshot, empowering decisions on maintenance. The platform allows using new tech, comparing it with old tech and historical data. It helps track changes, spot patterns, and foresee problems.

The Leonardo monitoring platform (Figure 15) is an agile tool, rapidly furnishing valuable new data. Its adaptability suits both research and operational contexts, while its direct infrastructure access and data comparison capabilities enable swift, accurate decision-making.

In Appendix 4 the description of technologies available on the Leonard platform are described[3].

In the following paragraphs we highlight the added technologies for this project:

- 3D Ground Penetrating Radar (GPR)
- Axle Box Accelerometers (ABA)

7.1.2 Leonardo platform: 3D Ground Penetrating Radar (GPR)

7.1.2.1 Motivation to add GPR as technology of Leonardo

Some years back, when the idea for developing the Leonardo platform was initiated, the aim was to gather information within a 5-meter radius around the measurement train: upwards, downwards, to the left, and to the right. A significant part of these objectives was accomplished using cameras, laser technology, and lidar measurement systems, except for the capability to inspect beneath the surface. The addition of a 3D ground radar with the latest technology has brought about a change in this aspect.

[3] The content this appendix reflects the details of deliverable D12.2 ("Tests and Validation") of the Shift2Rail project In2Smart, work package 12 ("Operational Asset Management in a Dutch Environment") and is added just to make this document readable without having to look into other documents.

Following an initial test with the Leonardo equipped with an underneath radar antenna, the breakthrough came: the 3D-radar (Kontur) differs from what had been used on the tracks until then. The 3D-radar has the ability to measure slightly deeper than the normally used air coupled antennas (horn-antennas) and provides higher resolution (measurement density), due to step frequency technology. The Kontur antenna scans in a frequency range of 50MHz to 3GHz and is a programmable multi-channel array up to 24 channels. This combination reveals much more details. We can now not only observe varying ballast thicknesses, but also cables and pipes, coupled rail tracks, tunnel structures along with associated buffers, and even the deeper soil layers. By merging topographic information with the radar data, it's possible to confirm many aspects. For examples see 7.1.2.3.

Objective / reasoning to use a ground penetrating radar*: Ground radar (geophysical investigation) is an excellent tool to better manage or reduce project risks, realising that it never provides 100% certainty.*

7.1.2.2 Background of GPR

In the past, ground penetrating radar (GPR) has predominantly found its application in the proactive examination of track beds and substructures. However, advancements in technology have ushered in new possibilities for integrating GPR data with information from other systems, broadening the scope of radar technology's utilization and is recognised within the sector, predominately providers of GPR technology [13].

It appears that new developments in GPR technology that could potentially offer greater accuracy in detecting unexplode ordnances (UXO). GPR is a non-destructive geophysical technique that utilizes electromagnetic pulses to investigate underground structures and properties. It is frequently used for locating buried objects such as pipes, cables, archaeological artifacts, and in some cases, it can be used to detect UXO.

There are new developments in GPR technology, these improvements could pertain to various aspects that enhance the accuracy and effectiveness of detection, which are realised in the state of the art 3D GPR that is mounted on the Leonardo:

Resolution: Enhancements in GPR system resolution can aid in identifying smaller objects, including UXO, that were previously difficult to detect. Resolution is in this case means higher grid density and step frequency technology.

Signal Processing: More advanced signal processing techniques can reduce noise and improve the signal-to-noise ratio, thus making the detection of hidden objects more visible.

Depth Range: If the new technology offers a greater depth range, it could be useful for detecting explosives buried deeper beneath the surface.

Multi-frequency GPR: Some modern GPR systems employ multiple frequencies to reveal different properties of underground materials. This can assist in identifying materials like explosives, which exhibit specific frequency-dependent characteristics.

Imaging Techniques: Improved imaging techniques, such as 3D imaging, can provide a better understanding of the spatial distribution of hidden objects, including explosives.

Automation and Artificial Intelligence: Integrating automated pattern recognition and machine learning can expedite the detection process and enhance reliability.

It's important to note that the accuracy of GPR technology also depends on factors such as the nature of the ground, terrain, and other environmental conditions. While new developments in GPR technology can certainly contribute to more accurate detection of old explosives, it remains a complex process that might require other methods and technologies to achieve reliable detection.

GPR serves multiple purposes, including pre-emptive inspections, acting as a valuable complement to track maintenance machinery, and documenting track renovation tasks like the implementation of protective layers for the formation. Moreover, GPR data plays a crucial role in planning activities involving ballast cleaning and track renewal machinery.

Obtaining high-resolution data at varying depths presents no challenges. The true value of this data emerges when delving deeply into distinct characteristics such as ballast depth, contamination levels, and moisture content. This in-depth analysis brings richer insights and more effective decision-making.

The radar depth does depend on the type of soil. In clay and peat soils, you can penetrate the ground about 1 - 1.5 meters deep; in sandy soils, we've reached depths of 3.5 - 4 meters. After initial solid tests, it was found that good results can be achieved with ground-based radar at a speed of 80 km/h. This aligns with the plan to have the Leonardo move at track speed between trains.

7.1.2.3 Examples of potential use

Based on first tests with the new equipment, we have following examples of potential use of the Ground Penetrating Radar:

Visualizing ballast pockets: the ground radar proves to be highly suitable for rail maintenance. Practical example: demonstrating/visualizing ballast pockets. These are points just before a level crossing where the ballast is pushed deeper due to extensive maintenance. Here, the sleepers are no longer properly supported.

Track Alignment: In a specific area of the Netherlands, there's a known issue of numerous switches with track alignment problems. This necessitates frequent use of tamping machines. With the ground radar, an indication was found that there are stretches beneath the track and under the sleepers where there is minimal ballast present. This unexpected finding occurred because traditional ballast thickness measurements are often conducted only at the sleeper heads. At another location, it became evident that over a 500-meter section, the ballast layer extends to a depth of 2.5 meters. This might be due to an old riverbed that was filled with ballast during the initial track construction.

Badger Setts: A current concern involves badger holes or setts. Ground radar can detect void spaces, but there's no clear label attached. A conduit can also appear as a void. This results in a similar image as a badger sett. Therefore, it becomes essential to verify if a conduit lies directly beneath the ballast. This isn't typically the case. If the passageway isn't entirely straight, suspicion of a burrow arises. Suspicious spots are marked with GPS coordinates, allowing on-site confirmation of possible sett entrances. For conduits, a link can be established with the asset manager's base maps (ProRail), aligning them with GIS-based measurement data.

Explosives: Occasionally, objects are visible without a plausible explanation. In such cases, caution is warranted. It can only be noted that there's an iron object requiring consideration. Updated GPR technology can help to be more sure what it is. Linked with old information about possible explosives (data from World War II), this can prompt extra vigilance.

7.1.2.4 Kontur radar system

On the Leonardo platform, the kontur 3D GPR hardware is mounted consists of an array antenna, a geoscope radar unit, a GPS receiver and an operator computer.

On the Leonardo this system is mounted with an 2100mm wide antenna array. To process the GPR data Examiner software is used.

For trackside GPR measurements Strukton Rail has created an electric quad using the GPR hardware from the Leonardo with 1200mm antenna array see Figure 16.

Figure 16: Radar system mounted of a vehicle

The antenna array consists of a grit with transmitters and receivers. De geocope radar unit sends step frequencies to the transmitters and the reflection signal is received by the corresponding receivers. By using transmitter-receiver grit in combination with frequency steps the signals are spread and have a deeper penetration. The advantage is that you can get full-coverage data from track in one measurement run and with a depth up to 4 meters (Figure 17).

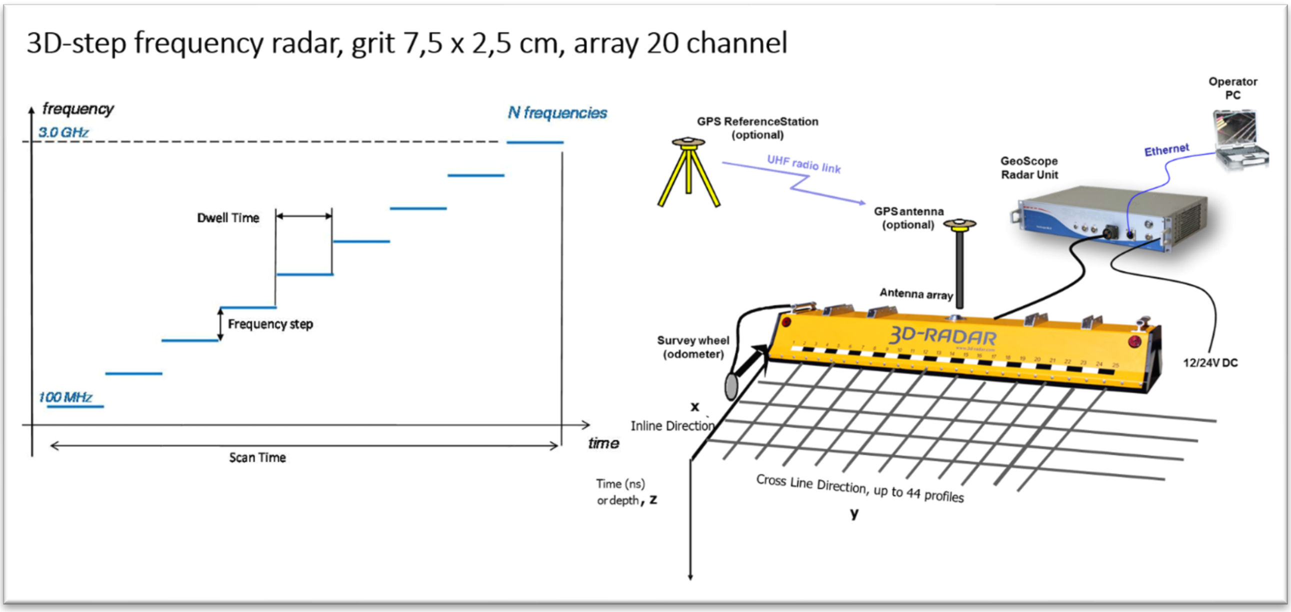

Figure 17: Kontur Radar system

What can we make visible, in general:

- Soil layers: ballast thickness, asphalt layer thickness;
- Point objects: pits, stones, utility markers, handholes, etc.;
- Linear objects: cables and pipes, foundations, tree roots, etc.;
- Empty spaces: excavated tunnels, washouts;
- Areas / disturbed soils: structures, disturbed soil (burials), filled ditches;

7.1.2.5 Export options

Following export options are available:

- Markings as 3D polylines or point files (x, y, z) in RD coordinates as DXF or DWG files
- Markings as shapefiles for GIS
- Amplitude maps as georeferenced PNG images
- As KML files (Google Earth)

7.1.2.6 Developments and ideas

We have following initial development ideas:

- Prepare radar interpretation using FME tooling for Red-Revision
- Distinguishing between clean and contaminated ballast
- Test track for ground radar validation

Below a more detailed description of these ideas:

Prepare GPR data interpretation using FME tooling for Red-Revision: This idea involves using FME software (Feature Manipulation Engine) to prepare and enhance the ground penetrating radar

(GPR) data interpretation for the purpose of Red-Revision. Red-Revision refers to a geospatial dataset containing the actual geometry and position of rail assets after accurate measurement. FME is software that provides tools for data transformation and integration between various platforms. By utilizing FME, the GPR interpretation can be refined and audited, ensuring that the data is accurate, comprehensive, and properly formatted for further analysis or presentation during the Red-Revision process.

Distinguishing between clean and contaminated ballast: Ballast refers to the layer of material, often gravel or stones, that is placed under the tracks of a railway to provide stability and drainage. In this idea, the focus is on differentiating between "clean" and "contaminated" ballast using GPR technology. "Clean" ballast would be material that is in good condition and suitable for its intended purpose, while "contaminated" ballast might have structural issues, debris, or other factors affecting its quality. Tools to assess ballast condition based on single transmitter/receiver/frequency GPR data already exist. For our case we will use a multi-channel, step-frequency GPR, which is able to acquire a full coverage scan of the entire track using a range of frequencies, all in one go. The goal is to develop a method to identify ballast conditions from our GPR data, which can help in making informed decisions about maintenance or replacement of ballast. Also, this method may highly improve efficiency compared to visual on-site inspection of ballast.

Test track for ground radar validation: This idea suggests creating a designated test track to validate and refine the capabilities of multi-channel, step-frequency GPR technology. A test track is a controlled environment where specific scenarios can be simulated and studied. In this case, it would involve installing various types of materials, structures, or features that mimic real-world conditions, on- and underneath a railway track. The GPR system would then be used to scan and collect data from this track to verify its accuracy and effectiveness in detecting and interpreting different objects and conditions (validation). This testing process helps ensure that the GPR technology performs reliably and consistently before being applied in actual operational settings.

7.1.3 Vehicle-Track-Interaction / Axle Box Accelerations

Assessing vehicle-track interaction is key to evaluate service safety and optimise the execution of maintenance operations. By monitoring Axle Box Accelerations (ABA), engineers can evaluate ride comfort for passengers, detect potential track irregularities, and ensure the safety and efficiency of railway operations. High-quality data on axle box accelerations aids in optimizing train design, maintenance, and track infrastructure, for a smoother and more reliable rail transport system. The use of this technology to evaluate the geometry of the track and other defects in the track is however a challenge in comparison with other technologies used by measurement vehicles. This section addresses different approaches that will be tackled exploiting this technology.

7.1.3.1 In-Service Track Measurement System (system A)

The technology and the methods currently used in Track Geometry Measurement Vehicles shall be adapted and modified to be possible to mount them onto, and operate them from, conventional passenger vehicles. Transferring the technologies and the methods onto a non-dedicated vehicle shall imply a reduction of measurement capabilities, not expecting to measure all the parameters defined in the EN13848 standard. Nonetheless, continuous unattended measurement during in-service hours shall be accomplished. In addition, other defects of rail indications shall be detected from the measured signals.

Basic measurement technologies include:

- Acceleration measurement on axle-box:
  - Vertical accelerations on axle box are to be measured up to a useful frequency of 4 kHz but must also include DC (0 Hz) components. Due to the fact that there is no current available technology able to manufacture accelerometers with such a wide bandwidth which includes DC, two sensor types will be used on each measurement point. Consequently, accelerometers with DC measuring ability (and up to around 1kHz depending on the manufacturer) and accelerometers measuring from around 5Hz up to 5kHz will be installed simultaneously. This way the desired bandwidth will be fully covered, with a shared measurement bandwidth between 5 Hz and around 1 kHz.
  - Lateral accelerations on axle box shall be measured also, but frequency content in the lateral direction shall be up to a few hundreds of Hz. That way, only capacitive accelerometers will be installed.
- Speed measurement: both linear speed of the vehicle and angular speed of the vehicle at one or various points will be measured. Alternatively, linear speed measurement shall be obtained from the vehicle's communication bus.
- Displacement sensors: vertical displacement of primary suspension of complete bogie.
- Signal condition and acquisition equipment, signal analysis equipment, communication, storing, reporting, and overall operating equipment: initial testing and research will be done using commercially available systems, which will need to be substituted by robust, dedicated electronic systems able to communicate with the vehicle.

7.1.3.2 ABA System Leonardo

7.1.3.2.1 Goal of the ABA system

Measuring the accelerations from a train axle is not a novel idea [14]. It is quite a busy field of research to fully harness its potential. One of the most popular applications of this technique is to replace commonly used (and typically more expensive) track geometry measurement systems. Another field of application is monitoring the rail wheel contact. Because these accelerations are measured as close as practically possible to the contact point, anything which has an influence on the contact response (such as rail head imperfection, insulated joints, or crossings), can be monitored with such a system.

Although collecting data using such a system is relatively simple and cheap, extracting meaningful information from such a system is much more complex. This is why adding such a system to the measurement platform is a good step forward. This will serve two benefits:

- As the platform is equipped with inspection grade measurement equipment, collecting the data simultaneously will enhance the development of stand-alone ABA applications.

- Even though the other measurement equipment is inspection grade, we expect that by combining ABA data, the analysis of the data can be enhanced by analysing the combination of measurement results.

7.1.3.2.2 Description of the system

The setup of the currently installed ABA system comprises of two triaxial accelerometers, installed on each side of a non-driven axle. The sensors are made by PCB, type 604B31. These are industrial grade accelerometers with a dynamic range of 50g. When it turns out that the dynamic range is not sufficient, accelerometers with 100g dynamic range will be sourced, but these are less commonly available. The installed sensor can be seen in Figure 18.

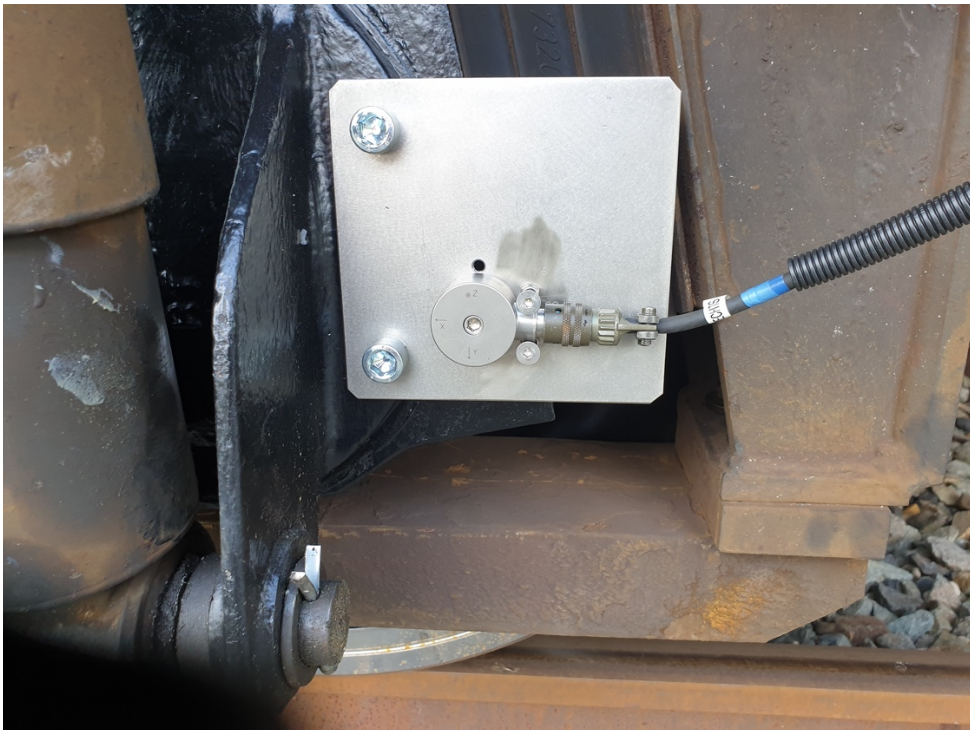

Figure 18: Installed sensor

Figure 19: ABA connections datalogger & output on computer screen

The accelerometers are connected to a datalogger from DEWEsoft, type DEWE-43A. This datalogger can handle data acquisition up to 200 kHz per channel. Additionally, GPS time is recorded and the DMI signal. The time signals are required for synchronisation with other measurement equipment, as well as for accurate positioning. The distance measurements are needed to process wavelength geometry. The datalogger is directly connected and controlled by a dedicated laptop, as shown in Figure 19.

7.1.3.3 ABA analytics and fusion with camera data

ABA data provide insights on the dynamic vehicle track interaction and can be used assess the condition of railway tracks. Data analyses can be carried out using different approaches and techniques. Model based methods rely on physical models that represent the dynamic vehicle-track system. A common approach is to double-integrate ABA data or to use simple quarter-car-models in combination with Kalman filter to retrieve the track geometry under ballasted conditions. The dynamic vehicle response excited by short track defects, such as rolling contact fatigue and corrugation is more complex to model, due to the broad frequency content of the ABA and the non-linear wheel-rail contact mechanisms. However, techniques using simplified physical models have also been successfully applied to detect corrugations using ABA sensors on low-speed revenue vehicles such as shunter locomotives [15]. In contrast, data driven models solely rely on the measured data itself and bespoke data processing and machine learning techniques. If ground truth data (labels) are available, supervised machine learning methods can be used, which have been advancing rapidly in the last decade. On the other hand, if labelled data are not available, unsupervised machine learning techniques, such as clustering and anomaly detection algorithms can be employed. In both cases, the accuracy of the predictions can be significantly improved by fusing information derived from different sensors and machine learning models. In particular, the combination of ABA based rail surface defect classification and video image classification has shown promising results [16]. In this context, Convolutional Neuronal Network (CNN) classifiers, based on camera data, for instance, have shown promising results for the identification and classification of rail surface defects [17]. It is expected that adding additional sensor data (e.g. GPR data) using multi-sensor systems (multi-purpose vehicles) as well as multiple vehicles (especially in-service monitoring fleets) will further enrich the knowledge gained by machine learning models and hence the insights on the track condition.

7.1.4 Simulation and Modelling

The simulation, in particular the multibody simulation of railway vehicles in order to innovate rolling stock design, optimize vehicle parameters, review running safety over a large range of operational conditions, investigate vehicle-track interaction and passenger comfort etc., is applied over several decades and has therefore become a state-of-the art technique in associated development departments. Even with regards to vehicle acceptance, which traditionally refers to physical testing, the use of simulation is increasing and already considered by the associated standards such as the EN 14363 [18].

The underlying models used for simulation represent the physics of the system and may therefore be interpreted as a knowledge basis. For technical and economic reasons, it makes sense to exploit this information as much as possible, i.e., to extend the applications of these models beyond the development phase and use them to monitor daily operations.

However, as every technical system, the behaviour of railway vehicles differs from the desired design and changes during operations due to manufacturing tolerances, environmental conditions, wear, deterioration, and degradation and so on. These change processes are initially not captured by the simulation models used in the development phase.

Though, there exists the state observer concept from control theory that is capable of monitoring these processes in comparison to the design models. Figure 20 presents this concept, which actually uses a very simple idea: since no system model perfectly corresponds to the real system, the model output will differ from the associated real sensor signal y, so the difference **can** be fed back in order to adjust the model in such a way that its states converge against the states of the real system. For the design of the feedback law L, a range of different and sophisticated Kalman filter design proposals exist even for nonlinear systems [19].

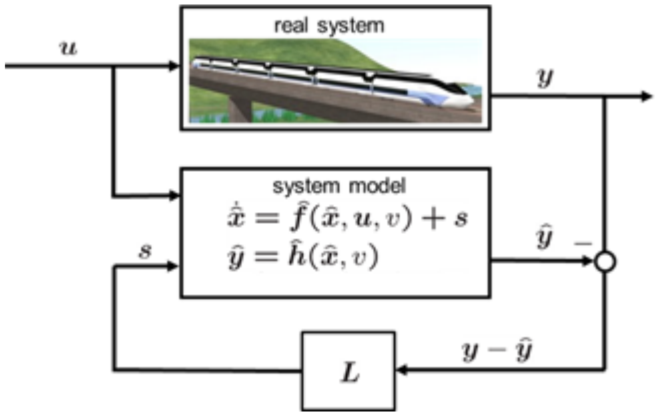

Figure 20: State observer concept from control theory & usage of nonlinear system models

7.2 Multi-Sensor wayside monitoring of switches

Assets digital capturing methods by way-side sensor systems enhanced by virtual sensors and synthetic data, where turnout data is pre-processed in an automated way and further automatically transmitted for storing in a historized asset database (S&C Digital Record) will be developed based on the architectures designed in previously. A solution to continuously store, process, and retrieve vital (high-speed) turnout data, both operational and diagnostic, but also information sharing principles will be developed and tested. Developing scalable and modular solutions is essential to effectively detect and isolate damage functions such as cracks, fatigue, stress, loosening, movement, tilting, and wear in rail systems. Integration of operational and way-side data, along with comprehensive rail system information and knowledge, is beneficial for making informed decisions regarding asset management.

7.2.1 Simulation and Modelling

The use of models and virtual frameworks allows a better understanding of the behaviour of assets, including anomalies and faulty conditions. Simulations are key to obtain synthetic datasets that represent realistic scenarios to support the development (and validation) of algorithms that assess the health condition of assets. This approach will be incorporated to complement the monitoring of turnouts.

First, Multi Body Simulation (MBS) and Finite Element Modelling (FEM) will be used to simulate the running of a vehicle through a crossing at different running conditions. On one hand, MBS simulations allow for calculating the contact patches between wheels and the turnout. On the other hand, FEM models are necessary to study the medium and high-frequency domain accelerations.

Then, different acceleration results from FEM simulations are evaluated to choose the best point(s) for real measurements. These synthetic accelerations are processed to obtain the most relevant KPIs which will define degradation trends for the assessed turnout at different running conditions.

7.2.2 Using novel multi-sensor systems for infrastructure wayside monitoring

Current sensors systems used for wayside monitoring address a wide range of different use cases related to railway infrastructure degradation. However, most of them use heterogeneous and incompatible technologies which aggravates data acquisition and multi-source data analytics. Especially the latter demands compatibility and comparability of data coming from different sources and measurement systems as the occurring damage mechanisms e.g. ballast degradation and rail wear or RCF, closely interact with each other. Therefore, it is of outermost importance to harmonise data coming from different monitoring systems addressing different use cases to facilitate multi-source and multi-purpose analytics of the obtained monitoring data.

The introduced multi-sensor platform provided by Voestalpine Railway Systems tackles those challenges by means of integrating multiple sensors for condition monitoring of railway components within one system. The multi-sensor includes a highly sensitive acoustic emission (structure borne noise) sensor, as well as a micro-electromechanical system (MEMS) for motion analyses and a temperature sensor module. It furthermore provides the possibility for signal conditioning and edge computing on the device which reduces the amount of data to be transmitted and processed significantly. The modularity and flexibility of the system enables monitoring of various damage mechanisms, degradation patterns, locations, and various components, all with a single system. The broad applicability of the introduced platform facilitates an efficient operation of the monitoring system as well as a straightforward connectivity with existing systems for infrastructure managers.

7.2.3 Integrated asset management and monitoring platform

Digital Track Management (DTM) is an asset and maintenance management software for railway infrastructure.

The added value of this tool consists in using asset monitoring data from ROADMASTER as a basis for condition based and prescriptive maintenance planning. This approach reduces downtimes and LCC compared to nowadays common maintenance plans based on fixed time intervals.

The DTM software is a ready-to-use application with pre-filled track content (asset- and maintenance register, checklists, damage catalogue, maintenance recommendations).

All routes, tracks and assets including the associated components, installation histories and all associated data (geometric parameters, quality documents, production data, etc.) of a railway infrastructure operator can be mapped and managed. Furthermore, the entire maintenance process can be created and executed in the software. Additionally, all maintenance work on the track can be facilitated and shortened by using the mobile application. Figure 21 shows the main functionalities of DTM.

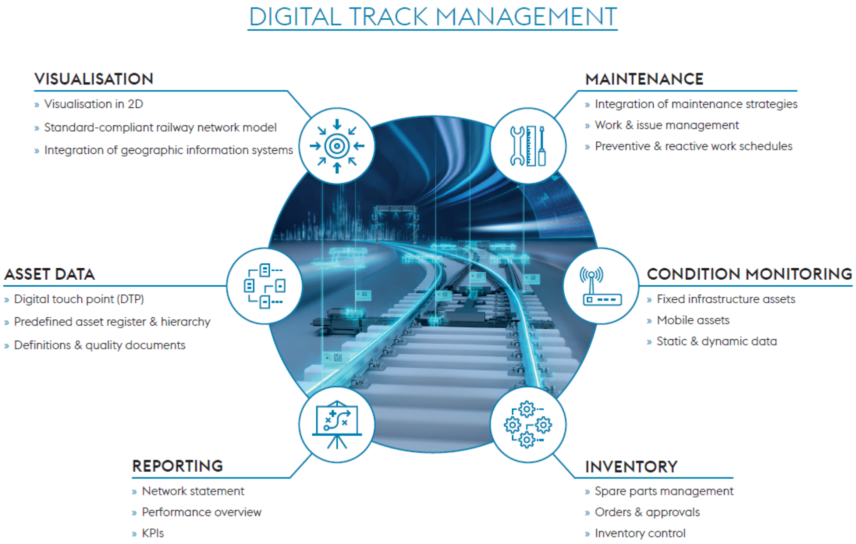

Figure 21: Main functionalities of DTM

All these DTM functionalities require data, which is obtained from ROADMASTER.

ROADMASTER is an intelligent diagnostic and monitoring platform for visualisation and processing of wayside asset monitoring data. As an effective support tool for railway operators it enables in-depth insights into the condition of assets and, in combination with DTM, ensures proactive condition-based maintenance that ensures the highest track availability while optimizing life cycle costs. The main functionalities of ROADMASTER are shown in Figure 22.

Figure 22: Main functionalities of ROADMASTER diagnostics and monitoring platform

Figure 23 shows a schematic illustrator of the data stream coming from a railway vehicle passing a smart asset which is subsequently joined with different data sources that are available in DTM leading to an added value for the operator.

Switch operations and further monitoring data is processed and visualized in ROADMASTER and subsequently passed to DTM where it represents the asset availability and health state. Based on this information, DTM provides capabilities for sophisticated inspection and maintenance planning of the asset, based on its actual (and predicted) condition.

Rolling stock data (operational data, inspection data and maintenance data) as well as infrastructure monitoring data coming from smart assets are integrated in order to incorporate as many parameters of the wheel-rail system as possible. DTM thereby facilitates a holistic asset management and the possibility for corrective measures at an early stage which increases the overall efficiency of the railway network.

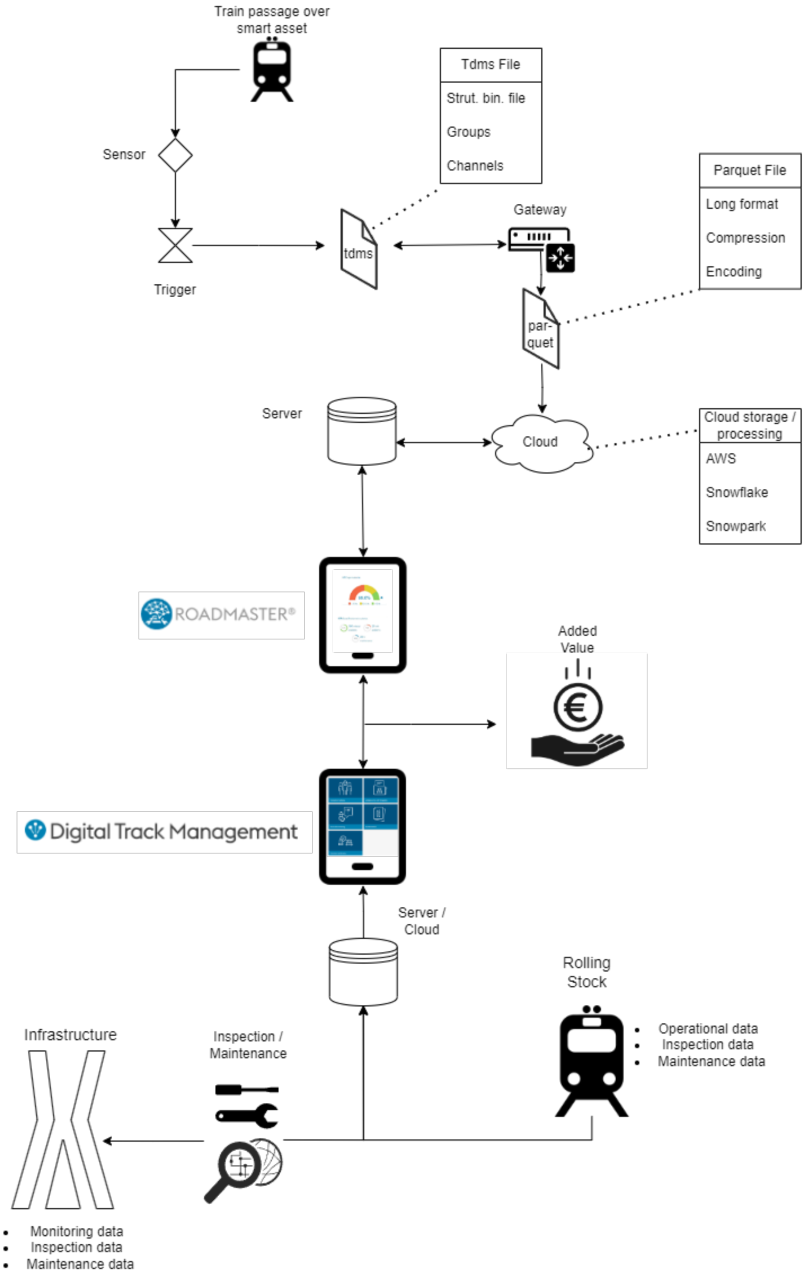

Figure 23: General System Architecture with ROADMASTER and DTM

7.2.4 Wayside monitoring system architecture

7.2.4.1 ROAMASTER Voestalpine

A high-level system architecture of the planned wayside monitoring system is shown in Figure 24. The system uses different set-ups based on the defined uses cases to be monitored with the introduced multi-sensor system. The sensors will be operated by a central gateway which covers data acquisition and pre-processing of the sensor data. The pre-processed data will be uploaded to a cloud where it can be stored for further processing and calculation of monitoring features for component health state assessment. These estimated monitoring features will be passed to the Voestalpine monitoring platform (ROADMASTER) where the monitoring data will be further processed and transformed into asset health state data. These data will be subsequently fed into the Voestalpine asset management platform DTM where it can serve as a decision support for inspection and maintenance planning for infrastructure managers.

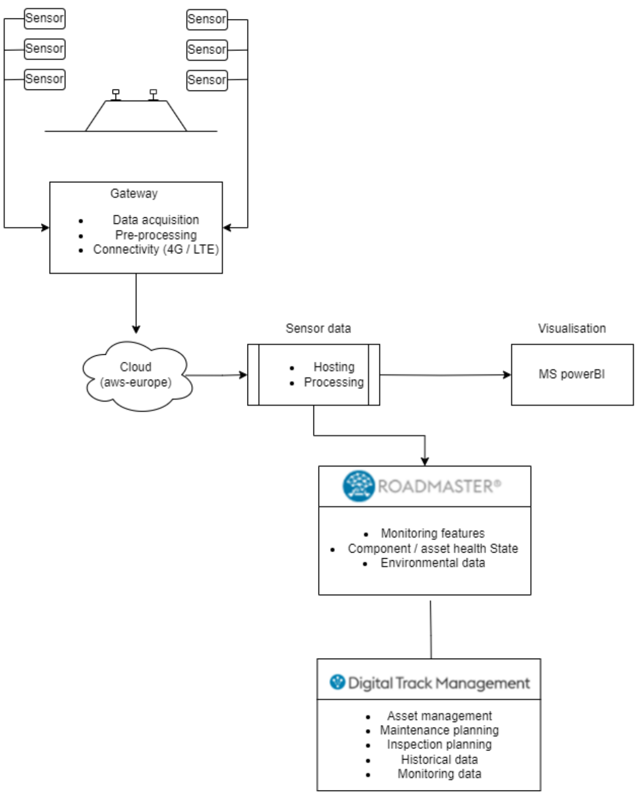

Figure 24: High level system architecture of wayside monitoring system

7.2.4.2 POSS Strukton

POSS is a condition monitoring system for assets in the railway and power industry. It consists of local dataloggers, as shown in Figure 25, and sensors that collect measurements and send the data to a central server where it is visualized in a user interface. An example of the lay-out of the user interface is given in Figure 26. The main focus in this project, and previously in In2Smart, lies on the monitoring of switches and point machines. We aim to expand on the previous work by including more sensors, data sources and analysis methods.

Figure 25: POSS datalogger

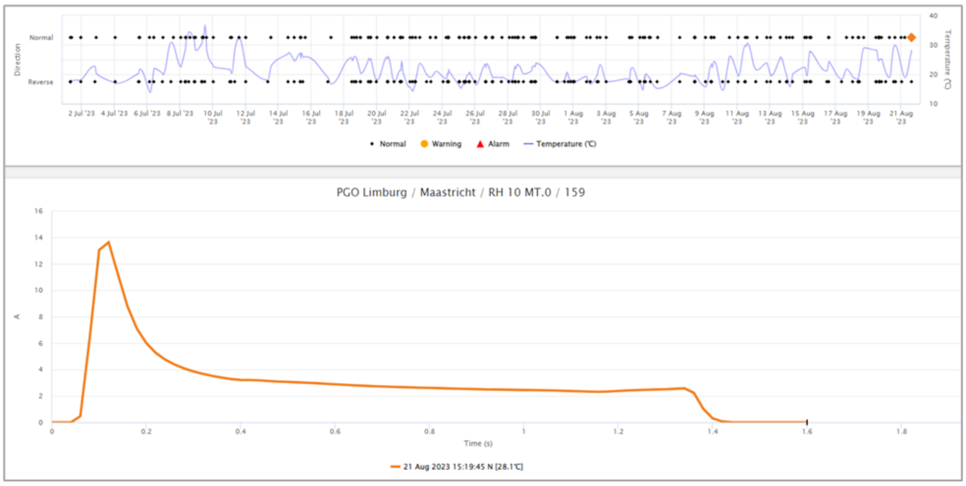

Figure 26: Example of POSS User Interface

Currently, the following sensor data is collected by POSS at the time of a switch throw:

- Current consumption
    - Point machine
    - Control circuit
- Relay states
    - Controlling and detection of the switch
    - Track occupation
- Ambient temperature

Earlier work on this topic in In2Smart on developing diagnostic model (see 7.3.1) has shown that the degradation of the switch is heavily influenced by factors not directly related to the actual operation of the switch. Environmental factors and conditions such as track geometry and weather influences play an important role.

7.3 Holistic analytics and decision support

Fusion of train borne and wayside monitoring information utilizing modular edge-computing architectures with relevant additional information sources such as historical data, traffic data and any exogenous data are addressing the creation of holistic condition information for track and switch components. There are development and evaluation of traceable/explainable diagnostic and prognostic tools based on hybrid approaches combining physical, statistical and machine learning based models. Moreover, integration and visualization of data in IAMS is required to support decision making based on multiple type and historical information data analysis as well as dedicated multiuser advanced tools..

7.3.1 Diagnostic Models for switch monitoring

Recent fault diagnostics for point machines often relies on current curve measurements – sometimes enriched by control circuit and power supply data – which are then interpreted by maintenance practitioners for triggering suitable maintenance actions. Modern approaches for automatically detecting anomalous current curves [20] [21] and identifying the underlying primary faults [22] [23] based on simple rule-based approaches or more advanced methods applying AI (Artificial Intelligence) and ML (Machine Learning) can help to make this process more effective while reducing the manual efforts.

In particular, the automatic data-based diagnosis of primary faults for complex assets like railway switches or point machines is still a major challenge. This is not least because of the lack of sufficient training data for simply applying deep learning or similar approaches for solving this difficult task. Based on some initial concept studies on suitable ways how to integrate expert knowledge on switches and data-based learning in a powerful hybrid approach [24] [25] the direct ancestor project IN2SMART2 ended up with the implementation of a prototypical diagnostic model [26] for a standard type of point machines (see Figure 27) similar to those located in FP3-IAM4RAIL’s Dutch pilot site (see Section 8.1).

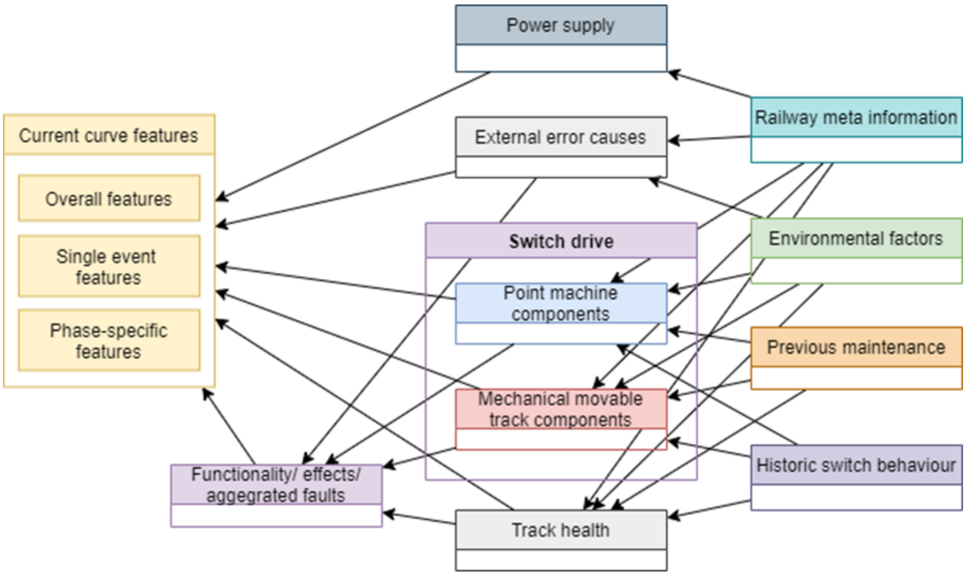

Figure 27: Schematic overview proposed diagnostic model (taken from D12.2, I2S2)

Here, Bayesian networks turned out to be a reasonable approach for bridging the gap between utilizing expert knowledge for model elicitation, interpretability by humans and mathematically powerful representation of complex relations in terms of data-based modelling [27].

As can be seen from Figure 27, the switch drive is in the focus of this current model while using statistical and (even more) geometrically motivated current curve features as main source of evidence when probabilistically reasoning about faults. Nonetheless, the model concept allows for integrating other kinds of sensor information and evidence as related to track health conditions, for instance, although this aspect needs to be elaborated further.

Note that environmental factors, past maintenance actions, historical switch behaviour, as well as other kinds of meta information on the considered switch are already taken into account to some basic extent. Clearly, this underlines the holistic approach of the diagnostic model as a possible support tool in context of data-driven diagnostics and decision making for maintenance in the future.

8 PILOT SITES

A total of three pilot sites have been selected for this project. Two of those are located on mixed traffic lines, one in The Netherlands and one in Spain. The turnouts at these locations were specifically selected to be as equivalent as possible in terms of characteristics. The third pilot site is located on a high-speed line in Spain.

8.1 The Netherlands

8.1.1 General

The selected turnout at the pilot site in the Netherlands, as shown in Figure 28is a 1:15 NSE2 turnout, manufactured by WBN (Voestalpine) and installed in 2005.

Figure 28: image of the location: view from the Leonardo

8.1.2 Detailed description of the location and assets

Nomenclature:

WP 63 (Switch 63 in Weesp)

Location:

The turnout is located near Weesp, to the southeast of Amsterdam, at GPS location [52.310569, 5.04665], as shown on the map in Figure 29.

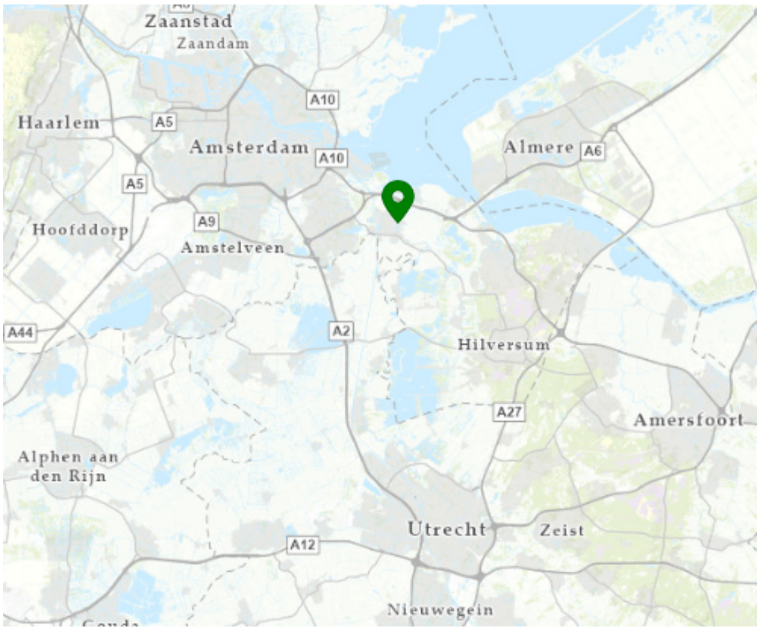

Figure 29: map of the location in the Netherlands

Figure 30 and Figure 31 show more detailed images of the turnout site, taken from Strukton's ArcGIS environment. It is located on the line Amsterdam – Hilversum, in the Geo area "Diemen aansl. - Weesp aansl." with geo code 128, at kilometre 13.3.

It is in the Geo area "Diemen aansl. - Weesp aansl." with Geocode 128 on kilometer 13.284-13.349.

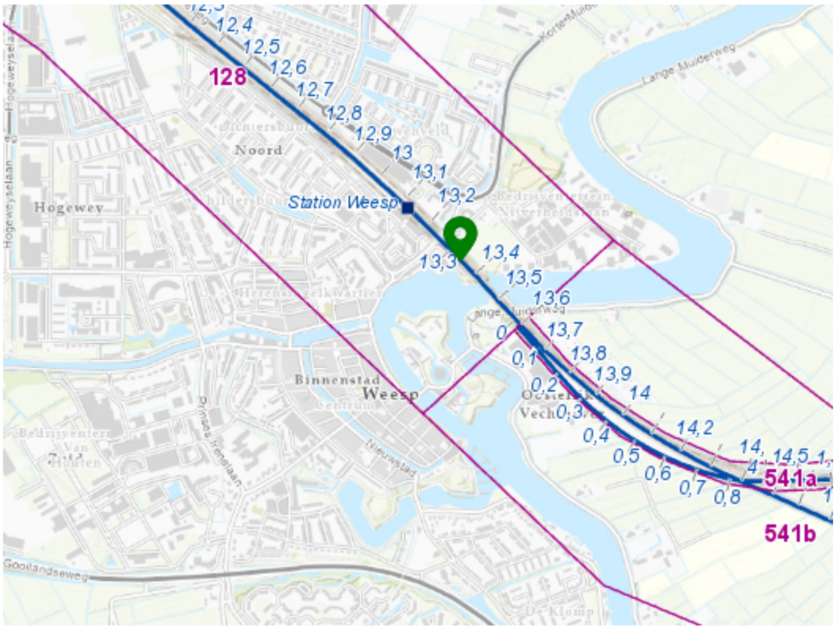

Figure 30: overview of the location in GIS

Figure 31: GIS view projected in satellite image

Characteristics:

- Length: 65 meters
- Rail type: 54E1
- Sleeper type: concrete
- Roller type: Ekos
- Radius: 725 meters
- Tangent: 1:15
- Manufacturer: WBN
- Maximum speed: 130 km/h
- Throws per day: ca. 60

8.1.3 Available Data sets

Data set	Meaning	Availability	Remarks
Current curves	Current consumption of point machine during switch throw	Since July 2019	
Control and detect relays	State of relays associated with controlling the throw (stuurrelais) and detecting that the switch blade	Since March 2023	

Data set	Meaning	Availability	Remarks
	reached the end position (controlerelais)		
Section relay	Shows the occupation of the switch section	Since March 2023	Also available for (some) neighbouring switches
Control current	Current consumption of the control circuit	Since March 2023	
Maintenance information	All maintenance actions carried out on the switch	Since July 2019	Uncertain how detailed this information is
Temperature data	Ambient temperature at the time of switch throws	Since July 2019	Measured at the relay cabinet, close to the switch
Soil	Soil type at the switch site	Unclear	Might be available at ProRail
Track geometry	Gauge, alignment, elevation, etc.	Unclear	

Table 2: overview data sets

Figure 32 shows an overview of measurements during a switch throw. From top to bottom:

- Blue: point machine current
- Green: control relay left and right
- Orange: detection relay left and right
- Purple: section relay
- Green: control current

Figure 32: overview of measurements during a switch throw

8.1.3.1 Planned measurement campaigns Voestalpine, Switch 63

Mixed traffic line demonstrator

The wayside monitoring system for the specified demonstrator turnout will cover the following *applications*:

- Track quality monitoring (see paragraph 9.11)
- Switch rail and frog monitoring (see paragraph 9.12)

The applications and utilised *technologies* are described more in detail in section 9.

8.2 Spain: High speed pilot site

The selected turnout, which is shown in Figure 33 is an AV3 provided by Voestalpine JEZ. (3rd evolution in high-speed turnouts).

Figure 33: High speed line turnout demonstrator

8.2.1 In general

The smart asset shall cover real needs and pains reported by the maintenance teams and serve as a demonstrator for innovative solutions for early detection of track defects addressing the following aspects:

- acquisition of inspection, monitoring and operational data
- set the requirements and system architecture of the proposed solution
- implement preliminary concepts of multi-sensor/multi-source modular systems for data acquisition
- data collection, processing and analytics
- decision making for maintenance optimization (TCM. Timely Identification of track fatigue, degradation and track defects)

Figure 34 shows the main components of the high-speed line turnout including the switch machines, the drive and detector rods, the movable crossing as well as the switch- and stock rail.

Figure 34: Main components of high-speed line turnout

8.2.2 Detailed description of the location and assets

Nomenclature:

S1 SCZ 2 – PB

Location:

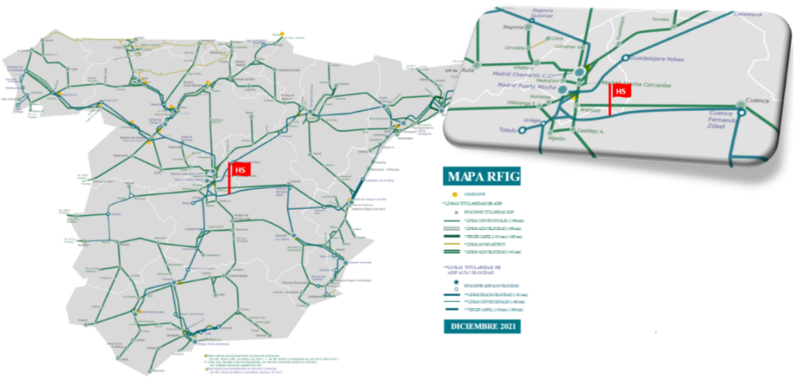

Figure 35: High Speed Line Demonstrator Location

This turnout is placed in the Madrid-Levante High Speed Line where it was installed in 2009. More specifically in Santa Cruz de la Zarza, Toledo province PK: 104+020, railtrack II.

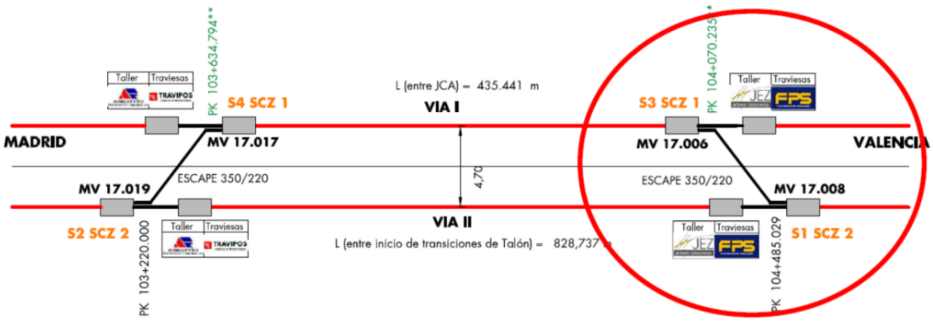

Figure 36: Location visualisation

Characteristics: (DSIH-AV3-60-17000/7300-1-50-CCM-I/D-T)

- Length: 180.00 meters
- Rail type: 60E1 R350HT. Welded continuous rail.
- Concrete sleeper.
- Asymmetrical low profile switch.
- Sleepers with switch rollers in the changing area. FURg 620 7(ZRV1) +4(ZRV2)
- Crossing with movable frog.
- Crossing angle 1:50
- Flexible fastening SKL-12
- German lock (CRBM)
- 10 point machines in the switch area and 4 in the crossing area.
- 14 hollow sleepers
- Maximum Speed by direct track: 350 km/h
- Maximum Speed by deviated track: 220 km/h

8.2.3 Specific Demonstrator Aims

Slack in the clamping joints of the devices remove or minimize

Mainly in this type of turnouts there is one usual problem that must be solved. The vibration caused by rail traffic generates switch machine movements. Usually point machines are placed on two plat bands which, are fixed to the closest rail. So, with every single train these plat bands vibrate, making the switch machine vibrate as well. From the switch machine, several bars go out towards the frog, see Figure 37.

Figure 37: Torsion bars to be monitored in high-speed line demonstrator

These bars are the responsible part of switching and locking devices, making the switch safely. These vibrations as time goes by, generate slack or looseness in the clamping joints of the devices.

This slack means that an activity with as much risk as that of activating the diversion, which is usually carried out in terms of security, is carried out in an environment of uncertainty.

8.2.4 Available Data sets

To achieve the objective described above, it is necessary to rely on a series of available data such as:

Technical characteristics of the turnout (as described above) and drawings of the turnout

An extensive collection of plans is available to be able to know in detail the characteristics of each element of the turnout. By knowing exactly each element of the turnout, shown in Figure 38, and understanding its movement, an extensive analyses of the system can be conducted.

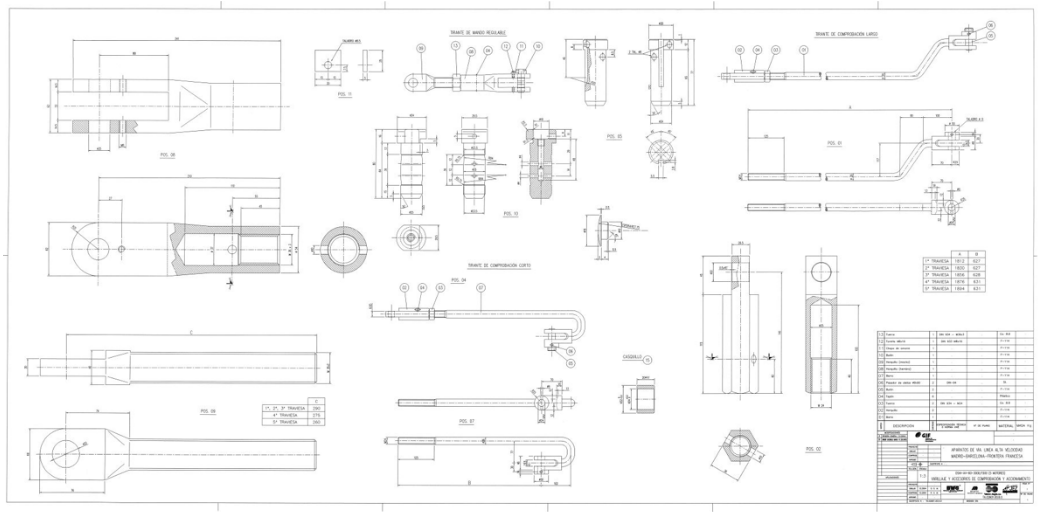

Figure 38: Drive rods drawing

Traffic traveling through the turnout

The daily traffic through the bypass and the characteristics of the rolling stock are key data to be considered and will be thus made available. The passage of each type of train will affect each element of the turnout in a different way. Figure 39 shows an example of the available traffic data.

PlanifWEB

SISTEMA DE GESTIÓN DE TRENES — Fecha: 16/06/2023 10:35:56

LISTADO DE TRENES EN ESTACIÓN — Usuario: 2863645

FILTROS APLICADOS

Paridad: Par
Fechas de circulación: 16/06/2023 - 16/06/2023
Nodo Principal: SANTA CRUZ DE LA ZARZA-A. V.
Tipo de paso: Paso / Parada / Origen / Destino
Empresa: ACCIONA RAIL SERVICES, S.A. / CONTINENTAL RAIL, S.A. / LOW COST RAIL, S.A. / CAPTRAIN ESPAÑA, S.A.U. / CSP LOGITREN, S.A. / TRACCION RAIL / RENFE OPERADORA / ADMINISTRADOR DE INFRAESTRUCTURAS FERROVIARIAS / RENFE MERCANCIAS, S.A. / TRANSITIA RAIL, S.A. / ALSA FERROCARRIL,
Producto: SERVICIO INTERNO ESTACION / MERCANCIAS / LARGA DISTANCIA Y AVE / SERVICIO INTERNO INFRAEST. / CERCANIAS / MEDIA DISTANCIA / SERVICIO INTERNO CIRCULACION / SERVICIO INTERNO T. MERCANC. / MANTENIMIENTO EXTERNO INFRAESTRUCTURA

Nº T.	V.	Nº CO.	EST.	AM.	ORIGEN	H. SALIDA	DESTINO	H. LLEGADA	N. PRINCIPAL	TIPO	H. LLEG.	H. SALIDA	P.COM.	TIP.PAR.	EMP.	PROD.	VIGENCIA
39904	2	39904	Prod. vigente	Amortizado	MADRID-CHAM	05:20	VALENCIA-JOAC	07:45	SANTA CRUZ DE	Paso		06:07			Administrado	Servicio interr	23/01/2023-09/12/2023
05662	8	05662	Prod. vigente	Amortizado	MADRID-P.ATOC	06:30	MURCIA DEL CA	09:56	SANTA CRUZ DE	Paso		07:02			Renfe Opera	Larga distanc	09/06/2023-09/12/2023
05064	5	05064	Prod. vigente	Amortizado	MADRID-CHAM	06:30	VALENCIA-JOAC	08:27	SANTA CRUZ DE	Paso		07:11			Renfe Opera	Larga distanc	23/01/2023-09/12/2023
06062	2	06062	Prod. vigente	Amortizado	MADRID-CHAM	06:45	VALENCIA-JOAC	08:35	SANTA CRUZ DE	Paso		07:25			ILSA	Larga distanc	16/12/2022-09/12/2023
05078	6	05078	Prod. vigente	Amortizado	MADRID-CHAM	07:00	ALACANT-TERM	09:32	SANTA CRUZ DE	Paso		07:40			Renfe Opera	Larga distanc	27/03/2023-09/12/2023
06472	4	06472	Prod. vigente	Amortizado	MADRID-CHAM	07:15	VALENCIA-JOAC	09:05	SANTA CRUZ DE	Paso		07:56			Ouigo Espa	Larga distanc	11/12/2022-09/12/2023
05070	5	05070	Prod. vigente	Amortizado	MADRID-CHAM	07:30	VALENCIA-JOAC	09:34	SANTA CRUZ DE	Paso		08:11			Renfe Opera	Larga distanc	23/01/2023-09/12/2023
06074	1	06074	Prod. vigente	Amortizado	MADRID-CHAM	07:45	ALACANT-TERM	10:11	SANTA CRUZ DE	Paso		08:26			ILSA	Larga distanc	02/06/2023-09/12/2023
05280	2	05280	Prod. vigente	Amortizado	BURGOS-ROSA	06:40	VALENCIA-JOAC	10:20	SANTA CRUZ DE	Paso		09:10			Renfe Opera	Larga distanc	08/03/2023-09/12/2023
06082	1	06082	Prod. vigente	Amortizado	MADRID-CHAM	08:45	VALENCIA-JOAC	10:41	SANTA CRUZ DE	Paso		09:26			ILSA	Larga distanc	24/02/2023-09/12/2023
05092	10	05092	Prod. vigente	Amortizado	LEON	06:45	ALACANT-TERM	11:25	SANTA CRUZ DE	Paso		09:40			Renfe Opera	Larga distanc	11/03/2023-09/12/2023
05962	8	05962	Prod. vigente	Amortizado	MADRID-CHAM	09:15	MURCIA DEL CA	12:12	SANTA CRUZ DE	Paso		09:56			Renfe Opera	Larga distanc	20/12/2022-09/12/2023
05890	1	05890	Prod. vigente	Amortizado	MADRID-P.ATOC	09:40	CASTELLO DE L	12:35	SANTA CRUZ DE	Paso		10:12			Renfe Opera	Larga distanc	11/12/2022-09/12/2023
05102	7	05102	Prod. vigente	Amortizado	MADRID-CHAM	10:00	ALACANT-TERM	12:18	SANTA CRUZ DE	Paso		10:41			Renfe Opera	Larga distanc	15/02/2023-09/12/2023
06504	4	06504	Prod. vigente	Amortizado	MADRID-CHAM	10:15	ALACANT-TERM	12:36	SANTA CRUZ DE	Paso		10:56			Ouigo Espa	Larga distanc	28/04/2023-09/12/2023
05100	4	05100	Prod. vigente	Amortizado	MADRID-CHAM	10:30	VALENCIA-JOAC	12:31	SANTA CRUZ DE	Paso		11:10			Renfe Opera	Larga distanc	23/01/2023-09/12/2023
06102	1	06102	Prod. vigente	Amortizado	MADRID-CHAM	10:45	VALENCIA-JOAC	12:41	SANTA CRUZ DE	Paso		11:26			ILSA	Larga distanc	10/02/2023-09/12/2023
39741	6	39741	Prod. vigente	Amortizado	LA SAGRA	09:46	SIETE AGUAS-A	15:30	SANTA CRUZ DE	Paso		11:37			Renfe Opera	Larga distanc	16/06/2023-30/06/2023
05110	6	05110	Prod. vigente	Amortizado	MADRID-CHAM	11:30	VALENCIA-JOAC	13:20	SANTA CRUZ DE	Paso		12:11			Renfe Opera	Larga distanc	10/02/2023-09/12/2023
04072	5	04072	Prod. vigente	Amortizado	SANTANDER	07:05	ALACANT-TERM	14:40	SANTA CRUZ DE	Paso		12:29			Renfe Opera	Larga distanc	10/06/2023-09/12/2023
11510	6	11510	Prod. vigente	Amortizado	MADRID-CHAM	12:10	VINAROS	16:36	SANTA CRUZ DE	Paso		12:52			Renfe Opera	Larga distanc	16/05/2023-03/09/2023
05124	5	05124	Prod. vigente	Amortizado	MADRID-CHAM	12:28	VALENCIA-JOAC	14:30	SANTA CRUZ DE	Paso		13:09			Renfe Opera	Larga distanc	23/01/2023-09/12/2023
06122	1	06122	Prod. vigente	Amortizado	MADRID-CHAM	12:45	VALENCIA-JOAC	14:35	SANTA CRUZ DE	Paso		13:26			ILSA	Larga distanc	24/02/2023-09/12/2023
06534	5	06534	Prod. vigente	Amortizado	MADRID-CHAM	12:51	ALACANT-TERM	15:12	SANTA CRUZ DE	Paso		13:32			Ouigo Espa	Larga distanc	28/04/2023-09/12/2023
05142	6	05142	Prod. vigente	Amortizado	MADRID-CHAM	14:00	ALACANT-TERM	16:31	SANTA CRUZ DE	Paso		14:41			Renfe Opera	Larga distanc	17/02/2023-09/12/2023
05742	5	05742	Prod. vigente	Amortizado	MADRID-P.ATOC	14:25	MURCIA DEL CA	17:51	SANTA CRUZ DE	Paso		14:57			Renfe Opera	Larga distanc	20/12/2022-09/12/2023
05140	7	05140	Prod. vigente	Amortizado	MADRID-CHAM	14:24	VALENCIA-JOAC	16:26	SANTA CRUZ DE	Paso		15:05			Renfe Opera	Larga distanc	17/02/2023-09/12/2023
6142	1	06142	Prod. vigente	Amortizado	MADRID-CHAM	14:45	VALENCIA-JOAC	16:35	SANTA CRUZ DE	Paso		15:26			ILSA	Larga distanc	05/05/2023-09/12/2023
05152	8	05152	Prod. vigente	Amortizado	MADRID-CHAM	15:00	ALACANT-TERM	17:24	SANTA CRUZ DE	Paso		15:41			Renfe Opera	Larga distanc	27/03/2023-09/12/2023
05150	4	05150	Prod. vigente	Amortizado	MADRID-CHAM	15:30	VALENCIA-JOAC	17:20	SANTA CRUZ DE	Paso		16:11			Renfe Opera	Larga distanc	23/01/2023-09/12/2023
06154	1	06154	Prod. vigente	Amortizado	MADRID-CHAM	15:45	ALACANT-TERM	18:11	SANTA CRUZ DE	Paso		16:26			ILSA	Larga distanc	02/06/2023-14/09/2023
05162	5	05162	Prod. vigente	Amortizado	MADRID-CHAM	16:00	ALACANT-TERM	18:33	SANTA CRUZ DE	Paso		16:41			Renfe Opera	Larga distanc	27/03/2023-09/12/2023
10310	8	10310	Prod. vigente	Amortizado	GIJON-SANZ CR	10:48	VINAROS	20:43	SANTA CRUZ DE	Paso		16:58			Renfe Opera	Larga distanc	11/06/2023-09/12/2023
05160	1	05160	Prod. vigente	Amortizado	MADRID-CHAM	16:30	VALENCIA-JOAC	18:20	SANTA CRUZ DE	Paso		17:11			Renfe Opera	Larga distanc	23/01/2023-09/12/2023
06162	1	06162	Prod. vigente	Amortizado	MADRID-CHAM	16:45	VALENCIA-JOAC	18:41	SANTA CRUZ DE	Paso		17:26			ILSA	Larga distanc	16/12/2022-09/12/2023
05178	6	05178	Prod. vigente	Amortizado	MADRID-CHAM	17:00	ALACANT-TERM	19:20	SANTA CRUZ DE	Paso		17:40			Renfe Opera	Larga distanc	27/03/2023-09/12/2023
06572	4	06572	Prod. vigente	Amortizado	MADRID-CHAM	17:15	VALENCIA-JOAC	19:05	SANTA CRUZ DE	Paso		17:56			Ouigo Espa	Larga distanc	11/12/2022-09/12/2023
05170	4	05170	Prod. vigente	Amortizado	MADRID-CHAM	17:30	VALENCIA-JOAC	19:20	SANTA CRUZ DE	Paso		18:11			Renfe Opera	Larga distanc	23/01/2023-09/12/2023

Figure 39: Example of one day traffic above SCZ turnout (2023-06-16)

Geometric inspections

A key element to prevent unexpected defects are geometric inspections of the turnout. These inspections are performed on a regular basis and the recorded data, as shown in Figure 40, will be provided throughout the project.

adif N TRATAR) SEGÚN *ETI INFRAESTRUCTURA*
DSIH-AV3-60-17000/7300-1:50-CCM-I/D-TC (Vel. Desviada ≥ 100 km/h)
DSIH-AV3-60-17000/7300-1:50-CCM-ID-TC (2022.01)
Hoja 1 de 2
ESP acciona TECSA COMSA VIAS UTE BASES VILLARRUBIA-GABALDÓN

Nº APTO:	040.S1 SCZ 2	EJE:	LEVANTE	LÍNEA:	040 MAD - VAL	ESTACIÓN:	PB Sta. Cruz de la Zarza (SCZ)	FECHA:	06/06/2023

ACCIONAMIENTOS

CAMBIO		1er Cerrojo		2do Cerrojo		3er Cerrojo		4to Cerrojo		5to Cerrojo		6to Cerrojo		7mo Cerrojo		8vo Cerrojo		9no Cerrojo		10mo Cerrojo	
*Carrera	TEÓRICO	220		220		220		220		220		220		220		220		220		150	
(Tol. ± 3 mm.)	Real																				
	Corregido																				
Abertura	TEÓRICO	120		120		120		120		120		120		120		120		114		92	
(Vdir/Vdes)	Real	116,0	120,0	115,0	119,0	115,0	118,0	117,0	120,0	115,0	120,0	116,0	120,0	120,0	120,0	120,0	120,0	118,0	120,0	94,0	95,0
(Tol. ± 10 mm.)	Corregido																				
Encerroj.	TEÓRICO	51,1		51,1		51,1		51,1		51,1		51,1		51,1		51,4		53,9		33,9	
(Vdir/Vdes)	Real	51,0	52,0	50,0	52,0	52,0	51,0	51,0	52,0	52,0	54,0	51,0	54,0	53,0	55,0	52,0	54,0	54,0	55,0	32,0	37,0
(Tol. ± 10 mm.)	Corregido																				

INTERVALOS DE INTERVENCIÓN PROGRAMADA (Cotas en mm)
Ancho Directa: Tol. (>4, ≤7), (<-2, ≥-3)
Ancho Desviada: Tol.(>6, ≤7), (<-2, ≥-3)
Peralte: Tol.(>3, ≤5), (<-3, ≥-5)
INTERVALOS DE ACCIÓN INMEDIATA (Cotas en mm)
(Correción inmediata si supera las tolerancias de Límite de Corección Programada)

CORAZÓN		11mo Cerrojo		12mo Cerrojo		13ro Cerrojo		14to Cerrojo	
Carrera	TEÓRICO	260		220		200		150	
(Tol. ± 3 mm.)	Real								
	Corregido								
Abertura	TEÓRICO	115		80,4		52	(+5,-2)	23	
(Vdir/Vdes)	Real	113,0	114,0	80,0	80,0	50,0	53,0	20,0	21,0
(Tol. ± 5 mm.)	Corregido								
Encerroj.	TEÓRICO	32		28		16		8	(+10, 0)
(Vdir/Vdes)	Real	33,0	34,0	26,0	27,0	17,0	16,0	9,0	11
(Tol. ± 10 mm.)	Corregido								

PARAMETROS DE SEGURIDAD	VIA DIRECTA		VIA DESVIADA	
	REAL	CORREGIDO	REAL	CORREGIDO
ENTRECALLE MINIMA >58 mm	61,0		61,0	
PASO LIBRE RUEDA CAMBIO ≤ 1380 mm	1376,0		1373,0	
ACOPLAMIENTO AGUJA - CONTRAAGUJA ≤ 1 mm	0,1		0,0	
ACOPLAMIENTO PUNTA CORAZON - CUNA ≤ 1 mm en la zona de acoplamiento	0,4		0,0	

ANCHOS Y PERALTES DE VIA

VIA DIRECTA								VIA DESVIADA							
TRAVIESA	ANCHO		PERALTE	TRAVIESA	ANCHO		PERALTE	TRAVIESA	ANCHO		PERALTE	TRAVIESA	ANCHO		PERALTE
- 30 traviesas	1435,0	1434,4	0,2	E 673 139	1435,0	1434,7	2,3					E 673 139	1435,0	1435,1	1,8
- 16 traviesas	1435,0	1434,4	2,5	E 673 169	1435,0	1435,1	2,1					E 673 169	1435,0	1434,7	0,7
- 8 traviesas	1435,0	1434,9	2,5	E 673 199	1435,0	1435,7	2,7					E 673 199	1435,0	1434,2	2,0
E 673 001	1435,0	1436,1	1,5	E 673 229	1435,0	1435,1	2,0					E 673 229	1435,0	1434,0	1,4
E 673 011	1445,7	1447,3	1,1	E 673 256	1435,0	1437,8	1,0					E 673 256	1435,0	1434,2	1,2
E 673 018	1446,8	1446,7	0,7	E 673 354	1435,0	1434,6	0,9	E 673 018	1446,8	1444,9	1,2	E 673 354	1435,0	1438,7	2,7
E 673 025	1448,1	1448,3	0,3	E 673 358	1435,0	1433,0	0,0	E 673 025	1448,1	1446,8	0,7	E 673 358	1435,0	1438,8	2,9
E 673 033	1450,0	1451,2	0,7	E 673 269	1435,0	1434,7	2,1	E 673 033	1450,0	1450,2	1,0	E 673 269	1435,0	1436,1	2,7
E 673 039	1448,8	1450,3	0,6	E 673 280	1435,0	1436,1	2,0	E 673 039	1448,8	1448,9	0,7	E 673 280	1435,0	1434,9	2,9
E 673 046	1446,9	1446,9	0,3	E 673 310	1435,0	1435,5	2,9	E 673 046	1446,9	1444,9	0,2	E 673 310	1435,0	1434,3	1,8
E 673 055	1444,7	1443,1	1,0	E 673 340	1435,0	1435,9	0,6	E 673 055	1444,7	1442,8	0,5	E 673 340	1435,0	1435,9	1,8
E 673 063	1442,5	1443,8	1,8	+ 8 traviesas	1435,0	1436,7	2,0	E 673 063	1442,5	1441,0	0,7	+ 8 traviesas	1435,0	1436,3	0,1
E 673 072	1440,3	1439,7	2,7	+ 16 traviesas	1435,0	1434,6	2,4	E 673 072	1440,3	1439,1	0,8	+ 16 traviesas	1435,0	1434,9	2,8
E 673 079	1438,2	1437,4	2,9	+ 30 traviesas	1435,0	1434,8	0,1	E 673 079	1438,2	1436,4	1,6	+ 30 traviesas	1435,0	1437,5	2,9
E 673 109	1435,0	1434,7	2,3					E 673 109	1435,0	1434,4	2,9				

Figure 40: June the 6th inspection report

8.2.5 Planned measurement campaigns

High speed line demonstrator Spain

The wayside monitoring system for the specified demonstrator turnout will cover the following applications:

- Detector/drive rod monitoring (see paragraph 9.9)
- Switch assembly monitoring (see paragraph 9.10)
- Track quality monitoring (see paragraph 9.11)
- Switch rail and frog monitoring (see paragraph 9.12)

The applications and utilised technologies are described more in detail in section 9.

8.3 Spain: Mixed traffic line pilot site

The chosen turnout for the mixed traffic line demonstrator is a DSH-P1-60-500-0,071-TC which is a very common turnout in the mixed traffic line. The turnout shown in Figure 43 was installed in 2016 and provided by Voestalpine JEZ.

Figure 41: Mixed traffic line demonstrator turnout

Nomenclature:

ADV 8 Rifá

Location:

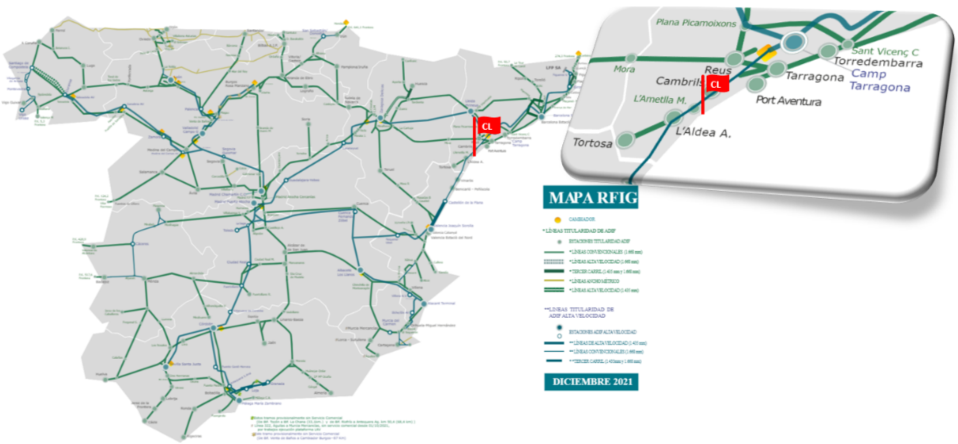

Figure 42: Mixed traffic line demonstrator location

This turnout is placed on Tarragona province in the Tarragona – Valencia mixed traffic line. , railtrack II, as shown in Figure 41, Figure 42 and Figure 43.

More specifically between Montroig and Hospitalet de ´L´Infante stations (PK 234+520)

Figure 43: Rifa Mixed traffic line turnout location

Characteristics: (DSH-P1-60-500-0,071-TC)

- Length: 46,870 meters
- Rail type: 60E1 R260. Welded continuous rail
- Concrete sleeper
- Assymetrical low profile switch
- Sleepers with switch rollers in the changing area
- Crossing with fixed frog
- Crossing angle 1:15
- Flexible fastening SKL-12
- 3 points machines in the switch
- 3 hollow sleepers
- Maximum Speed by direct track: 200 km/h
- Maximum Speed by deviated track: 40 km/h

8.3.1 Demonstrator aims

The aim of this demonstrator is to develop an automatic predictive maintenance system that provides the health state of the turnout, especially the frog, as well as its future behaviour, by detecting anomalies that cannot be detected manually or visually. Figure 44 shows the frog of the demonstrator turnout to be monitored.

Figure 44: Frog of mixed traffic line demonstrator turnout

Specifically, it is necessary to detect internal cracks in the material, fundamentally in the lower area of the frog, which are not currently detectable with the inspection systems available.

The crossing of the turnouts is considered a key point of these infrastructures, because both their service and maintenance require special attention. In this sense, periodic technical inspections are mandatory, as well as the execution of the appropriate repairs in each case in order to reduce risks and reduce maintenance costs. Figure 45 shows the main components of the mixed traffic demonstrator turnout including the point machine, the switch rods, the crossing and the switch area.

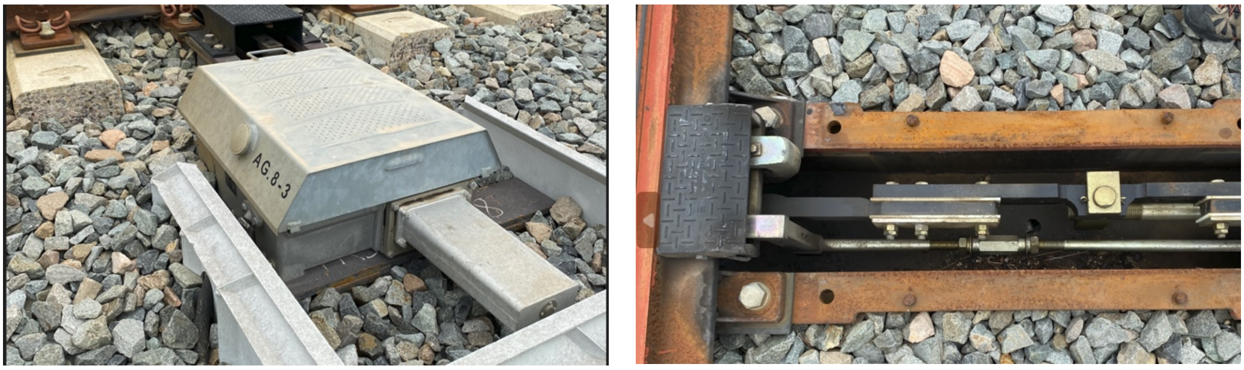

Figure 45: Main components of mixed traffic line demonstrator

8.3.2 Available data sets

To achieve the objective described above, it is necessary to rely on a series of available data such as:

Technical characteristics of the turnout (as described above) and drawings of the turnout

An extensive collection of component drawings, as well as layout plans, shown in Figure 46, is available to be able to know in detail the characteristics of each element of the turnout.

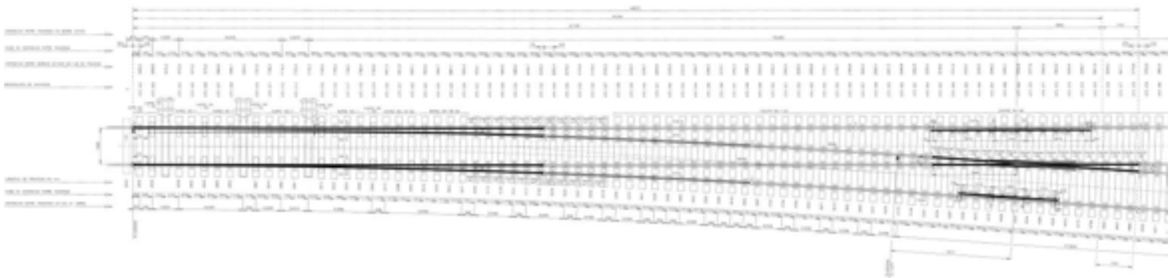

Figure 46: Turnout geometry

Traffic traveling through the turnout

The daily traffic through the bypass and data including the characteristics of the rolling stock are available for the mixed traffic demonstrator turnout.

Planif WEB | SISTEMA DE GESTIÓN DE TRENES | Fecha: 16/06/2023 12:11:46
LISTADO DE TRENES EN ESTACIÓN | Usuario: 2863645

FILTROS APLICADOS

Paridad: Par
Fechas de circulación: 16/06/2023 - 16/06/2023
Nodo Principal: RIFA
Empresa: ACCIONA RAIL SERVICES, S.A. / CONTINENTAL RAIL, S.A. / LOW COST RAIL, S.A. / CAPTRAIN ESPAÑA, S.A.U. / CSP LOGITREN, S.A. / TRACCION RAIL / RENFE OPERADORA / ADMINISTRADOR DE INFRAESTRUCTURAS FERROVIARIAS / RENFE MERCANCIAS, S.A. / TRANSITIA RAIL, S.A. / ALSA
Producto: SERVICIO INTERNO ESTACION / MERCANCIAS / LARGA DISTANCIA Y AVE / SERVICIO INTERNO INFRAEST. / CERCANIAS / MEDIA DISTANCIA / SERVICIO INTERNO CIRCULACION / SERVICIO INTERNO T. MERCANC. / MANTENIMIENTO EXTERNO INFRAESTRUCTURA

Nº T.	V.	Nº CO.	EST.	AM.	ORIGEN	H. SALIDA	DESTINO	H. LLEGADA	N. PRINCIPAL	TIPO	H. LLEG.	H. SALIDA	P.COM.	TIP.PAR.	EMP.	PROD.	VIGENCIA
30820	2	30820	Prod. vigente	Amortizado	TORTOSA	05:47	BARNA.-EST. DE	08:27	RIFA	Paso		06:30			Renfe Opera	Media distanc	05/03/2023-09/12/2023
30824	2	30824	Prod. vigente	Amortizado	TORTOSA	07:29	BARNA.-EST. DE	10:25	RIFA	Paso		08:16			Renfe Opera	Media distanc	05/03/2023-09/12/2023
10072	4	10072	Prod. vigente	Amortizado	VALENCIA-ESTA	06:55	BARCELONA-SA	10:10	RIFA	Parada		08:49		Técnica	Renfe Opera	Larga distanc	26/02/2023-09/12/2023
33826	1	33826	Prod. vigente	Amortizado	TORTOSA	09:15	BARNA.-EST. DE	12:27	RIFA	Paso		10:07			Renfe Opera	Media distanc	20/05/2023-05/07/2023
10093	2	10093	Prod. vigente	Amortizado	ALACANT-TERM	07:15	BARCELONA-SA	12:16	RIFA	Paso		11:00			Renfe Opera	Larga distanc	26/02/2023-09/12/2023
30828	3	30828	Prod. vigente	Amortizado	TORTOSA	11:32	BARNA.-EST. DE	14:28	RIFA	Paso		12:18			Renfe Opera	Media distanc	19/03/2023-09/12/2023
10113	2	10113	Prod. vigente	Amortizado	ALACANT-TERM	09:20	BARCELONA-SA	14:16	RIFA	Paso		13:10			Renfe Opera	Larga distanc	26/02/2023-09/12/2023
81565	2	81565	Prod. vigente	Amortizado	SAGUNT	09:23	BARCELONA-CA	16:28	RIFA	Paso		14:14			Renfe Merca	Mercancias	14/03/2023-29/07/2023
30832	2	30832	Prod. vigente	Amortizado	TORTOSA	13:51	BARNA.-EST. DE	16:27	RIFA	Paso		14:32			Renfe Opera	Media distanc	05/03/2023-09/12/2023
10460	6	10460	Prod. vigente	Amortizado	MURCIA DEL CA	08:55	BARCELONA-SA	16:44	RIFA	Paso		15:13			Renfe Opera	Larga distanc	26/02/2023-09/12/2023
30834	2	30834	Prod. vigente	Amortizado	TORTOSA	15:37	BARNA.-EST. DE	18:25	RIFA	Paso		16:25			Renfe Opera	Media distanc	05/03/2023-09/12/2023
11152	3	11152	Prod. vigente	Amortizado	VALENCIA-JOAC	15:03	FIGUERES-VILA	19:27	RIFA	Paso		16:55			Renfe Opera	Larga distanc	12/03/2023-09/12/2023
30836	3	30836	Prod. vigente	Amortizado	TORTOSA	16:32	BARNA.-EST. DE	19:27	RIFA	Paso		17:18			Renfe Opera	Media distanc	19/03/2023-09/12/2023
10163	2	10163	Prod. vigente	Amortizado	ALACANT-TERM	13:55	BARCELONA-SA	18:53	RIFA	Paso		17:40			Renfe Opera	Larga distanc	26/02/2023-09/12/2023
10695	5	10695	Prod. vigente	Amortizado	CADIZ	07:35	BARCELONA-SA	20:17	RIFA	Paso		18:57			Renfe Opera	Larga distanc	01/06/2023-09/12/2023
10265	5	10265	Prod. vigente	Amortizado	CARTAGENA	12:00	BARCELONA-SA	20:45	RIFA	Paso		19:08			Renfe Opera	Larga distanc	26/02/2023-09/12/2023
30840	3	30840	Prod. vigente	Amortizado	TORTOSA	18:30	BARNA.-EST. DE	21:25	RIFA	Paso		19:20			Renfe Opera	Media distanc	19/03/2023-09/12/2023
80246	2	80246	Prod. vigente	Amortizado	FORD	14:57	CERBERE	00:41	RIFA	Paso		19:37			Renfe Merca	Mercancias	05/02/2023-09/12/2023
11412	2	11412	Prod. vigente	Amortizado	VALENCIA-ESTA	18:15	BARCELONA-SA	22:10	RIFA	Paso		20:47			Renfe Opera	Larga distanc	12/05/2023-09/12/2023
64502	1	64502	Prod. vigente	Amortizado	VALENCIA-F.S.L.	17:19	ZARAGOZA-PLA	05:46	RIFA	Parada		21:41		Técnica	Op. Ferrov. e	Mercancias	11/12/2022-09/12/2023
10193	2	10193	Prod. vigente	Amortizado	ALACANT-TERM	17:18	BARCELONA-SA	22:16	RIFA	Paso		21:04			Renfe Opera	Larga distanc	26/02/2023-09/12/2023
30898	3	30898	Prod. vigente	Amortizado	TORTOSA	20:24	BARNA.-EST. DE	23:24	RIFA	Paso		21:17			Renfe Opera	Media distanc	22/03/2023-09/12/2023
81573	3	81573	Prod. vigente	Amortizado	SAGUNT	17:32	CASTELLBISBAL	23:35	RIFA	Paso		21:21			Renfe Merca	Mercancias	17/04/2023-18/08/2023
30844	2	30844	Prod. vigente	Amortizado	TORTOSA	20:55	BARNA.-EST. DE	23:49	RIFA	Paso		21:45			Renfe Opera	Media distanc	05/03/2023-09/12/2023
80248	1	80248	Prod. vigente	Amortizado	FORD	20:09	CERBERE	04:32	RIFA	Paso		23:59			Renfe Merca	Mercancias	11/12/2022-09/12/2023

Figure 47: Example of one day traffic above SCZ turnout (2023-06-16)

Geometric Auscultations

Inspection data is continuously recorded and provided throughout the project, as shown in Figure 48, and provided for analyses and data fusion purposes.

KM	Metros	Ancho(mm)	Ancho 3-25m(mm)	Ancho_25_70(mm)	Ancho 70-oo(mm)	Peralte(mm)	Peralte 70-oo(mm)	Peralte 120-oo(mm)	Peralte 200-oo(mm)	Curvatura(1/km)	Curvatura 120-oo(1/km)	Curvatura 200-oo(1/km)	Curvatura_Var_120-oo(1/km*m)	Curvatura_Var_200-oo(1/km*m)	Peralte_Var_70-oo(mm/m)	Peralte_Var_120-oo(mm/m)	Peralte_Var_200-oo(mm/m)	Peralte_Def_120-oo(mm)	Peralte_Def_200-oo(mm)	Peralte_Def_Var_120-oo(mm/s)	Peralte_Def_Var_200-oo(mm/s)
234	0.00	0.18	0.15	-0.51	0.29	0.93	0.66	0.55	0.81	-0.006	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.10	-0.36	-0.30	-0.16
234	0.25	-0.09	0.10	-0.51	0.28	0.95	0.66	0.55	0.81	-0.006	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.10	-0.36	-0.30	-0.16
234	0.50	-0.11	0.04	-0.52	0.28	1.08	0.66	0.55	0.81	-0.006	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.10	-0.36	-0.29	-0.16
234	0.75	0.01	0.00	-0.52	0.28	1.11	0.66	0.55	0.81	-0.006	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.10	-0.36	-0.29	-0.16
234	1.00	0.06	-0.02	-0.52	0.28	1.09	0.66	0.55	0.82	-0.005	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.11	-0.36	-0.29	-0.15
234	1.25	-0.03	-0.04	-0.52	0.27	1.23	0.67	0.56	0.82	-0.005	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.11	-0.36	-0.29	-0.15
234	1.50	-0.21	-0.05	-0.51	0.27	1.35	0.67	0.56	0.82	-0.005	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.11	-0.36	-0.29	-0.15
234	1.75	-0.21	-0.05	-0.51	0.26	1.30	0.67	0.56	0.82	-0.005	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.11	-0.36	-0.29	-0.15
234	2.00	-0.01	-0.03	-0.50	0.26	1.29	0.67	0.56	0.82	-0.004	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.11	-0.36	-0.29	-0.15
234	2.25	0.15	-0.02	-0.50	0.26	1.28	0.67	0.56	0.82	-0.004	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.11	-0.37	-0.29	-0.14
234	2.50	0.02	-0.02	-0.49	0.26	1.25	0.67	0.56	0.82	-0.004	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.12	-0.37	-0.29	-0.14
234	2.75	-0.20	-0.02	-0.48	0.25	1.24	0.67	0.57	0.82	-0.004	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.12	-0.37	-0.29	-0.14
234	3.00	-0.30	-0.03	-0.47	0.25	1.33	0.67	0.57	0.82	-0.003	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.12	-0.37	-0.29	-0.14
234	3.25	-0.08	-0.04	-0.46	0.25	1.08	0.67	0.57	0.83	-0.003	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.12	-0.37	-0.29	-0.14
234	3.50	0.10	-0.07	-0.44	0.25	0.90	0.68	0.57	0.83	-0.002	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.12	-0.37	-0.29	-0.14
234	3.75	0.00	-0.13	-0.43	0.25	0.87	0.68	0.57	0.83	-0.002	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.12	-0.37	-0.29	-0.14
234	4.00	-0.20	-0.20	-0.41	0.25	0.75	0.68	0.57	0.83	-0.002	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.12	-0.37	-0.29	-0.13
234	4.25	-0.40	-0.28	-0.40	0.25	0.26	0.68	0.58	0.83	-0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.13	-0.37	-0.29	-0.13
234	4.50	-0.42	-0.35	-0.38	0.25	0.22	0.68	0.58	0.83	-0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.13	-0.37	-0.29	-0.13
234	4.75	-0.35	-0.41	-0.36	0.25	0.14	0.68	0.58	0.83	-0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.13	-0.37	-0.29	-0.13
234	5.00	-0.34	-0.44	-0.34	0.25	0.12	0.68	0.58	0.83	0.000	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.13	-0.37	-0.29	-0.13
234	5.25	-0.36	-0.44	-0.32	0.25	0.07	0.68	0.58	0.83	0.000	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.13	-0.37	-0.29	-0.13
234	5.50	-0.27	-0.42	-0.29	0.25	-0.06	0.69	0.59	0.83	0.000	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.13	-0.37	-0.29	-0.13
234	5.75	-0.27	-0.37	-0.27	0.26	-0.08	0.69	0.59	0.84	0.000	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.14	-0.38	-0.30	-0.13
234	6.00	-0.25	-0.29	-0.25	0.25	-0.11	0.69	0.59	0.84	0.000	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.14	-0.38	-0.30	-0.13
234	6.25	-0.17	-0.20	-0.22	0.25	-0.17	0.69	0.59	0.84	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.14	-0.38	-0.30	-0.13
234	6.50	-0.05	-0.11	-0.20	0.25	-0.12	0.69	0.59	0.84	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.14	-0.38	-0.30	-0.13
234	6.75	0.00	-0.03	-0.17	0.25	-0.10	0.69	0.59	0.84	0.001	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.14	-0.38	-0.30	-0.13
234	7.00	0.11	0.01	-0.14	0.25	0.05	0.69	0.60	0.84	0.002	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.14	-0.38	-0.31	-0.13
234	7.25	0.31	0.01	-0.11	0.24	0.06	0.69	0.60	0.84	0.002	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.15	-0.38	-0.31	-0.13
234	7.50	0.37	-0.04	-0.09	0.24	0.12	0.70	0.60	0.84	0.002	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.15	-0.38	-0.31	-0.13
234	7.75	0.17	-0.16	-0.06	0.24	0.07	0.70	0.60	0.84	0.003	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.15	-0.38	-0.31	-0.13
234	8.00	-0.21	-0.31	-0.03	0.23	0.13	0.70	0.60	0.85	0.003	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.15	-0.38	-0.32	-0.13
234	8.25	-0.38	-0.45	0.00	0.23	0.30	0.70	0.61	0.85	0.003	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.15	-0.38	-0.32	-0.13
234	8.50	-0.44	-0.56	0.02	0.23	0.25	0.70	0.61	0.85	0.004	0.001	0.001	0.00	0.00	0.00	0.00	0.00	-0.15	-0.38	-0.32	-0.13

Figure 48: May the 26th inspection report

8.3.3 Planned measurement campaigns

Mixed traffic line demonstrator

The wayside monitoring system for the specified demonstrator turnout will cover the following applications:

- Track quality monitoring (see paragraph 9.11)
- Switch rail and frog monitoring (see paragraph 9.12)

The applications and utilised technologies are described more in detail in section 9.

9 RESEARCH: APPLICATIONS, APPROACHES, TOOLS

9.1 Holistic Switch Monitoring and Switch Diagnostic Model

Data from various sensors and their combination are the foundation for the holistic monitoring of railway assets such as switches and crossings. Often, there are relations (or relations can be expected) where parts of the infrastructure directly and physically interact with each other but are still monitored separately in practice. Ballast condition and general track geometry, for instance, usually lack of an integration with the health monitoring of the point machines (including mechanical switch elements such as slide chairs and rods etc.) in context of maintenance and fault diagnostics.

Intending to foster the development of enhanced tools for integrated health monitoring and fault diagnostics via simulation-based physical models and/or modern data-driven approaches, a comprehensive and synchronized research data set has been and is being collected in the Netherlands, see paragraph 8.1. The train-borne information as measured via the LEONARDO platform, see paragraph 7.1.3 comprise axle-box acceleration data, geo-referenced video material of the track and its surrounding from various perspectives (incl. catenary and vertical images of sleepers and ballast), Ground Penetrating Radar (GPR) data, and LIDAR-based measurements of the track. All this will be accompanied by current curve (incl. control circuit) and power supply measurements for the point engines see paragraph 7.2.4.2 and paragraph 8.1 together with environmental data such as temperature and humidity. Synchronized maintenance and manual inspection data will help to validate and interpret the automatically generated measurements as well as the results that are going to be derived from them algorithmically.

9.2 Crack and surface damage detection in railways using microwaves

9.2.1 Brief introduction to the application (problem description)

Inspecting the railways for detecting defects such as cracks is a crucial activity, needed to guarantee the safety and determine maintenance activities such as repairs or even railway replacement. Cracks of depth bigger than 4mm and/or length bigger than 30 mm are already considered severe and need corrective actions, while if the depth is bigger than 5mm, railway replacement is required. These cracks are produced, mainly, both in ruptures of the welds, and in specific locations due to rolling contact fatigue.

This application addresses this problem, by proposing a method based on autonomous inspection of the railway using microwaves.

A basic diagram of the proposed system is depicted in Figure 49. At a high level, the detection principle to be analysed here is based on radar technique using radiofrequency/microwave technologies, with the ability to illuminate the moving lane when placed on a measurement vehicle or similar platform. The reflections received by this radar must be treated and processed to detect the presence of cracks and ideally be able to diagnose their severity, in order to execute the required mitigation actions (e.g. grinding).

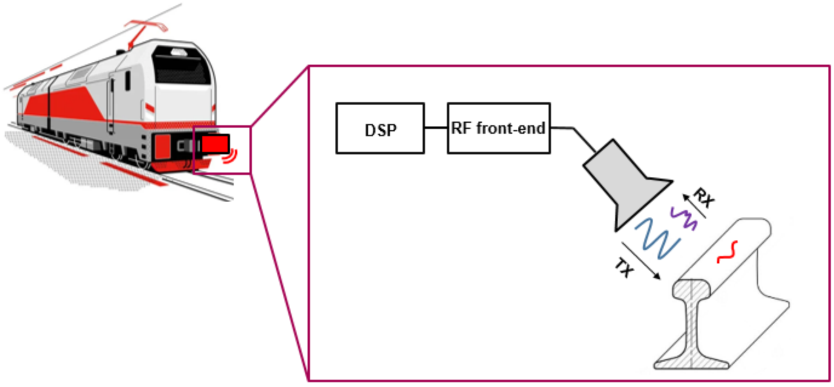

Figure 49: Railway inspection using microwaves

Beyond the basic principle in RF (Radio Frequency), several other challenges have been identified for an appropriate solution. These are the mechanical constraints of positioning of the reading and receiving head with respect to the rail, the implementation of the system embedding it on a moving platform and the processing capability of the data to be analysed. These points influence the viability of the potential product, so it is convenient to consider them from the initial stages of analysis. In this work package, we will work on the preliminary concepts of these three aspects.

9.2.2 Description of the technology

To the date, most of the railway inspection methods are based on visual techniques, by the maintenance workers, or on electromagnetic sensing using Eddy Currents [28]. The former are slow and costly in terms of work force, as well as subject to human failures, while the latter require close proximity or even contact between the sensor and the railway, which means low inspection speed and high wear and tear due to friction.

In the recent years, some non-contact techniques to inspect superficial damages in metal structures using microwaves have been proposed [29]. A summary of these techniques is provided in Figure 50 below.

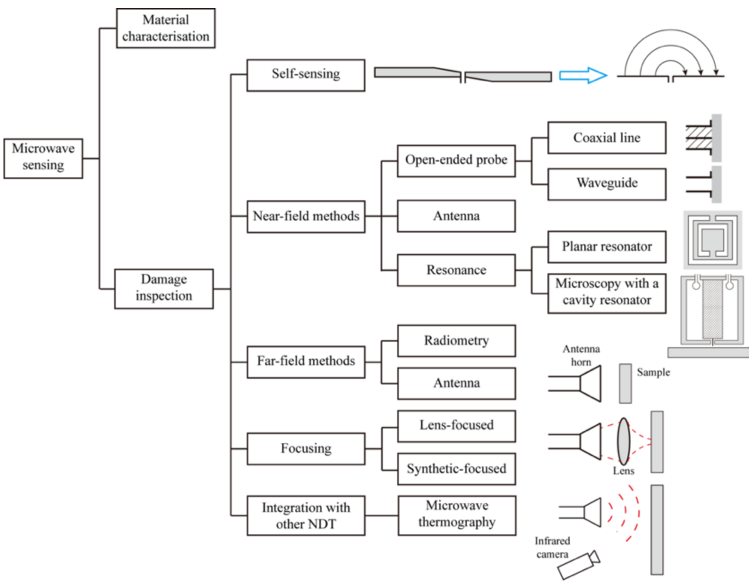

Figure 50: Crack detection methods using microwaves (Tree diagram)

As a result, the preferred technique for the use of the challenge presented here is the near field method, preferably with an open-ended probe or antenna. As a summary of the operation principle, the problem consists of measuring the amount of electromagnetic energy dispersed by the crack in the railway, by measuring the impedance matching of an antenna or the transmission between two antennas pointing at the railway. After comparing the results to what is measured when there are no cracks, which is presumably the most of time in an operational rail, it is possible to determine if a defect is present in the rail.

However, most of the presented works focus on proving the concept in the laboratory, such as [30]. When applied to crack detection in railways, there are different papers and patents proposing methods such as laser [31], infrared [32] or ultrasound [33], while none of them proposes to use a non-contact method based on microwaves as in this project.

Another important challenge is digital signal processing (DSP) of the acquired signals, in order to clean imperfections and facilitate the detection. Many different works have reported DSP techniques, such as the "Canny" algorithm proposed in [34] or the neural network approach of [35]. These and other methods will be assessed during the project, in order to obtain as much information as possible from the acquired analog signals.

For the final system proposal, however, further inputs from the operational procedures of the infrastructure manager are needed. These will allow properly sizing the frequency of interest and the distance of the measurement equipment. The speed of operation and the deepness of the algorithm are going to set the requirements for the signal processing power.

9.2.3 Methodology

In order to build the proposed inspection system, it is essential to first carefully analyse the problem, assess different solutions and to test them in the laboratory. The main challenges are associated to (1) the electromagnetic analysis of the railway, (2) the digital signal processing of the acquired data and (3) the mechanical stability of the system when placed onboard. To ensure the success of the project, an iterative process with the following steps is proposed:

1. System requirements derived from user needs
2. Research on State of the art
3. Definition of test protocol and development of laboratory test bench
4. Electromagnetic simulations of the problem (ANSYS)
5. Off-line processing of laboratory signals and simulations
6. Proof of Concept at Laboratory
7. Proposal for system architecture and refining of system requirements.

9.2.4 Description of the data

9.2.4.1 Input data used (simulations, measurements, technical information, etc.)

As input data for the system analysis, sizing and design, the following will be required:

- Technical operational requirements: detection speed, distance to the railway, minimum crack size and geometry to be detected, etc.

- Technical information on material and processes: typical railway material, possible shapes, which defects are important to detect and which are innocuous, etc.
- Real rails with and without defects: pieces of railway, with and without defects, to proof the concept in the laboratory and in the field.

9.2.4.2 Output data generated (simulations, results, etc.)

With the aforementioned data, the performed simulations and laboratory tests will produce the following data:

- Ideal data from electromagnetic simulations. This data will be S-parameters such as transmission between two antennas (S21) and reflection at the antenna port (S11) or the radar cross section of a railway with and without defects. The data will be provided for a wide range of frequencies.
- Raw S-parameter data obtained from measurements of real railways in the laboratory. Data will be obtained for setups with different antenna types and placements.
- Outcomes of the digital processing of both the simulation and laboratory data, which will include refinement, filtering, etc, to help in determining the presence of a defect.

9.3 Occlusion Monitoring Due To Vegetation

9.3.1 Brief introduction to the application

This application focuses on the use of artificial intelligence and computer vision techniques for the detection infrastructure elements' occlusions due to vegetation on the surroundings. For both manual and automatic driving, visibility of the surroundings and above all of signalling is key to safety and therefore the maintenance of infrastructure is key. The aim of this task is to improve maintenance efficiency and move towards intelligent maintenance that can autonomously inspect vegetation and plan the necessary tasks to ensure the visibility of signals and traffic lights in the railway environment.

Figure 51: Overview of the application on a road scene[4]

9.3.2 Description of the technology

In general terms, the technology used in this project will be based on artificial vision and machine learning techniques (Deep Learning). Specifically for image analysis, semantic segmentation and object detection techniques will be used.

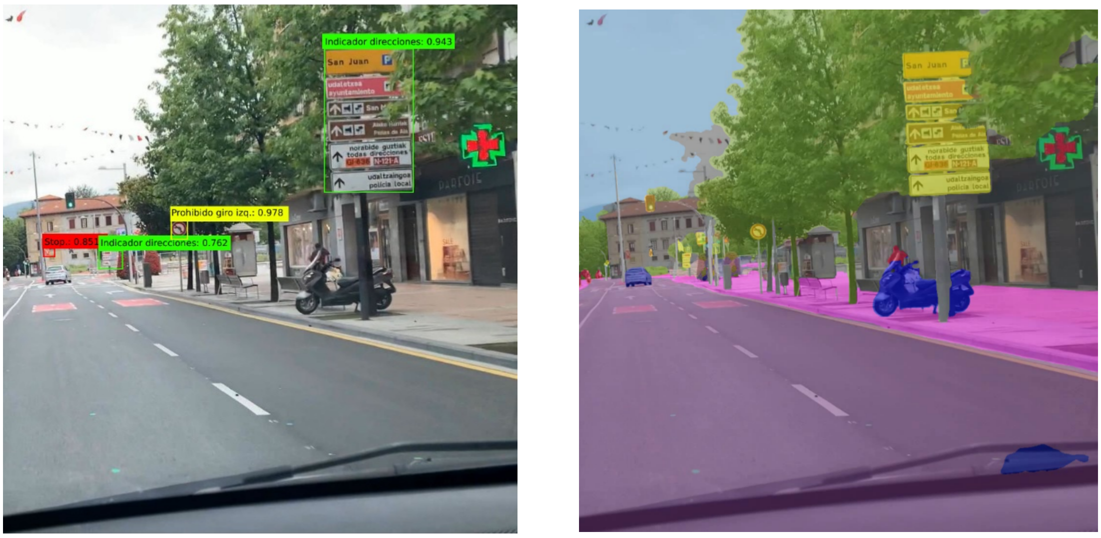

Figure 52: (left) object detection traffic signals, (right) complete scene segmentation

For the application of this Deep Learning techniques, the following state-of-the-art algorithms have been studied so far:

Object Detection: some of the most popular state-of-the-art models are being studied such as YOLOv8 [36], Faster-RCNN [37] and SSD [38] due to their precision and processing

[4] Note that for the first analysis carried out, work has been done in the road environment due to the greater availability of data and reference works compared to the railway environment.

speed. As for the framework, YOLO has its own environment called Ultralytics while for the rest of the models Tensorflow's Object Detection Api have been used.

Semantic segmentation: OCRNet+HRNe [39], PSNet [40]and DeepLabV3+ [41] pre-trained models have been tested as they are among the state-of-the-art for the task of traffic scene segmentation. All through their segmentation framework. In the next steps it is also intended to analyse other models such as YOLOv8 which also have this segmentation functionality.

As far as the hardware for data acquisition is concerned, 2D images have been used so far. However, the state of the art has shown that using a stereo camera could improve the three-dimensional perception of the environment [42]. The combination of stereo imaging and 3D reconstruction techniques could provide greater accuracy in the detection of occlusions generated by vegetation.

In addition to the aforementioned approaches, another relevant research area in the field of computer vision is the use of generative adversarial neural networks (GANs) [43]. GANs are used to generate realistic and synthetic images that can help improve the performance and generalisation of computer vision models. In this project, the use of GANs could be considered to generate additional synthetic data to help increase the diversity and quantity of training data, which could improve model performance in vegetation-generated occlusion situations.

9.3.3 Methodology

In order to build robust AI models, it is essential to have a dataset that captures all representative scenarios relevant to the use case with high quality.

Therefore, the first step in this application will be to test whether the algorithms trained with the images of road scenarios are sufficient to obtain good results in the railway environment. And, if necessary (which foreseeably will be), to create new datasets to reinforce the training of these models.

For the training of new models, the transfer learning technique will be applied. Here, pre-trained models are used and trained with new data. This fine-tuning of the neural networks freezes the first layers of the network where very high-level characteristics have been learned that are still useful in the new model. Therefore, the training is focused only in the last layers which are responsible for discerning much lower-level characteristics specific to the particular use case.

Subsequently, it is necessary to test the performance of these new models (accuracy, processing time, etc.) with test data sets.

These AI models will be used to perform three different tasks: (1) detect infrastructure assets, (2) segment vegetation and (3) benchmark objects against vegetation for occlusion estimation. Although it remains to be defined how to address this process, there are several papers that provide us with ideas and approaches to perform this comparison. There are studies such as [44], which propose a multi-technique system to study the flow in an urban scene, which could help us to estimate the distances and overlapping of objects. Besides that, [45] generates synthetic datasets to train models that approximate the level of occlusion of vegetation.

9.3.4 Description of the data

9.3.4.1 Input data used

As input data, different image datasets will be used for railway infrastructure object detection and scene segmentation. Some of the known public datasets for this application are the following:

- RailSem19 (scene segmentation)[5]
- FRSign (traffic sign recognition - France)[6]
- GERALD (traffic sign recognition - Germany)[7]
- OSDaR23 (object detection)[8]

Other relevant dataset that are not focused on railway environment are Cityscapes[9] and Mapillary[10] datasets.

Datasets captured with Leonardo (historic and new within the project).

However, for real environment tests, in addition to the images captured by the on-board camera, it will be necessary to complement them with a GPS sensor to properly locate the alerts of the final algorithm and plan at which point of the railway section it is necessary to perform maintenance operations.

9.3.4.2 Output data generated

Image segmentation

Detection of objects/context:

- Evolution of vegetation
- Occlusions in signals owed to vegetation encroachment

9.4 Track Monitoring using ABA

This section describes the monitoring of the track and its components using Axle Box Accelerations. In particular, the detection and diagnosis of anomalies in rail fasteners, and their implication in track geometry and the apparition of other defects (e.g. rail corrugation).

9.4.1 Brief introduction to the application

Keeping the rail infrastructure in an optimum state of maintenance is a vital task for rail infrastructure managers, with increasing demands on axle loads, speed and frequency of service. Track maintenance is one of the main cost drivers in railway OPEX.

[5] https://openaccess.thecvf.com/content_CVPRW_2019/papers/WAD/Zendel_RailSem19_A_Dataset_for_Semantic_Rail_Scene_Understanding_CVPRW_2019_paper.pdf
[6] https://arxiv.org/pdf/2002.05665v1.pdf
[7] https://journals.sagepub.com/doi/abs/10.1177/09544097231166472
[8] https://arxiv.org/pdf/2305.03001v1.pdf
[9] https://markus-enzweiler.de/downloads/publications/cordts15-cvprws.pdf
[10] https://openaccess.thecvf.com/content_ICCV_2017/papers/Neuhold_The_Mapillary_Vistas_ICCV_2017_paper.pdf

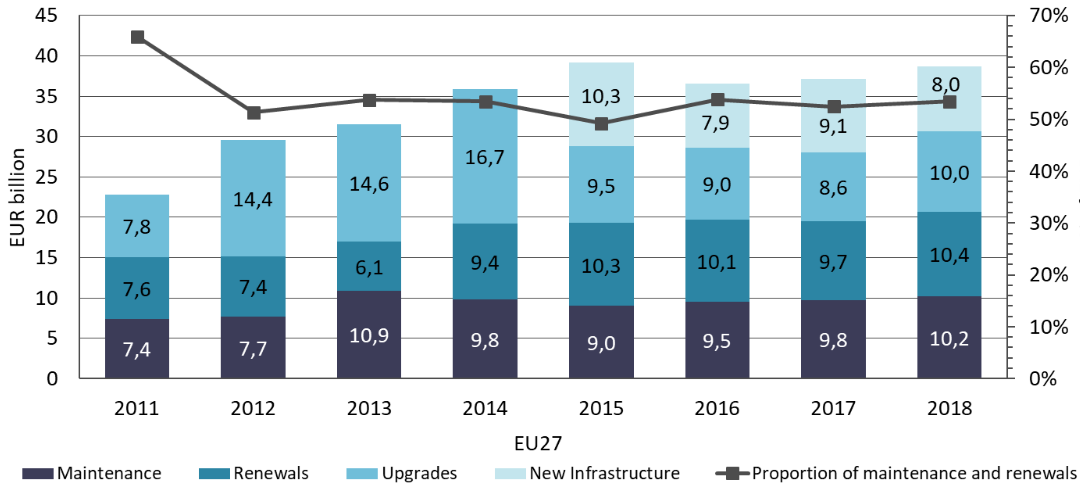

Figure 53: Infrastructure expenditure: see maintenance & renewals (€ billion, 2011-2018)[11]

Over time, railway lines are subject to different types of degradation that affect the quality of the track (track gauge, cant, rail wear, breakage of fastening elements or loss of tightness, among others).

The aim of monitoring, condition-based, and predictive maintenance techniques is to optimise the life cycle of the entire railway infrastructure, i.e., to improve reliability by having continuous information on assets, resulting in a reduction of both maintenance costs and operational disruptions. However, the inspection of certain track elements, such rail fastenings, is currently carried out manually, by walking along the track, and the assessment of their condition is based on a visual evaluation. This makes the process non-efficient and potentially unreliable, as it is subjected to the operator's subjectivity.

For that reason, the continuous acquisition of track condition data using ABA (Axle Box Accelerations) and its subsequent analysis is a key factor in maintenance decision making by asset and maintenance managers.

9.4.2 Description of the technology

Track-side systems are widely used to monitor critical areas of the infrastructure, such as switches and crossings [46]. On the other hand, on-board [47] systems are commonly used to monitor any section of the track. This second line will be the focus of the research, mainly based on the acquisition of acceleration data by using accelerometers installed in the axle boxes of rail vehicles in service [48] [49].

Finally, according to the type of track defects or problems to be detected and the main types of sensors used different signal filtering techniques and algorithms may be implemented to analyse the recorded signals. In this work, we will use ABA data to assess the condition of rail fasteners, investigating the related impact on the condition of track geometry (e.g. misalignments) and the apparition of other defects in the track (e.g. corrugation).

[11] Source: RMMS, 2020

9.4.3 Methodology

Using low-cost on-board systems, such as axle box accelerometers, the condition of the track and its components will be monitored. It will be necessary to investigate new methodologies and algorithms for the generation of relevant information on the condition of the track from the data captured by the sensors.

The methodology that will be used to develop this application can be summarized as follows:

- Develop a simulation framework that is able to generate synthetic data by means of virtual sensors, representing realistic ABA.
- Develop a mathematical model that represents the defects and anomalies to be detected and diagnosed, in order to integrate those effects in the simulation framework.
- Generate scenarios that represent realistic operation in different conditions (speed, track irregularities, etc.), including faulty conditions owed to the anomalies to be detected and diagnosed.
- Obtain a dataset (i.e. synthetic data) for the generated scenarios.
- Develop signal processing techniques and algorithms that are suited to axle box accelerometers that will allow obtaining a set of features that will potentially contribute to the detection and diagnosis of failures and anomalies.
- Develop Machine Learning algorithms for the detection and diagnosis of anomalies in the track, potentially exploring the condition of rail fasteners and its impact in the track geometry (e.g. misalignment) and the rail (e.g. apparition of corrugation).
- Validation of results. First using the synthetic dataset to assess the detection and diagnosis of well identified failures and anomalies. Then, the technology will be demonstrated using real data provided by Leonardo platform, up to TRL5/6.

9.4.4 Description of the data

9.4.4.1 Input data used

Information related to the NED pilot scenario:

- Technical information: track layout and characteristics of its components (e.g. fasteners, sleepers, etc.). NED pilot scenario.
- Inspection data of the track, including track geometry, visual inspection reports, detection of defects, etc.
- Maintenance data: history of maintenance actions and activities carried out on the track.
- ABA data captured with Leonardo platform in different measurement campaigns along the project.

To develop anomaly detection/diagnosis algorithms, synthetic data representing the conditions of the NED scenario will be used. Synthetic datasets will be generated and used as inputs.

9.4.4.2 Output data generated (simulations, results, etc.)

- Synthetic data corresponding to all generated scenarios will be shared with partners of WP10/11
- Report on anomalies detected/diagnosed.

9.5 Turnouts monitoring: acceleration signals

This section describes the monitoring system that is being developed to establish the health status of turnouts using acceleration signals.

9.5.1 Brief introduction to the application (problem description)

Turnouts are a critical asset of the railway system, enabling train vehicles to take different directions. A turnout is split into two main parts (switch and crossing) and has up to four possible running modes (through or diverging direction and facing or trailing move). The dynamic forces due to wheel-rail contact are heavily affected by the degradation of the crossing nose and/or wing rail mainly by wear degradation.

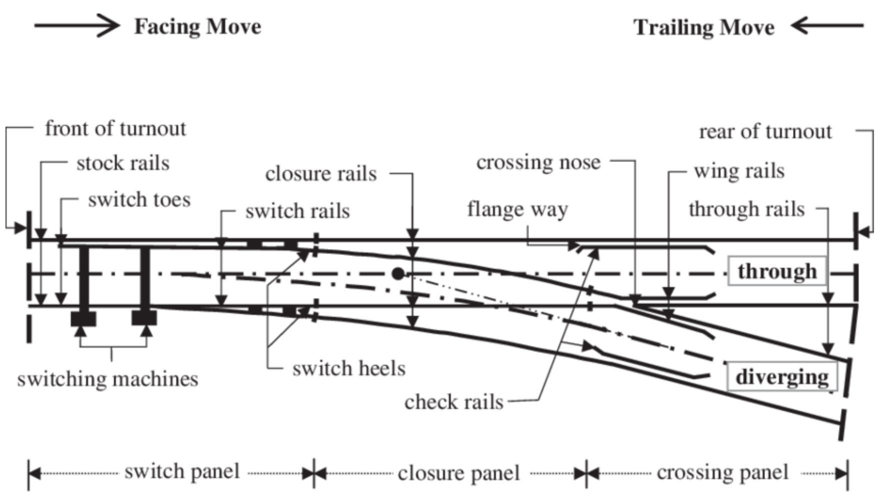

Figure 54: Components of a turnout (source Chalmers University, paper July 2010)

The measurement of these geometries is difficult and costly. Therefore, low-cost devices should be developed to monitor degradation and enhance maintenance.

9.5.2 Description of the technology

The technology to develop aims to detect the health status of the crossing by means of some accelerometers.

Fan et al [50] have used recently co-simulations to vehicle track interaction with a multibody system (MBS) and a finite element method (FEM) model. These simulations should consider for example the effect of unsupported sleepers [51]. The different works related to the topic [52] can be further developed to enhance a low-cost monitoring solution.

9.5.3 Methodology

The methodology to define the location of accelerometers and which are the required KPIs is based on simulations, signal processing and field tests.

First, MBS and FEM models are used to simulate the running of a vehicle through a crossing at different running conditions. On the one hand, MBS simulations allow for calculating the contact patches between wheels and the turnout. On the other hand, FEM models are necessary to study the medium and high-frequency domain accelerations.

Then, different acceleration results from FEM simulations are evaluated to choose the best point(s) for real measurements. These synthetic accelerations are processed to obtain the most relevant KPIs which will define degradation trends for the assessed turnout at different running conditions. The following flowchart shows the methodology using both MBS and FEM models.

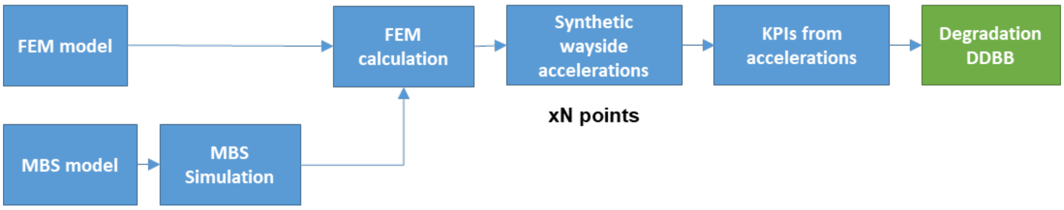

Figure 55: FEM model in context

Finally, field tests are going to be necessary to validate the developed system.

9.5.4 Description of the data

9.5.4.1 Input data used

The inputs required are:

- Geometry:
  - The nominal (CAD) geometry of a specific turnout.
  - Real geometry of a specific turnout at different degradation levels.
- Simulation models:
  - MBS models with several rail profile sections for the definition of the crossing.
  - FEM model to calculate accelerations using MBS results as inputs.
- Measurements:
  - Preliminary measurements for the validation of simulation models (3D point clouds).
  - Acceleration measurements to estimate the health status of the crossing.

9.5.4.2 Output data generated

Within the research work, MBS and FEM models are generated to assess the effect of crossing degradation on acquired acceleration signals. Nevertheless, the eventual data generated are databases using acceleration KPIs to establish a degradation level or index.

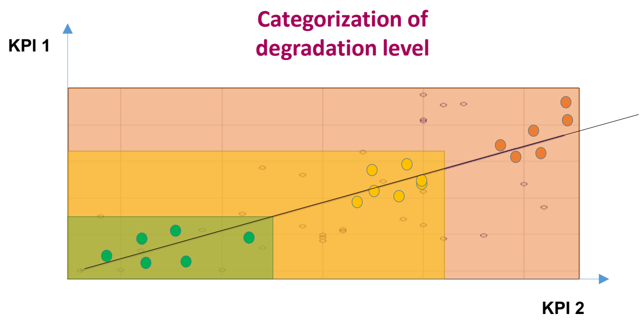

Figure 56: categorisation of degradation level

Once the low-cost monitoring solution is developed each KPI from the real acceleration signal is defined from an average value using a certain time window. Finally, the output generated is the definition of the health status.

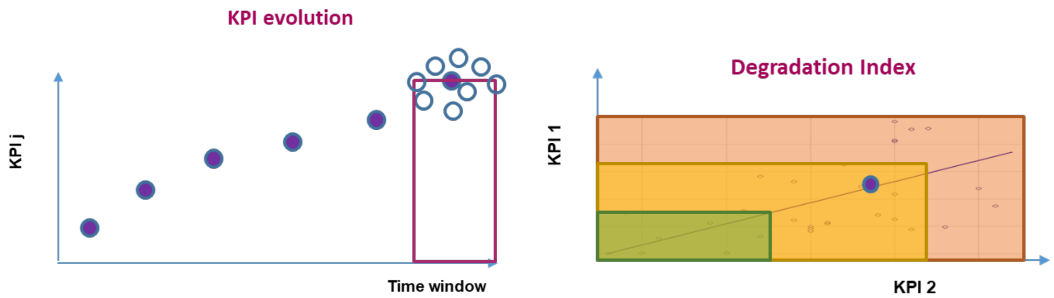

Figure 57: KPI evolution and degradation index

9.6 Inspection of Turnouts: analysing 3-dimensional reconstruction

This section describes the inspection system to be developed to establish the health status of turnouts by analysing their three-dimensional reconstruction.

9.6.1 Brief introduction to the application

Turnouts are a critical asset of the railway system, enabling train vehicles to take different directions. A turnout is split into two main parts (switch and crossing) and has up to four possible running modes (through or diverging direction and facing or trailing move). The dynamic forces due to wheel-rail contact are heavily affected by the degradation of the crossing nose and/or wing rail mainly by wear degradation.

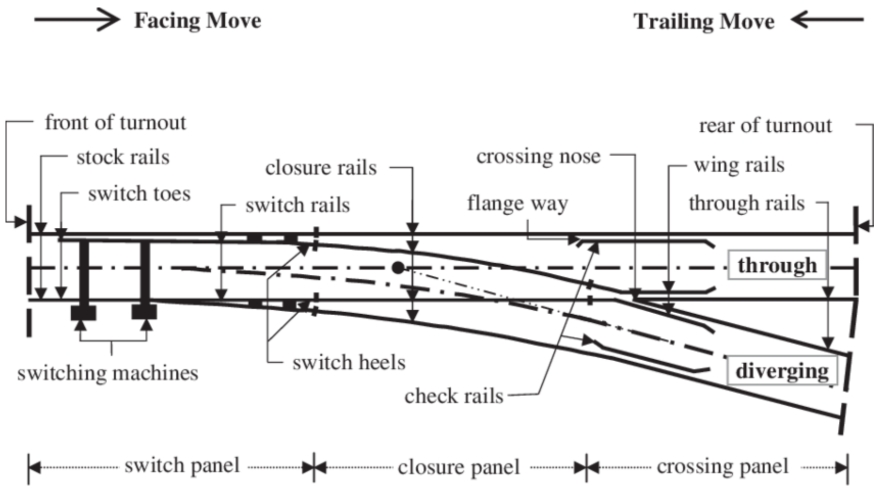

Figure 58: image descitption to added

Turnouts are critical components of railway infrastructure, and their condition is essential to ensuring the safe and efficient operation of trains. Traditional methods of turnout monitoring, such as visual inspection and manual measurements, are labour-intensive and time-consuming, and they can be unreliable.

An automatic inspection system, based in linear scanners, will be developed with the aim of carrying out three-dimensional reconstruction of train crossings. After creating detailed 3D models of turnouts, this information will be used to identify defects and track their development over time.

9.6.2 Description of the technology

The technology to develop aims to detect the health status of the crossing by means of 3D vision inspection system. The system would consist of two linear scanners mounted on the underside of a railway vehicle. The scanners would be arranged in a line, so that they could scan the turnouts as the train passed over them. The scanners would emit a laser beam that would reflect off the turnouts, and the reflected beam would be detected by the scanners. The data from the scanners would be used to create a 3D model of the turnouts.

The use of this technology to inspect train rails is widespread [53]. The advantage with the rails is that they have a very simple geometry, which facilitates the implementation of this technology. However, the aim is to extend this technology to inspect other rail assets such as turnouts. Currently, inspection of turnouts is made “by hand” by maintenance staff, using special rulers and portable measurement devices. This technology will allow automating these inspection tasks in an autonomous way. Ebadi et al. [54] already presented a paper where 3D scanning was used for the inspection of turnouts.

9.6.3 Methodology

In the methodology two different parts can be found; on the one hand the three-dimensional reconstruction of the turnout and on the other hand the analysis to identify defects.

9.6.3.1 Turnout 3D reconstruction

Line laser scanners are widely used in various industries for dimensional measurement and inspection of objects. These scanners project a laser line onto the surface of an object and capture the profile of the laser line using a camera.

The laser scanners will be placed on a vehicle that will travel on the railway track. The scanner returns a profile for each capture. To obtain the three-dimensional reconstruction of the turnout, all these profiles must be integrated into a 3D model. This requires knowledge of the relative pose of the scanner among all the captures. Two methods will be used to obtain this information:

- The vehicle will be equipped with a series of sensors that capture its speed and orientation. By synchronizing the information from these sensors with the instant of capture, an estimate of the relative pose can be made.
- If a 3D model of the turnout is available, this model can be used as the basis for the new reconstruction. This model can be the original CAD of the turnout or a reconstruction made during a previous inspection. Even if the shape is not exactly the same due to wear, this information is useful.

One aspect to consider is occlusions. The laser scanner can only reconstruct what it sees. However, the complexity of the geometry of the junction causes different areas to self-occlude. It is important to carry out an analysis to determine:

- The best position to locate the scanners.
- Determine that the part visible from that position gives sufficient information to identify defects.
- Identify the need for additional scanners.

9.6.3.2 Turnout health analysis

The geometry and operation of the turnouts causes that the defects are generated in specific areas. The type of defect in each area is different and has its own characteristics. This means that the algorithms to be developed to identify them must be adjusted to these characteristics.

Therefore, the first step is to identify the different areas where wear and defects appear.

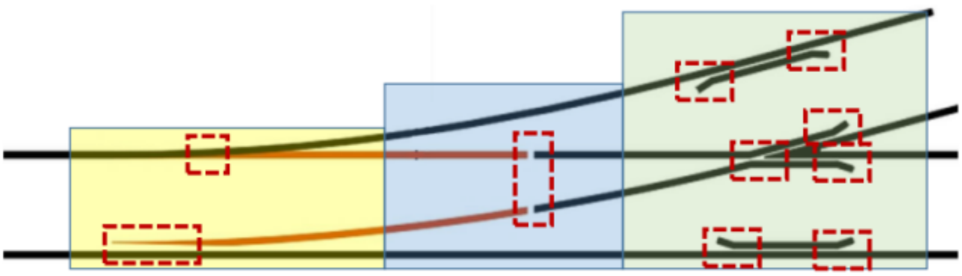

Figure 59: Components of a turnout (source Chalmers University, paper July 2010)

Once the different zones are identified, an analysis will be carried out to identify the defects associated with each zone.

The main errors will be wear and the way to identify and quantify it will be by comparing the 3D reconstruction with the original CAD model. Before the comparison can be made, a registration phase is necessary where the CAD model and the 3D reconstruction are positioned in a common coordinate system.

9.6.4 Description of the data

9.6.4.1 Input data used (simulations, measurements, technical information, etc.)

- Inspection system:
    - A series of profiles of the turnout. Each profile is a 2D point cloud.
    - Each profile will have associated with it a set of data resulting from the sensors integrated in the vehicle. The data will consist of velocity, orientation, etc.
- Auxiliary data:
    - A CAD model of the turnout or a previous 3D reconstruction of the turnout. The data type in both cases can be different. Normally, the CAD file will be stored in step format and the reconstruction will be a 3D point cloud.

9.6.4.2 Output data generated (simulations, results, etc.)

- 2D point clouds of selected turnouts (raw)
- 3D point clouds of selected turnouts (processed-reconstructed)
- A quantitative analysis of wear along the turnout

9.7 3D-modelling underground infrastructure: pipes & cables

9.7.1 Brief introduction to the application

This application focuses on visualizing available data related to pipes and cables. ProRail, as the asset manager of rail infrastructure and, consequently, of pipes and cables, distributes what are known as "KS-bladen." These are DGN drawings depicting the geometry of pipes and cables around the trackbed in a 2D format. Each DGN drawing is associated with a unique attribute value per cablebed, which contains multiple cables and pipes. Information about the specific cables and pipes within a cablebed is stored in a separate ProRail database.

Within this application, we consolidate all the diverse parameters and generate a 3D model of the pipes and cables surrounding the trackbed. Additionally, we enhance the cablebed information with a dataset of specific cables.

This application plays a crucial role in ERTMS deployment. By visualizing pipes and cables in 3D, it facilitates work preparators in planning the placement of ERTMS balises and prevents potential clashes with the existing infrastructure.

9.7.2 Description of the technology

Using the Ground Penetrating Radar data to enrichment data in a 3D-model of the underground infrastructure. In this 3D BIM model data from the Trackscan, Lidar is combined with cables and pipes data provided by ProRail. The GPR data is used to check the cables and pipes data, see yellow arrows in Figure 60.

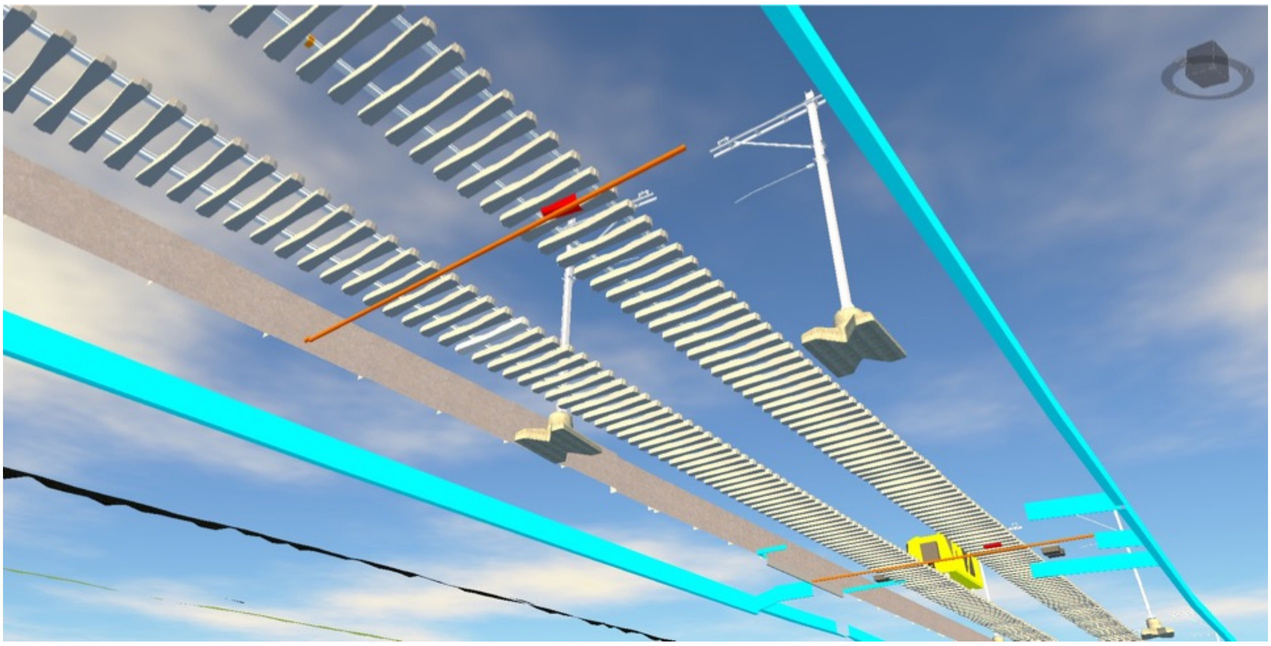

Figure 60: Underground objects visualised, example

9.7.3 Description of the Data

Use of existing data (drawings) compared with GPR data.

9.8 Track geometry measurement from passenger vehicle

9.8.1 Brief introduction to the application

Due to the need for a dedicated vehicle, track geometry measurement campaigns are performed few times in a year, or even after longer periods. If passenger vehicles are endowed with the ability to perform track geometry measurements, maintenance plans can be optimized while at the same time safety is increased due to early identification of track defects.

9.8.2 Description of the technology

The challenge in the application comes not that much from developing new technologies but from integrating them onto a passenger vehicle, building a system that can be almost autonomously operated, robust, and with proper measurement capabilities.

The technologies are based on usual railway industry sensors (like accelerometers, speed sensors, angular speed sensors, displacement sensors and corresponding conditioners) and recording and analysis devices, as well as communication system with the vehicle. Track geometry will be calculated by postprocessing acquired signals. The gap and the challenge arises from developing the needed hardware and software for giving any passenger train the ability to include the measurement capabilities, communication with vehicle, with data storage, data access and suitable user interfaces to access and analyse the data.

9.8.3 Methodology

The proposed methodology for the development of the system is:

1. Identification of parameters to be measured
2. Research on measurement techniques and technologies. Identification of adaptation process to a passenger vehicle.
3. Test runs for validation of proposed measurement methods from a non-Track Geometry Measurement Vehicle.
4. Off-line processing of pilot signals.
5. Characterization of measured geometry magnitudes compared against external measurements from Track Geometry Measurement Vehicle.
6. Definition of data management and communication modules to integrate the system onto the vehicle's normal operation abilities.

9.8.4 Description of the data

The data will consist of track geometry data:

I. Measured by the proposed adapted system
II. Measured by a Track Geometry Measurement vehicle

Considering the data sets from both origins, in addition, data of the comparison and characterization of the obtained geometry magnitudes will also be accomplished:

a) Repeatability
b) Reproducibility
c) Estimation of uncertainty of measurement

9.9 Drive/Detector rod monitoring

9.9.1 Brief introduction to the application

Drive and locking components are part of signalling and setting system of a turnout and thus highly safety critical. In the past maintenance teams reported repeated issues with defect detector rods in the drive / locking system. This application shall address this potential source of failure and increase the overall safety and availability of the turnout.

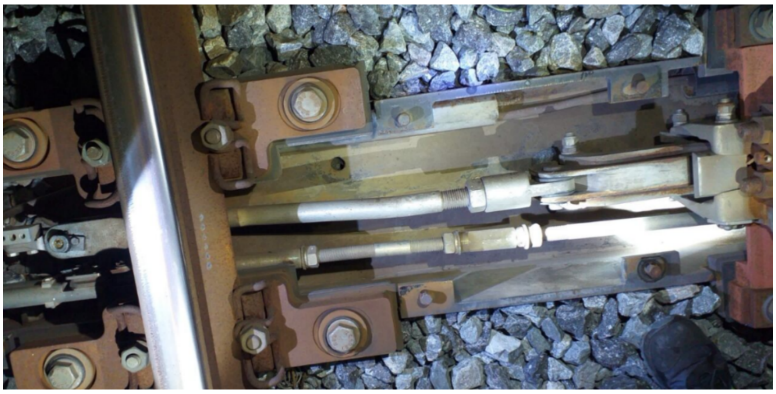

Figure 61: High Speed Line Turnout bars to be analysed

9.9.2 Description of the technology

The installed setting components are generally subjected to high dynamic loads which can induce significant vibrations. If these vibrations are superimposed with eigenfrequencies of the system, the excitation can lead to severe defects of the components. Therefore, the installed monitoring system will use high frequent structure borne noise measurements to monitor these effects, provide warnings with sufficient lead time and prevent component failure.

9.9.3 Methodology

A highly sensitive and high-frequent structure borne noise sensor will be installed in every setting level for monitoring of component vibrations. The data will be analysed in both, time and especially in the frequency domain. Found anomalies will be reported to the inspection and maintenance teams and compared to inspection and conventional measurement data. Dynamic simulations of the setting assembly will provide additional insights about stress concentrations in certain areas and the underlying damage patterns. Model based, as well as data driven analyses shall provide a comprehensive system understanding and component health state assessment for maintenance decision support.

9.9.4 Description of the data

9.9.4.1 Input data used

The application will use different types of data as input such as:

- Inspection and maintenance data reported by maintenance teams and measurement cars
- 3D models and dynamic simulations of the analysed components
- High frequent sensor data (structure borne noise)

9.9.4.2 Output data generated

The generated output data will include:

- Monitoring features and parameters from the monitoring systems
- Simulated system data such as forces, stress distributions and damage criteria
- Asset health state assessment

9.10 Switch assembly monitoring

9.10.1 Brief introduction to the application

This application refers to the position of the switch blades, as this parameter is crucial for a safe operation of the switch device. The system estimates the position, and respectively the gap between switch rail and stock rail, in order to detect and predict upcoming issues before the endpoint detector cannot achieve its end point and the track is blocked. This system reduces downtimes and enables predictive maintenance actions thereby increasing the overall availability of the track.

9.10.2 Description of the technology

The utilised technology is based on contactless inductive measurements. The sensors are placed in critical cross sections of the switch, namely the beginning and the nearest flangeway. A continuous monitoring of the switch rail position after every setting operation and train passage provides valuable information about the switch assembly health state and gives warnings if certain levels are exceeded.

Figure 62: Example of the inductive position sensor utilised for switch assembly monitoring

9.10.3 Methodology

The position of both (straight and diverging) switch rails is monitored after every switching operation as well as after every train passage. The estimated distances between switch- and stock rail are stored and evaluated for switch health state estimation and prediction of upcoming errors before the endpoint detector system is triggered and the track section is blocked.

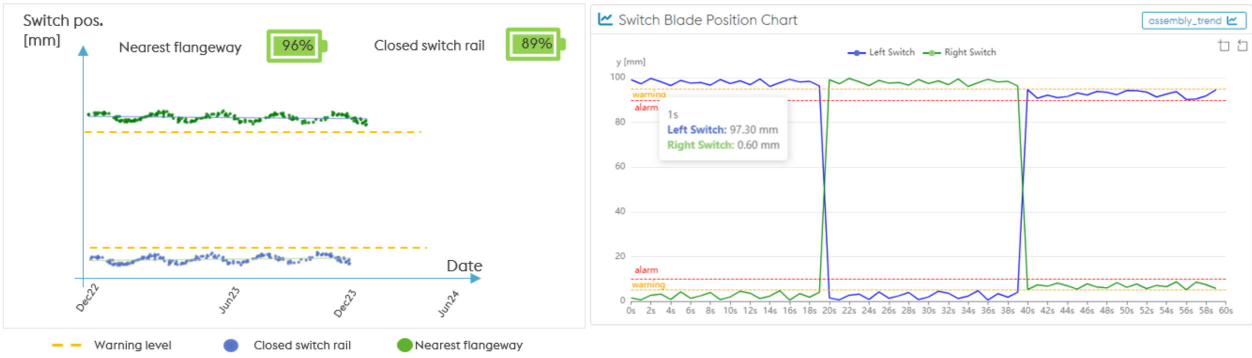

Figure 63: Long term and single transition analyses of switch assembly monitoring application

9.10.4 Description of the data

9.10.4.1 Input data used

The application will use different types of data as input such as:

- Inspection and maintenance data reported by maintenance teams and measurement cars
- Low frequency sensor data (switch rail position)

9.10.4.2 Output data generated

The generated output data will include:

- Monitoring features and parameters from the monitoring systems
- Availability of the switch
- Asset health state and fault allocation

9.11 Track quality monitoring

9.11.1 Brief introduction to the application

The track quality monitoring system estimates ballast degradation and detects upcoming voids. Track settlement and stiffness changes are a frequent problem in ballasted track and can increase the dynamic loads in the switch- and crossing area significantly. The increased loads, as a result, facilitate the degradation of other mechanical components such as rails, fasteners as well as the rolling stock components. Therefore, this system provides valuable information about the track condition in different regions of the turnout (switch and crossing area).

9.11.2 Description of the technology

The utilised technology is based on a multi sensor system which estimates the sleeper displacement and rotations of the component. This approach enables a detailed and multi-layer analysis of the asset health state and can detect various failure modes and defects.

Figure 64: Multi-sensor system used for track quality monitoring

9.11.3 Methodology

This application focuses mainly on ballast degradation, stiffness changes and upcoming voids in ballasted track. Therefore, a multi sensor system is used to estimate sleeper displacements and rotations of every passing axle which can be used for health state assessment and monitoring of the track quality. Besides, dynamic simulations of the analyse demonstrator will provide information about the structural system response and loads depending on different system parameters. Together with data from regular inspections the application will provide an asset health state assessment tool for a condition-based maintenance planning.

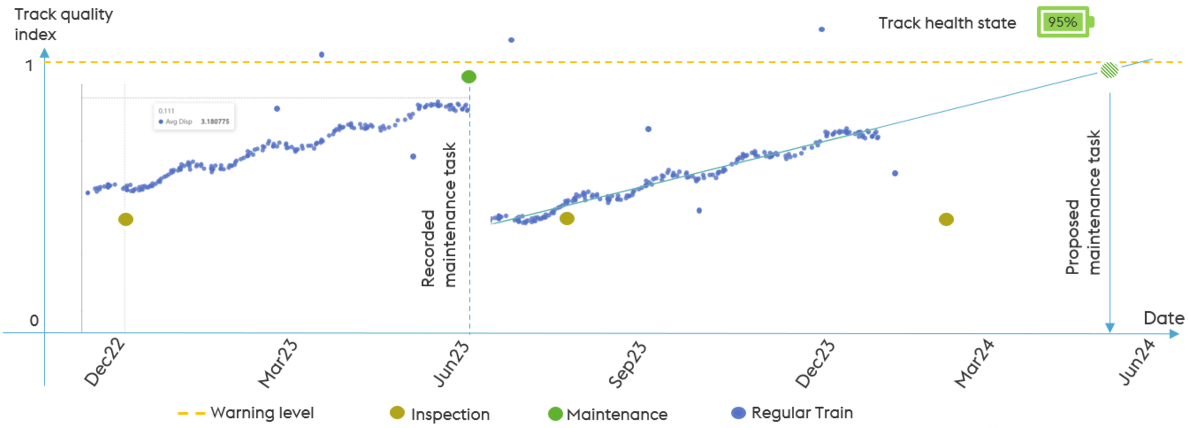

Figure 65: Long term track monitoring application

9.11.4 Description of the data

9.11.4.1 Input data used

The application will use different types of data as input such as:

- Inspection and maintenance data reported by maintenance teams and measurement cars
- High frequent multi-channel sensor data
- Dynamic simulation data (FE & MBD) of the analysed turnouts

9.11.4.2 Output data generated

The generated output data will include:

- Monitoring features and parameters from the monitoring systems

- Simulated structural response based on various system parameters for health state assessment
- Asset health state and proposed maintenance tasks

9.12 Frog / switch rail monitoring

9.12.1 Brief introduction to the application

This application addresses the degradation of rail components such as switch rails and (rigid and movable) frogs. As these components are subjected to high impact and creep forces, they are usually exposed to different damage mechanisms. The proposed system shall monitor the actual and predict the upcoming component health states in order to propose maintenance actions with sufficient lead time.

9.12.2 Description of the technology

The utilised technology for this application is based on a multi sensor system providing motion and vibration data. This approach enables the monitoring of different damage patterns on various component by a single system. The introduced sensor system can be mounted on the rails in critical areas where high dynamic loads can be expected and damage is likely to occur.

Figure 66: Multi-sensor system used for frog / switch rail monitoring

9.12.3 Methodology

The vibration and motion data are captured and analysed in both time and frequency domain in order to estimate structural changes in the monitored component. The high bandwidth of the multi sensor system facilitates the coverage of different damage patterns such as RCF, wear and plastic deformation. The gathered data is subsequently evaluated and translated to a component condition index which serves for service life assessment and prescriptive maintenance tasks.

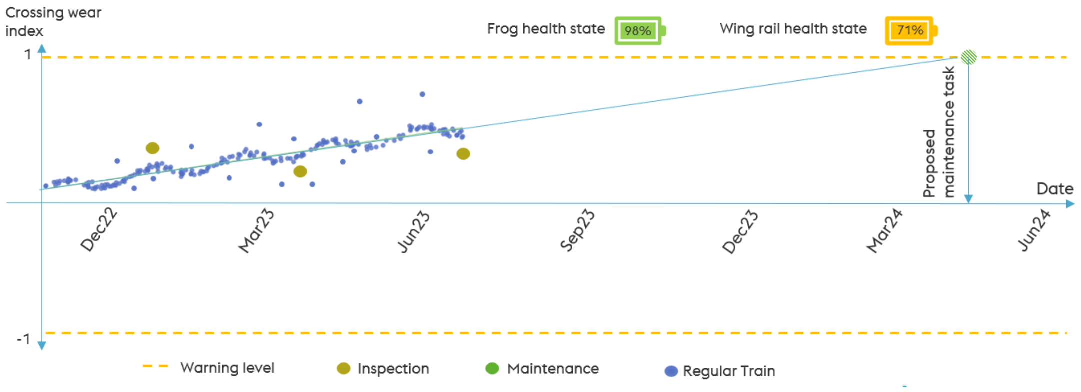

Figure 67: Long term trend of frog / switch rail monitoring application

9.12.4 Description of the data

9.12.4.1 Input data used

The application will use different types of data as input such as:

- Inspection and maintenance data reported by maintenance teams and measurement cars
- High frequent multi channel sensor data
- Dynamic simulation data (FE & MBD) of the analysed turnouts or components

9.12.4.2 Output data generated

The generated output data will include:

- Monitoring features and parameters from the monitoring systems
- Simulated loads and stress distributions for health state assessment
- Asset health state and proposed maintenance tasks

10 CONCLUSIONS

Work Package 10 (WP10) and Work Package 11 (WP11) are interrelated and work together within Cluster D of FP3-IAM4RAIL, focusing on Infrastructure Asset Management. WP11 primarily handles the development tasks, including demonstrating applications initially conceived in WP10, specifically for the multi-source/multi-purpose (MSMP) asset management platform. Together, WP10 and WP11 form a cohesive unit within Cluster D, which also includes other components like long-term maintenance and costs (WP8), track systems (WP9), and civil assets (WP12 and WP13).

Work package 10 aims to deploy innovative rail infrastructure asset management solutions in an operational environment. These solutions build upon previous EU projects like IN2SMART and IN2SMART2 but elevate their application to a higher level of maturity. The focus is on "short-term asset management" and off-site work preparation, integrated as a Multi-Source/Multi-Purpose (MSMP) asset management platform.

This deliverable's goal is to present an initial High-Level Architecture outlining WP10's approach. Task 10.1, named "Requirements and System Architecture for MSMP initial developments," focuses on defining requirements and scope. It aligns with user expectations and leverages insights from previous Shift2Rail projects like In2Smart and In2Smart2. This deliverable encompasses the outcomes of Task 10.1, including high-level system architecture, approach, technology utilization, introduction of planned applications, and the identification of pilot locations in Spain and the Netherlands, along with relevant available data.

The MSMP Integrated Asset Management System (IAMS) provides a framework which enables the fusion of all relevant information provided by all involved stakeholders to support the day-to-day decisions of the maintenance experts and asset managers. This comprises information about actual and historic asset condition, maintenance activities and loading. Basis of the MSMP IAMS is the continuous, automatic condition monitoring during ongoing railway operations based on embedded vehicle-borne and wayside sensors. Easy-to-use decision support tools feed with reliable and traceable diagnostic and prognostic information are the interface to the individual asset managers. In between, at the heart of an MSMP IAMS, are self-learning anomaly detection, diagnostic and prognostic models based on sophisticated algorithms and artificial intelligence including unsupervised and supervised machine learning as well as reinforcement learning.

The MSMP Integrated Asset Management System (IAMS) is designed to amalgamate crucial information from all stakeholders to aid maintenance experts and asset managers in their daily decisions. This encompasses details about both current and historical asset conditions, ongoing maintenance activities, and load status. The core of MSMP IAMS lies in continuous, automated condition monitoring during active railway operations using embedded sensors on vehicles and along the tracks. The system incorporates user-friendly decision support tools, providing asset managers with dependable diagnostic and prognostic data.

The high-level system architecture involves several components: onboard and wayside systems, diverse data sources, data integration, analytics, decision support, planning and execution, and visualization. Onboard systems refer to vehicle-installed components like sensors and communication devices. Wayside systems encompass infrastructure along the tracks, such as signals and trackside sensors. Other data sources encompass external databases, weather information, and third-party systems. Data integration involves the aggregation and harmonization of data for comprehensive analysis. Analytics involves extracting insights from the integrated dataset. Decision support tools aid informed decision-making based on generated insights. Planning and execution functionalities involve task scheduling, resource allocation, and coordination. Visualization presents data and analytics results in a visual format for easier interpretation. This high-level architecture likely pertains to a complex system, such as railway or transportation management, integrating diverse data sources, employing analytics, and supporting informed decision-making for efficient operation planning and execution.

The approach we adopted established a strong foundation for organising and structuring the tasks within the specific work package. This approach allowed for a flexible framework where different pieces of work could be effectively carried out by various partners, emphasizing collaboration, and leveraging two distinct locations (Spain and the Netherlands). While each individual task receives sufficient focus, the framework ensures a cohesive approach, leading to an integrated system through a modular methodology.

In addition to establishing a robust foundation for a cohesive system, this approach serves as a cornerstone for fostering collaboration with other work packages and flagship projects. It sets the stage to ensure that practical outcomes from these other developments seamlessly integrate into our ongoing efforts.

Achieving high Technology Readiness Levels (TRLs) within the project can pose challenges, particularly when implementing novel technologies. Striking a balance between immediate practical applications and delving into research activities to explore the untapped potential within the vast array of data generated is crucial. This is especially true when integrating diverse data sources.

By ensuring access to operational usage, we can advance towards higher TRLs while simultaneously incorporating researchers into our team. Their involvement enables us to tackle more intricate challenges and contribute to the innovation pipeline by incorporating results at lower TRLs into the next developmental phase. This synergy between practical application and research-driven exploration enhances the project's overall progress and potential.be addressed and feeding the innovation pipeline with lower TRL results for the next phase.

This deliverable serves as a comprehensive representation of the progress achieved within the scope of Work Package 10 up to this point. It encapsulates the successful completion of tasks and milestones set out in the project for the first ten months. This aligns with the stipulations laid out in the grant agreement, specifically for Deliverable D10.1 and its corresponding Task 10.1, indicating an alignment to the project's established guidelines and goals.

The forthcoming actions involve a sequential process. Initially, data acquisition will be carried out using various technologies. Following this, an in-depth analysis of the collected data will be conducted, and efforts will be dedicated to developing the suggested applications.

Furthermore, the project will entail an exploration of latent opportunities within the data. This exploration will involve integrating data from multiple sources and closely relating it to real-world challenges that arise in the daily maintenance of infrastructure. The aim here is to identify potential solutions for addressing these issues at an early stage.

Importantly, this process represents an interactive synergy between research activities and the practical aspects of infrastructure maintenance. It underscores the dynamic interplay between theoretical investigation and the real-world demands and challenges faced in the daily practice of infrastructure maintenance.

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Appendix 1 Intdemo #4: Asset Management & Infrastructure

In the Grant Agreement seven integrated demonstrators are mentioned. WP10/11 contributes to integrated demonstrator #4: Asset Management & Infrastructure. This demonstrator is defined in the table below:

Main objective (see section 1.1.1.4)		**DO4: To develop new monitoring and inspection systems for infrastructure assets**
Technical objectives covered. (see section 1.1.1.2)	-	- TO1: information sharing between IAMS and TMS - TO2: monitoring and inspection systems for infrastructure - TO4: leveraging infrastructure asset diagnosis (inc. anomaly detection and failure prediction) for prescriptive analytics for decision support. - TO5: Digital Twins integrated with BIM. - TO8: preparation work in view of future demonstrators
Capabilities addressed	-	- Information sharing across the supply chain and TMS. - Unmanned and non-invasive monitoring and inspections - Advanced and holistic asset decisions
Link to technical enablers	-	- Enabler 1: exchange information (e.g. health condition of infrastructure assets) between IAMS and TMS o Data exchange (secure standardised interfaces, methods, and processes) o edge computing solutions coupled with secure communication networks. - Enabler 2: asset diagnostic and inspection systems, including. o AI solutions and ML algorithms to analyse and combine information provided by different inspection systems o precise timestamping, synchronization, and accurate positioning for data integrity o energy-efficient solutions - Enabler 4: new methodologies and technologies to leverage advanced and holistic asset decisions. o Operational and IoT data to enable cooperative diagnostic between assets. o AI-based hybrid decision support based on predictive and prescriptive data analytics. - Enabler 5: interface between BIM and design models

<table>
<tr><th>Expected results</th><th>Related WPs</th><th>KPIs</th><th>Means of verification</th><th>Link to FAs</th></tr>
<tr><td>Practical solutions for sensing superstructure system components (inc. intelligent sleepers, ballast, rail, and contact lines)</td><td>WP9, WP10 & WP11</td><td rowspan="3">- reduction of maintenance costs up to 10%
- 25% reduction of in-service failures</td><td rowspan="3">Algorithmic and statistical approach over the demos operational time

- Maintenance expenditures accounted comparison with baseline in similar periods of time.
- Control of percentage for number of affected trains (according to PRIME affected train (by an asset failure) definition)) SIS-EN 13306:2010</td><td>-</td></tr>
<tr><td>Practical solutions for infrastructure monitoring using optic fibre</td><td>WP9</td><td>-</td></tr>
<tr><td>New approaches for track geometry and S&C condition, including new methods for existing data, new sensing solutions, and with validation campaigns using existing and on-board measurements coming from passenger trains</td><td>WP9, WP10 & WP11</td><td>-</td></tr>
</table>

Expected results	Related WPs	KPIs	Means of verification	Link to FAs
in operation or dedicated diagnostic trains				
Prescriptive maintenance of railway infrastructure (inc. passenger, mixed traffic and freight lines)	WP9			FA1
Adaption and new development of Track Infrastructure standards, rules & regulations, and a new technical railway standard for Distributed Acousting Sensing (hardware, algorithm and data aspects)	WP9			-
Multi-sensor / Multi-source monitoring of tracks, surrounding and switches for short-term asset management	WP10 & WP11			-
Multiscale monitoring of civil assets: satellite, aerial and UAV data collection and processing approaches, ground data collection strategies, data analysis methodologies and verifications and user data browsing platform	WP12 & WP13			-
Bridges and earthworks asset management aided by geotechnics: earth observation and ground data acquisition and processing, and algorithms and platform for asset management	WP12 & WP13			-
Monitoring and predictive maintenance of tunnels, sub-ballast layers, and subsoil	WP12 & WP13			-

Appendix 2 Linking (new) monitoring technologies to asset management issues

This use case contributes to demonstrator #4 (Asset Management & Infrastructure) of the project by serving as the first step in implementing new sensor technologies in an operational rail environment. It aims to assess the feasibility and effectiveness of integrating these technologies into the existing asset management framework.

The use case focuses on linking (new) monitoring technologies to asset management issues in an operational environment. It involves deploying the sensors on the rail infrastructure subsystems, including wayside and onboard sensors, to gather diagnostic and prognostic information. By utilizing these sensors, the project aims to provide traceable data for continuous asset condition monitoring, enabling maintenance experts and asset managers to make informed decisions. By conducting experiments and data analysis, the use case helps identify potential challenges that may arise from the deployment of new (embedded) monitoring systems. It serves as a crucial groundwork to identify specific asset issues that can be identified, possibly at an early stage and being able to predict its evolvement and plan timely interventions.

By exploring and analysing the data collected from the new sensor technologies, the use case aims to identify relevant patterns and insights that can address specific asset management issues. This helps bridge the gap between the potential of the new technologies and their practical implementation in the rail industry. The use case also demonstrates the interoperability and cross-border applicability of the solutions by conducting early demonstrations in different operational scenarios across EU member states.

Overall, this use case plays a crucial role in the demonstrator of the project by laying the foundation for the integration of new sensor technologies in the rail infrastructure. It helps assess the compatibility, effectiveness, and potential challenges of these technologies in an operational environment. The insights gained from this use case will inform subsequent steps and developments in the project, leading to further advancements in asset management practices and ultimately improving the performance and reliability of the rail infrastructure subsystem.

Overall aim of the use case

Problem to be solved

The problem to be solved is the assessment of how new monitoring technologies can contribute to existing and critical asset management issues in the rail industry. While these technologies offer potential capabilities in detecting specific issues, their integration and usage may introduce unforeseen challenges and complexities. To fully understand the insights provided by the data collected through these monitoring technologies, experimentation and data analysis are necessary. For example, axle box accelerometers may reveal both rail wear and rail geometry issues, while ground penetrating radar could identify ballast problems as well as unexpected issues like badger burrows. It is crucial to leverage data experiments and the expertise of data scientists to uncover the comprehensive range of asset management issues that can be addressed by these technologies. The problem to be addressed is identifying patterns that can be seen and linking them to specific issues.

Industry current position / baseline

The baseline for monitoring solutions in the rail industry varies for each technology, while some technologies may have no prior experience or relevant tests in the rail sector, others may have limited experience in addressing specific issues while remaining unexplored for other issues. This means that the latent potential of some technologies is often unexplored. While some sensors may initially appear expensive in relation to their perceived benefits, the industry recognizes that their true value lies in serving multiple asset management issues. Currently, asset management processes heavily rely on traditional inspection methods and limited data sources, leading to suboptimal decision-making, inefficient resource allocation, and increased maintenance costs. However, by effectively integrating new monitoring technologies, the industry aims to overcome uncertainties and risks, unlock their full potential, and enhance asset management practices. This proactive approach allows for the comprehensive utilization of the data gathered, enabling the detection of relevant patterns and insights that can highlight underlying asset management issues. By harnessing the capabilities of these technologies, the rail industry can optimize maintenance planning, minimize disruptions, and achieve cost benefits that surpass their initial perceived expenses. Ultimately, this integration will lead to improved asset performance, enhanced safety, and increased operational efficiency.

Subproblem addressed by the use case and measurable objectives

The use case addresses the subproblem of identifying and addressing asset management issues that will be enabled by the integration and combined usage of new monitoring technologies. The measurable objectives include:

a) The use case addresses the subproblem of identifying and addressing asset management issues that will be enabled by the integration and combined usage of new monitoring technologies. The measurable objectives include:
b) Experimenting with the data collected from the new monitoring technologies to identify relevant patterns and insights related to asset management.
c) Leveraging the expertise of data scientists to analyse the data and detect potential issues or challenges that may impact asset management processes.
d) Developing a deeper understanding of the relationship between the data generated by the monitoring technologies and the asset management objectives.
e) Identifying specific asset management issues that can be addressed through the integration of new monitoring technologies and proposing suitable solutions.
f) Assessing the feasibility and effectiveness of integrating the new monitoring technologies into the asset management framework through pilot projects or demonstrations.

Influence of the proposed innovation on the IM/RU problem

The proposed innovation of linking new monitoring technologies to asset management issues addresses not only the rail infrastructure manager's problem but also caters to the needs of various users, such as engineering companies and maintenance service providers. By proactively identifying and mitigating potential challenges and risks, this innovation benefits multiple stakeholders involved in asset management. Through data experimentation and collaboration with data scientists, the innovation enables the detection of relevant patterns and insights that unveil underlying asset management issues. This proactive approach empowers the industry as a whole to anticipate and tackle these issues before wider deployment, resulting in minimized disruptions, optimized maintenance planning, and reduced costs. Ultimately, this innovation empowers rail infrastructure managers, engineering companies, and maintenance service providers to make informed decisions based on a comprehensive understanding of asset conditions. This comprehensive approach leads to improved asset performance, enhanced safety, and increased operational efficiency, benefiting all stakeholders involved in the rail ecosystem.

Definition of KPIs

The KPI is defined as[12]:

$$KPI2 = \frac{\#\ of\ anomalies\ diagnosed\ by\ algorithms\ and\ confirmed\ in\ ground\ truth\ data}{\#\ of\ anomalies\ in\ ground\ truth\ data} \times 10$$

[12] This version of the KPI is still under review.

Appendix 3 Fusion of monitoring data for an enhanced fault detection and diagnosis

This use case contributes to demonstrator #4 (Asset Management & Infrastructure) of the project by focusing on the fusion of onboard and wayside monitoring data – and potentially other sources – to improve fault detection and diagnosis in the rail infrastructure subsystem. The objective is to develop a holistic monitoring environment that exploit multi-sensor and multi-vehicle modular architectures, combined with advanced algorithms and models, to enable enhanced fault detection and diagnosis capabilities. The use case aims to demonstrate the effectiveness of fusing data from different sources for more accurate and timely detection of faults, leading to improved maintenance decision-making.

OVERALL AIM OF THE USE CASE

PROBLEM TO BE SOLVED

The problem at hand is the limited effectiveness of current fault detection and diagnosis methods in the rail industry, as existing monitoring systems rely on either onboard or wayside sensors, providing only a partial view of asset condition. This limitation hampers accurate and timely fault detection, leading to increased maintenance costs, operational disruptions, and potential safety risks.

This use case addresses the problem by focusing on the fusion of individually tested data sets from onboard and wayside monitoring solutions. The main objective is to combine these data sets to confirm and enhance the accuracy of findings for specific asset issues, while also identifying new asset issues through the utilization of combined data. The approach involves integrating and analysing data from various monitoring sources to improve fault detection and diagnosis in the rail infrastructure subsystem.

By combining data findings and utilizing advanced algorithms and models, the use case aims to develop comprehensive and effective solutions for maintenance decision-making. This requires the application of new data analytics techniques to handle multiple data sets of different kinds and nature. Through this use case, valuable insights will be gained on how to approach the integration and analysis of diverse data sets, leading to improved maintenance strategies and the overall readiness of the technology for real-world implementation in the rail industry.

INDUSTRY CURRENT POSITION / BASELINE

Currently, fault detection and diagnosis in the rail industry heavily rely on manual inspections, periodic maintenance activities, and limited sensor data. These approaches are time-consuming, labour-intensive, and may not capture subtle or intermittent faults. Additionally, there is a lack of integration between onboard and wayside monitoring data, limiting the overall effectiveness of fault detection and diagnosis.

Furthermore, the industry has not fully leveraged the potential of combining data sets from different sources, and the application of modern data analytics techniques is still relatively new. This means that the industry has yet to explore the benefits of utilizing advanced algorithms and models to analyse and interpret the combined data. By overcoming these challenges and embracing the integration of data sets and modern data analytics, the rail industry can significantly enhance fault detection and diagnosis capabilities, leading to improved maintenance practices, more efficient resource allocation, and ultimately, safer, and more reliable rail operations.

SUBPROBLEM ADDRESSED BY THE USE CASE AND MEASURABLE OBJECTIVES

The use case addresses the subproblem of fusing onboard and wayside monitoring data to enhance fault detection and diagnosis in the rail infrastructure subsystem. The measurable objectives include:

a) Developing monitoring systems that utilize multi-sensor and multi-vehicle modular architectures for data acquisition, this includes collecting the data from the different sources and matching the different data sets based on the asset, the location, and the time.
b) Implementing advanced algorithms and models for fault detection and diagnosis, leveraging the fused data from onboard and wayside sensors as well as additional relevant information.
c) Demonstrating the capability to assess the health condition of turnouts through anomaly detection and early prediction of failures.
d) Developing decision support tools based on unsupervised, supervised, and reinforcement learning approaches to aid maintenance decision-making.
e) Achieving higher TRL (Technology Readiness Level) for the developed fault detection and diagnosis solutions, indicating their readiness for real-world implementation.

INFLUENCE OF THE PROPOSED INNOVATION ON THE IM/RU PROBLEM

The proposed innovation of fusing onboard and wayside monitoring data for enhanced fault detection and diagnosis greatly improves the rail infrastructure manager's ability to identify and address faults in a timely and accurate manner. By integrating data from multiple sources, the innovation provides a more comprehensive view of the asset condition, enabling the detection of subtle or intermittent faults that may otherwise go unnoticed. This allows for proactive maintenance interventions, reducing the risk of asset failures, minimizing operational disruptions, and improving safety. The application of advanced algorithms and models further enhances the accuracy and reliability of fault detection and diagnosis, enabling maintenance experts to make informed decisions and optimize maintenance planning. Ultimately, the innovation improves the overall asset reliability, reduces maintenance costs, and enhances the operational performance of the rail infrastructure subsystem.

Definition of KPIs

The impact of this Use Case is aligned with the general KPIs that apply to the demonstrator #4 (Asset Management & Infrastructure)

- Reduction of maintenance costs up to 10%
- 25% Reduction of in-service failures

To contribute to those high-level KPIs, the following specific KPIs are proposed for this Use Case:

- Detection of anomalies

- Diagnosis of anomalies

KPI1 - <Detection of anomalies>

Short description

Sensitivity of the anomaly detection algorithms, i.e. the amount of anomalies detected by the algorithms with regards to ground-truth datasets.

How to compute KPI1

$$KPI1 = \frac{\#\ of\ anomalies\ detected\ by\ algorithms\ and\ confirmed\ in\ ground\ truth\ data}{\#\ of\ anomalies\ in\ ground\ truth\ data} \times 100$$ [13]

KPI2 - <Diagnosis of anomalies>

Short description

Sensitivity of the anomaly diagnosis algorithms, i.e. the amount of anomalies diagnosed (e.g. classification and severity) by the algorithms with regards to ground-truth datasets.

How to compute KPI2

$$KPI2 = \frac{\#\ of\ anomalies\ diagnosed\ by\ algorithms\ and\ confirmed\ in\ ground\ truth\ data}{\#\ of\ anomalies\ in\ ground\ truth\ data} \times 100$$ [14]

[13] Still under review
[14] Still under review

Appendix 4 Leonardo on-board monitoring platform

The content of this appendix derives from D12.3.

The Leonardo platform has three main systems:

1 Geocondao video
2 Lidar met 360 camera
3 Track scan

I: Geoconda Video System

The Geoconda video system consists of 2 sets with 2x 360-degree cameras and 6x flat image cameras with which 8 different camera angles are realized on both ends of the Leonardo. Depending on the direction of travel, the viewpoints "Leonardo front" or "Leonardo back" are used for making video images.

Camera's

We currently use 2 types of action cameras;

Sony RX0 II

- Exmor RS Cmos-sensor, 15,3 megapixel (4K), 1 inch
- Video resolution 3840×2160
- Sensitivity ISO 125-12800
- Image size H264
- Lens 24 mm F 4
- Micro SD 256 of 512 GB

The Sony cameras are set to 25 or 50 fps depending on their position on the Leonardo. During daytime shooting, the ISO is automatic and the shutter speed is 1/2000, 1/3200 or 1/10,000. During shooting at night, the ISO is at 12,800 and the shutter speed is automatic.

Figure 68: SONY RX0 II

Garmin VIRB 360

- Video resolution 4K/30FPS, in camera stitched
- Spherical stabilisation

- Picture view 360 degrees, vertical and horizontal

Figure 69: Garmin VIRB 360

Camera control

On the Leonardo platform are 2 wifi networks: "Leonardo front" and "Leonardo Back". The cameras are linked via this Wi-Fi network to tablets (Ipad and Samsung S10) both running the camera apps Garmin VIRB and Sony Imaging Edge for setting up, controlling, and monitoring the cameras.

The video images are stored on Micro SD (256 or 512 GB) cards in the cameras.

Camera perspectives / view points:

On both ends of the Leonardo, the following 8 camera views are in use:

1) Left 360
2) Train driver perspective
3) Right 360
4) Left side
5) Track
6) Right side
7) Overhead wire left
8) Overhead wire right

Figure 70: Camera views front of the Leonardo

Mobile Geoconda videosystem:

In some parts of the network (Netherlands), the Leonardo cannot or is not allowed to drive because of train detection system. In that case the Leonardo is used in combination with a locomotive or the measurement systems are mounted on a rail-road vehicle. For this magnet tripods are developed that are equipped with USB power banks. In combination with 2 mobile Wi-Fi routers, recordings can be made for 2 days in a row. The mobile Geoconda video system is often combined with the mobile Lidar or the Trackscan.

Data postprocessing

A day of video recordings generates at about 1.5 TB of data. Postprocessing is needed before the user can see the images in the Geoconda viewer. The postprocessing consists of compressing the data from H264 to H265. This reduces the data by cá 80% to 300GB. In the video files, every 5 frames an additional key-frame is placed. This is a frame with the full picture. The use of additional key frames allows the user to navigate through the video images faster.

The GPS signal is used to retrieve the related track location data from a database so that the corresponding video images can be linked to the rail mileage at frame level. This is done with the help of files recording the trip.

If the user clicks on a drive (trip), the correct video images are streamed together with the correct track location.

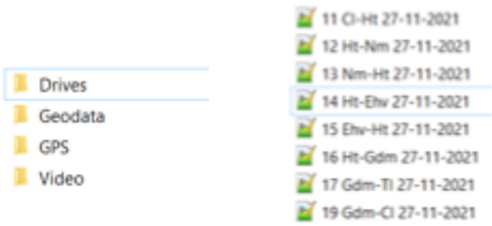

Figure 71: Navigation through the trips

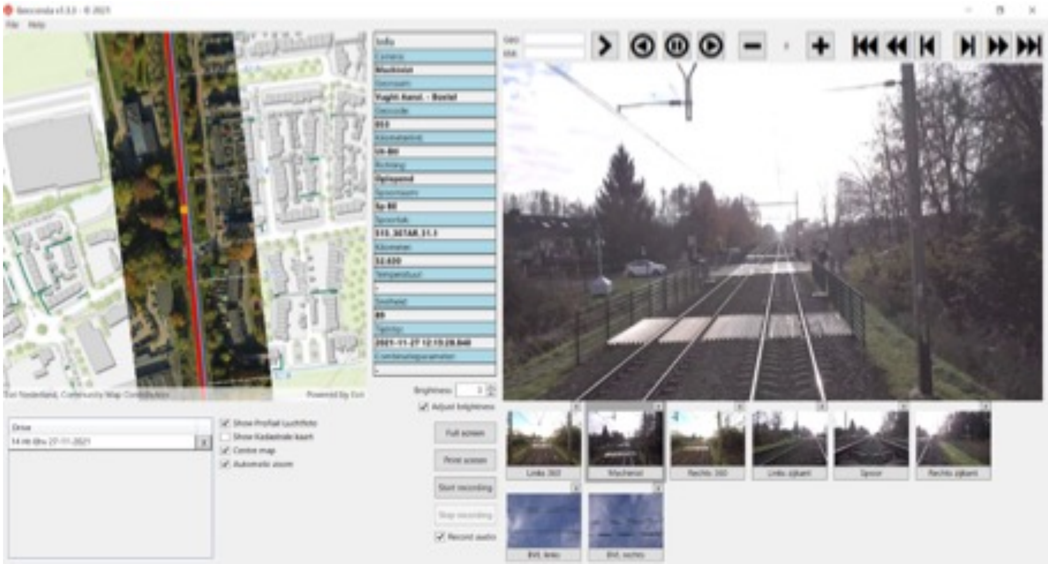

Figure 72: Geoconda viewer trip 14 Ht-Ehv 27-11-2021

1) A list of the selected inspection trips
2) The Rail map with the (red) selected trip, the yellow dot is the track location of the video images. When the video is played, yellow stop on the rail map runs with it. In the rail map, information layers can be made visible, such as the aerial photos of ProRail.
3) The track location information, when was driven and which camera is selected in the main screen.
4) The available camera views on this ride. By clicking on the name of the camera you can switch images that are visible in the main screen (5).
5) The main screen with video image of the selected camera. The main image can also be viewed full screen and zoom in.
6) The video exposure can be increased or decreased in case the video images are too dark or too light. A print screen can also be made in which arrows, circles or texts can be drawn in the image. The print screen can be saved as JPG or PDF in a preselected folder.

Users

The Geoconda viewer is used in all steps of the work process, for example for; the calculation, engineering, work preparation, inspections and delivery of work carried out.

The users had an important role in the development of the functionality of the Geoconda viewer: only based on their feedback further development could take place leading towards usable and practical results.

Their feedback also extended the possible usage of the data obtained, for example to recognize invasive plant species that grow along the track and need to be removed and exterminated to avoid serious damage to track and surroundings, like the Japanese knotweed[15] or the giant

[15] Japanese knotweed is an invasive non-native species. Prompt action to deal with knotweed is necessary where it affects safe operation of the railway. See guidance of Networkrail.

hogweed. Models have been trained with which invasive exotics such as the giant hogweed can be recognized. If an object is recognized, a photo is taken and stored with the GPS data.

Figure 73: Recognition Giant Hogweed in the camera view "Right side"

Object recognition

Various types of track objects or even rail welds can be recognized.

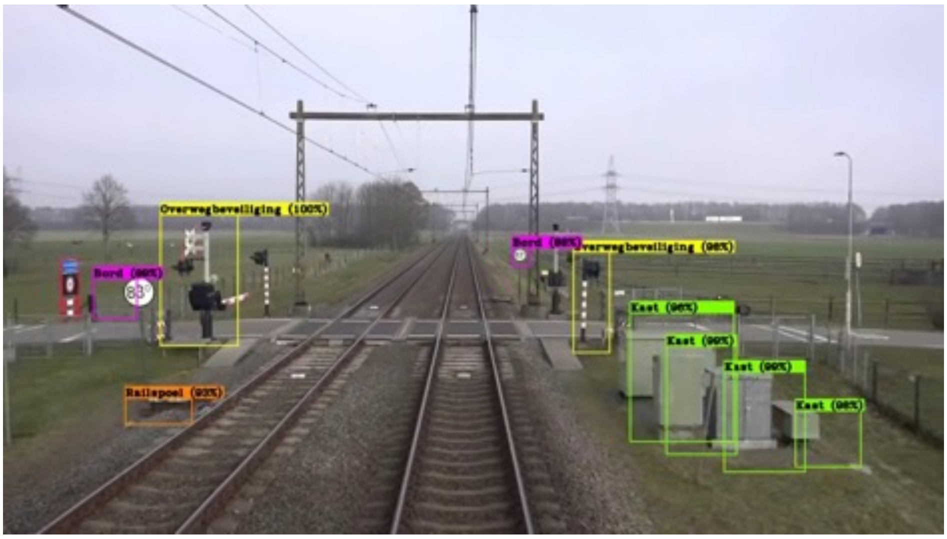

Figure 74: Track objects recognized in the image of the camera view "Train driver"

Figure 75: Thermite weld recognized in the camera view "Track"

II: Lidar System

In 2021, the Leonardo will feature a calibrated Lidar system lidar Velodyne, 360 degree camera (Flir Ladybug) and an Applanix POS LV box. Velodyne's lidar generates point clouds. With the Ladybug (equipped with 6 cameras) photos are made that are software-based to a 360-degree photo. With the Applanix box the GPS position is recorded. The calibrated Lidar system is mounted on the Leonardo. The Leonardo is an old stopping machine (CSM) that is no longer used as a stopping machine.

The calibrated Lidar system can be slid onto the Leonardo within 5 minutes by means of a sled construction. The CSM is equipped with measurement targets with the aim of being able to place multiple sensors in a calibrated environment.

The systems were mounted on the CSM in the workshop in Zutphen. The system has been tested on the free track and adjustments have been made where necessary. The delivery arms of the various systems have been measured and further optimized and recorded by means of postprocessing. Fine-tuning the system took a lot of effort. The combination of the Track Scan, the separate cameras and the lidar system has been further developed and the two Applanix boxes (Track Scan and lidar system) are coordinated with each other through the measurement targets.

Additional new systems can be placed on the vehicle without any extra effort. The heart and direction of the systems must be recorded surveying in relation to the existing targets.

The lidar system is connected to a laptop. The laptop is in a suitcase. The case is mounted under the lidar system. The data is stored on the hard disk. By means of a connected tablet, the software is operated on the computer.

Practice shows that the operation and connection of the tablet to the computer is unstable. Loss of connection between the tablet and the computer can sometimes occur while driving. After a lot of testing, it was decided to move the laptop to the cabin of the CSM. This requires new and longer cables. A number of tests were carried out to mount the new and longer cables. The results of the tests are that the new cables and lengths are insensitive to failure. The new cables are mounted on the CSM and space for the laptop has been created in the cabin.

After performing several test drives at various speeds, the collected data was analyzed for positioning and point density. Combining the Track Scan and Lidar data is possible if the post-processing for both systems is carried out with one and the same parameters.

After processing the data, the development of products started. Products that are under development are the digital generation of laying plans, contact wire height, hanging wires, scope determination and analysis of contractual differences.

Objective

The objective for Strukton is to record the absolute position of the objects along the track, to calculate quantities of objects, to carry out release inspections and to calculate distances to determine the amount of work for maintenance and new construction work.

Input needed input

Internally Strukton, the objective question is to provide real-time correct absolute 3D data of the rail environment. With the supplied data, analyses are made for the correctness of the management and contract environment. We record the deviations in Relatics and are communicated with the execution and the client. It is expected that Strukton will be able to acquire and deliver the contracts to be procured and realised with more margins. The risks are transparent and the quality can be optimized.

Output

The development is the digital measurement of the overhead line hanging wires (figure 1). The research shows that the existing length of the hanging wire can be measured in a photo. The measured accuracy at 60 km/h is between 0 and 5 cm. At a speed of 40 km/h, the measurement accuracy is between 0 and 3 cm. The tolerance is currently insufficient because the hanging wires may have a maximum measuring tolerance of 1 cm. A new test to be carried out with a 150-megapixel camera is included in the planning for mid-2022. The expectation is that this camera will deliver the desired accuracy. In case of positive result, image recognition software must be trained to automatically generate the length of the hanging wires. Automatic measurement from 3 points of view is then a must. Measuring manually from the photo is now too laborious. The point cloud from the lidar can support the photo.

Figure 76: measuring length of hanging wires

For the other products that Strukton can generate, a measurement tolerance of 5 cm is now sufficient. In particular, making a digital laying plan is possible with the data from the Leonardo.

Generating automatic laying plans from the track scan and checking with the lidar is now possible. The track scan generates a laying plan by using image recognition software. The image recognition software is trained and can now recognize objects itself and load symbols at the absolute location (x,y,z). With the geo-referenced 360 degree photo and the lidar, the outcome can be checked. In the software (Digispoor) the automatically generated laying plan can be shown as a shapefile. The absolute location of the two systems correspond to each other. The differences can be tested as a 4-eyes principle and recorded as verification.

The next test is the use of RTK. With RTK, the postprocessing step can be skipped. The absolute accuracy with RTK is 1.5 cm. The required software package and the work process must be adjusted accordingly. The advantage of using RTK is that the point cloud can be generated in real time. This has major advantages for demonstrating the safe rideability of the track. Projects that take place in a decommissioning can thus safely put the railway into service.

III: Track Scan System (Network Scan)

Background

There is in increasing demand for more, objective data about the state of the network. There are a plethora of inspection systems and complete inspection trains available. However, these are typically not certified for local track networks. Also, the operation of dedicated inspection trains is quite complex as they typically need to work to a very tight schedule to be as effective as possible.

This means that in practice there will always be gaps in the track condition data, which requires a more flexible solution to make sure that every part of the network is safe to use, as well as inspected in a safe way.

Strukton Network Scan: The Track Scan was developed as part of the Strukton Network Scan. The

Strukton Network Scan comprises of two modules, one for overhead wire condition and one for the track condition. These modules can be easily used simultaneously but are also fully functional individually.

Objective and requirements

The goal of the Strukton Network Scan is to provide data acquisition capabilities also for smaller-scale networks. Therefore, this setup is modular and thus more flexible to operate than conventional systems.

This does not mean that it cannot also be used for large scale data acquisition, but it primarily excels in areas which are too large to cover with trolleys and too small to justify the use of a dedicated measurement train. For example, urban tram/metro networks, hot spots in the network where coverage of normal inspection trains is lacking or measurement frequencies are too low, or to verify whether a local renewal or maintenance activity is performed properly.

Data collection

Data collection with the Track Scan can be done in two ways. The frame that holds the Track Scan is designed in such a way that it can be easily installed on different types of hi-rail vehicles. The benefit of this solution is that it can be used to measure a very specific section of a track network as it can reach the desired location via normal roads. Additionally, it can utilise vehicles which are already certified if specific requirements are needed.

Figure 77: Measuring equipment on a lorry

The downside of using hi-rail vehicles is that it typically requires train free periods to do the measurements and therefore the maximum speed is limited. To circumvent these problems, the system can also be installed on normal trains, like the Leonardo video inspection train.

Figure 78: Measuring equipment on a re-used tamping machine

Data analytics and algorithms

The track scan produces a high-definition point cloud. Both the lateral and longitudinal resolution are 1 mm for speeds up to 50 km/h. The longitudinal resolution increases by mm for every multiple of 50 km/h, so the longitudinal resolution would be 3 mm for speeds up to 150 km/h.

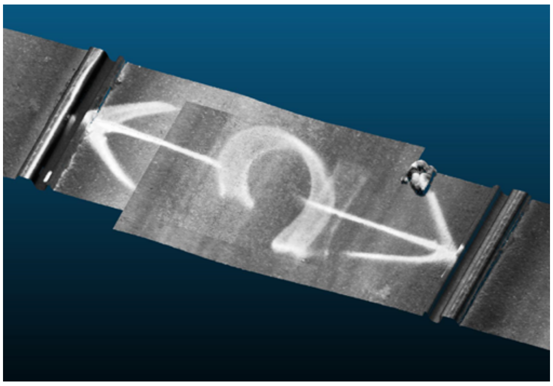

Figure 79: Point cloud measurement by the Track Scan

After the measurements from the different sensors is combined into a single dataset, the real processing and data extraction can be performed. This might appear cumbersome; this is the actual reason why this system is so flexible.

The data processing can be divided into two groups. The first is object detection, so the location and type of objects are defined. The second step is taking measurements, so track related parameters can be quantified.

Object detection

A very important part of the processing is the detection of track related objects.

Although not as trivial as expected, the most import object to detect are the rails. These are obviously the most important parts to detect properly and the fact that this is done in a post processing stage is key to the flexibility of the system. Because of this, the Track Scan can be used for various rail types, as well as a wide range of track gauges.

The next component to be detected are the sleepers if present. This detector reports the boundary and centre point of the sleeper. This information is then used for further analysis, such as skew angle, sleeper interval, or used for the sleeper rating algorithm. This is the second stage of the sleeper inspection, where the algorithm defines the material and detects cracks in the sleeper. Based on the material, the cracks are rated differently, which determines the actual state of the sleeper.

Related to the rail structure are the fastening system. These come in different types, with different failure modes. For this purpose, a different is trained with classes for each combination of type and state of the fastener. The different states are present, which means the fastener is detected as properly functional in shape, defective which means part of the fastener is missing and covered, which indicates that the state could not be visually identified due to the presentence of ballast or other track components. The missing fastener state is independent of the fastener type, as it is not the purpose of the algorithm to determine which type should have been installed.

The fastener detection is linked to the tie detection. This has many advantages. One of the most notable is that for every intersection between rails and sleeper, there should be a fastener on every side of the rail. This connection is also helpful to determine the type of sleeper and the fastener information can be reported per sleeper. Other fasteners are detected as well, such as fasteners for additional support rails, or fasteners on bridges and slab track.

Another detection related to the track structure are the spike detection. These are the screws used to secure the fastening system to the sleeper, or to the slab. The typical screw spike is used to fixate a support plate onto a sleeper. Currently there are only two states for this type of spike, present or missing. Other states, like not fully screwed down, will requires the assembly of a specific training set. The other type of spike that is detected by this model are a specific bolt cover used in slab track. This type of spike is protected by a bolt cover, which can easily be damaged. So for this type, a defective state is also defined.

To enable switch measurements, the related components need to be detected. For a switch, this means that the toe and the heel of the switch blade needs to be detected. Especially the heel requires some effort, as there are various construction types used in the rail networks. Other parts that need to be detected are the beginning and end of the check rail, as well as the wingrail. These locations are then used to extract the relevant switch measurements.

The final rail components that are detected are the joints and thermite welds. This is not a unique feature, but what this system does better than others is that the location of the detected object is directly known.

The used object detection techniques are a combination of classifiers based on deep learning, as well as more traditional algorithms. Both classifiers rely on common logic such that it is possible to yield very good results with a relatively small training data set. For instance, thermite welds can only be found in the rails, not elsewhere and the algorithm is trained with that information.

Measurements

When the desired objects are detected, quantitative measurements can be taken.

For the rail, the 14 mm below top of rail points are determined at a very small interval. This measurement can be treated as an almost absolute measurement of the rail position. The absolute accuracy is determined by the GNSS system and this needs additional input to meet the demands for absolute rail measurements.

The measurements are however very well suited for relative geometry measurements, by applying the right calculations. So the gauge, cant and vertical and lateral alignment can all be derived from these measurements, as well as the change of these parameters.

The second measurement to be taken from the rails are the condition of the rails. The rail wear is determined by taking slices of the rail and compare that with a selection of possible nominal rail profiles. Again, because this measurement is done during post processing and part of an overall process a lot of typical errors related to rail wear measurements are typically avoided, such as the correct definition of the point to determine the lateral head wear.

After the fasteners are detected, the overlap between the fasteners and the rail foot is measured. This is much easier to do as a measurement, as opposed to defining defect classes for sufficient overlap or not. That would require a very well defined and much larger training set.

The required switch measurements can be derived after the right components are detected. The switch measurements take the same approach as the rail geometry measurements. The 14 mm below top of rail points are defined for the respective switch components. Those are used as input for the switch inspection charts.

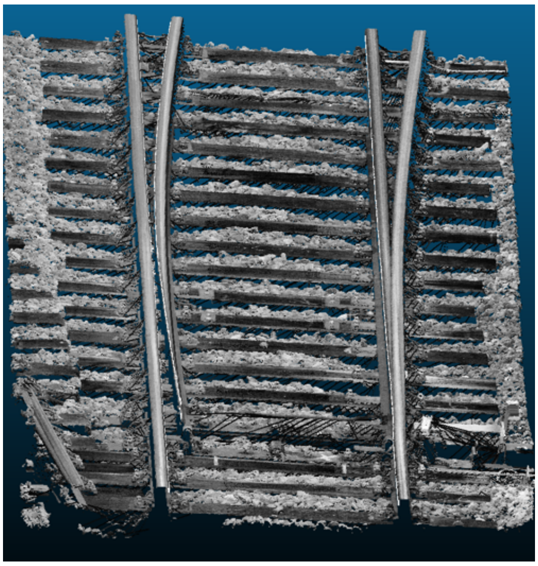

Figure 80: Rhe356