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Deliverable D2.1

End user requirements of SIA and validation plan

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Executive Summary

The present document constitutes the Deliverable D2.1 “End-user requirements of SIA and validation plan” in the framework of the Project titled “System for vehicle-infrastructure Interaction Assets health status monitoring” (Project Acronym: SIA; Grant Agreement No 776402, www.siaproject.eu).

This document has been prepared to provide the **high-level requirements** associated to the functionality of the four services to be developed within the project.

The first chapter of this document includes a short **introduction**, which presents the project and the goals of the project, as well as provides some context about the new maintenance services that SIA will bring to the market. On the other hand, the **methodology** followed for the derivation of the high-level functionality of SIA is described in chapter 2.

Chapter 3 compiles the current **strategies for the maintenance of the assets that are relevant to SIA**, i.e. catenary, pantograph, wheelset and rail. This chapter also describes the failure modes associated to each of the assets, in order to set the baseline for the derivation of the functionality of the system, based on a subset of these failure modes.

Chapter 4 defines the **use cases** that will be the main focus of the project. Six relevant use cases have been defined from the complete set of failure modes. SIA will deploy its full functionality (i.e. predictive capabilities based on physical degradation modelling) with regard to these use cases:

a) Wear, incorrect height and stagger of the overhead contact line
b) Wear of the contact strips of the pantograph
c) Flats and polygonization wear of the wheelset
d) Corrugation and short-wave defects on the rail

Chapter 5 describes the **high-level functionality** of SIA, as well as the context in which the system will operate, and the external interfaces and actors with which SIA will interact. On the other hand, the **non-functional set of requirements** is compiled in chapter 6.

The **preliminary validation plan** of the four services of SIA is presented in chapter 7. This validation will be carried out by the end-users of the consortium, within four pilots in two different scenarios, by assessing the successful operation of the system with regard to the high-level requirements. Finally, the **conclusions** of this document are described in chapter 8.

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Abbreviations and acronyms

Acronym	Description
ABA	Axlebox Acceleration
AC	Alternating Current
ADIF	Administrador de Infrastructuras Ferroviarias. Spanish national railway infrastructure manager
APF	Adjacent Post Fixation
CAT	Corrugation Analysis Trolley
CW	Contact Wire
CWR	Continuously Welded Rail
DC	Direct Current
DoA	Description of Action
EGNSS	European Global Navigation Satellite Systems
FGC	Ferrocarrils de la Generalitat de Catalunya. Spanish regional train operator
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GSA	European Global Navigation Satellite Systems Agency
ID	Identity / Identification
IF	Interface
IM	Infrastructure Manager
IO	Integrated Operator
IRJ	Insulated Rail Joints
IT	Information Technologies
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging, Laser Imaging Detection and Ranging
LPI	Liquid Penetrant Inspection
MT	Maintainability
NDE	Non-destructive Examination
OBB	Österreichische Bundesbahnen- Austrian Federal Railways, national train operator
OCL	Overhead Contact Line
OP	Operability
PCB	Printed Circuit Board
PF	Performance, Post Fixation
RAMS	Reliability, Availability, Maintainabiliay and Safety
RCF	Rolling Contact Fatigue
REQ	Requirement

SBE	Electrical Lowering Device
SIA	Systerm for vehicle-infrastructure Interaction Assets health status monitoring
SP	Supportability
SW	Software
TOC	Train Operating Company
UPN	European standard for U channel
WP	Work Package

1 Introduction

SIA (System for vehicle-infrastructure Interaction Assets health status monitoring) has the objective of developing four ready-to-use new services to provide prognostic information about the health status of the railway's most demanding assets in terms of maintenance costs, at the points of the interaction between the vehicle and the infrastructure (wheelset, pantograph, rail and catenary). More specifically, the common features of the new services (iWheelMon, iPantMon, iRailMon and iCatMon) are detailed below:

1. Plug-in SW based on Web Application to be integrated with already existing maintenance information systems, avoiding the need to replace the entire system.
2. Real time information about assets health status and views of prognostic health status with different time frames to make projections of future scenarios (e.g. future maintenance costs, remaining useful life of the rail and estimated necessary investment).
3. Gateway to maintenance work flow managing software which can trigger maintenance actions and to traffic management information systems to inform about early detected failures in components that can trigger speed restriction or line blocking.

In addition, the specific characteristics of the new four services are highlighted below:

- iWheelMon, which is intended for TOCs (Train Operating Companies) and IOs (Integrated Operators), will provide real time information about wheel status (e.g. presence of wheel flats) and prognostic health status information within a certain time frame such as predicted wear, RCF and polygonization, and maintenance recommendations for meeting ISO 1005-8 and TOC specific requirements.
- iPantMon, which is intended for TOCs and integrated operators, will provide real time information about the pantograph status (e.g. incorrect vertical damping forces of upper arm) and prognostic health status information in a certain time frame such as wearing of contact stripes, and maintenance recommendations for meeting EN 50405 [1] and TOC specific requirements.
- iRailMon, which is intended for IMs and maintenance subcontractors, will provide real time information about the rail status and prognostic health status information in a certain time frame such as squats, corrugation, wear and RCF, and maintenance recommendations according to IM specific maintenance requirements.
- iCatMon which is intended for IMs and maintenance subcontractors, will provide real time information about the catenary status (e.g wearing of cable) and prognostic health status information in a certain time frame such as inclination of the mooring balance with respect to the rail, break of the automatic regulation pulley, wear of cables, and maintenance recommendations for meeting EN50119 [2].

Figure 1 illustrates one example of the new information that iRailMon will provide to the infrastructure manager.

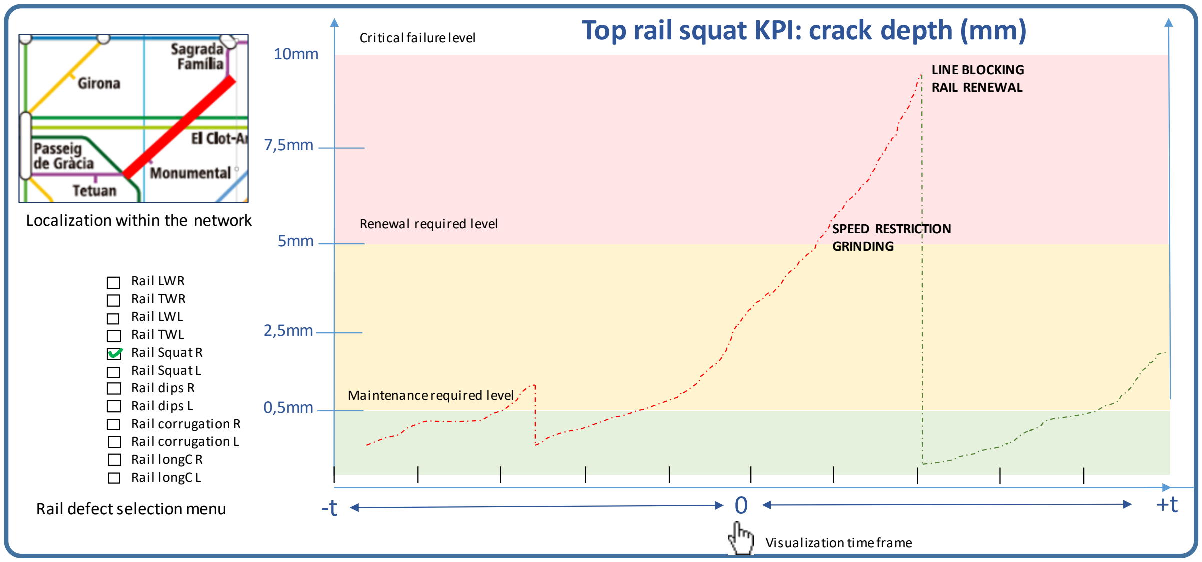


Figure 1. Example of information provided by *iRailMon* to the infrastructure manager

The technical features of the services, the business model and end-user experience will be validated during the scheduled four pilot projects with the following characteristics:

- Pilot project 1 – new end-to-end service iWheelMon involving end user OBB and UIC perspective, 235 km of line Wien-Graz, Vehicles Siemens (mainly ES64U2 and ES64U4), plus 20 services per day and over 120M passengers
- Pilot project 2 – new end-to-end service iPantMon involving end user FGC and UIC perspective, 60 km of line Barcelona-Vallés, Vehicles S114 Alstom-CAF 2 pantographs per vehicle -VDC1500V Faiveley, 175 trains per day and over 80M passengers per year
- Pilot project 3– new end-to-end service iRailMon involving end user OBB, VIAS and UIC perspective, 235 km of line Wien-Graz, Vehicles Siemens (mainly ES64U2 and ES64U4), plus 20 service per day and over 120M passengers
- Pilot project 4 – new end-to-end service iCatMon involving end user FGC and UIC perspective, 60 km of line Barcelona-Vallés, Fixed and flexible catenary system type UPRESAL and over 175 trains per day

This document describes the end user functionality of SIA as a set of high-level functional requirements. This definition includes the functional requirements, non-functional preliminary requirements, the interfaces and the preliminary description of the validation plan. From the user needs definition, the system requirements will be derived as the input for the technical developments to be carried out within WP3, WP4, WP5 and WP6. Standards and guidance documents have also been considered after reviewing applicable latest versions, as well as a preliminary survey to potential end-users external to the consortium.

1.1 Relevant definitions

FAILURE	The lack of ability of a component, equipment, sub system, or system to perform its intended function as designed. Failure may be the result of one or many faults (definition from [3] Industrial automation systems and integration – product data representation and exchange).
DEFECT	Historically, in railroad industry, the term 'defect' has been associated with some visible artefacts, e.g., fissures developed during service. Customarily, in physical metallurgy this term is used in relation to crystallographic imperfections such as dislocation, stacking fault etc. Defects may form intrinsically during processing or may be initiated during service. Defect is any characteristic and/or event that potentially leads to failure in a given asset, component, etc. An abnormal condition or Defect at the component, equipment, or sub-system level which may lead to a failure (definition from [3] Industrial automation systems and integration – product data representation and exchange).
INSPECTION	In this document, the term inspection is referred to any means of examination to assess the health status of a given asset / component that does not require any physical contact. Examples of inspection are visual inspection, thermographic inspection, etc.
AUSCULTATION	In this document, the term inspection is referred to any means of examination to assess the health status of a given asset / component that does not require any physical contact. Examples of inspection are visual inspection, thermographic inspection, etc.
KPI	Key Performance Indicator. The health of assets / components is assessed in terms of a given set of KPIs. It could be any variable and/or combination of variables/parameters. An example of KPI could be “mm of lateral wear in a rail”.
MAINTENANCE ACTION	Maintenance actions are required to repair / substitute damaged assets after a failure has occurred (i.e. corrective action) or before a failure has occurred (i.e. preventive, predictive action. Based on the value (or values) or a given KPI (or a set and / or combination of KPIs) a related maintenance action is required.

2 Methodology

2.1 Description

The methodology followed for the derivation of the high-level functionality of the services that SIA will deploy is shortly described in this section.

- End-users in the consortium analyze potential failures and damage mechanisms of the relevant assets (catenary, pantograph, wheelset and rail) and review the associated maintenance actions, based on
    - standards and normative (if any apply)
    - own experience
- A questionnaire will be distributed for potential end-users (external to the consortium). This questionnaire includes general questions about the exploitation, and more importantly a set of failure modes that, having been previously identified, will be assessed in terms of impact in the maintenance and frequency of appearance. The questionnaire also provides additional feedback for the functionality, such as the requirements concerning localization, desired features of the systems to be developed and further information that will be useful in a later stage of the project, i.e. for the exploitation plan.
- With all the information collected considering the points above, the use cases that will drive the functionality of SIA and will be subject for final validation will be derived. These use cases (i.e. specific defects that will exploit the predictive capabilities of the system) will consider the most relevant failure modes in terms of their impact. That said, it will be selected among all set of defects also considering their feasibility in terms of technology deployment.
- The use cases will summarize the information required for the assessment of high-level functionality, the actors with which SIA services will interact and the required external interfaces.
- Non-functional requirements will be based in the feedback from end-users and the relevant standards.
- Finally, the preliminary validation plan will consider the requirements related to the high-level functionality. The methodology that end-users of the consortium will use for the validation of SIA services within the pilot demonstration will also be derived in this analysis.

2.2 Input collection

The collection of input data that will shape the functionality of SIA is described in this section. This information will consist on the feedback from the end-users of the consortium, the analysis of the relevant standards and best-practice guides and additional input collected from external end-users via electronic questionnaire. First, the potential end-users of the services that SIA will bring to the market are described in the following section.

2.2.1 Description of potential end-users

The potential end-users of the new services brought by SIA are described in this section.

2.2.1.1 Integrated operators

They are typically metro, trams, regional lines or national main lines in some countries like France where the liberalization of the railway sector has not been developed. This type of end users is a public company which is responsible not only of the vehicle operation but also of the infrastructure. This type of organizations is typically managed by civil services which are usually very conservative when making decisions. Therefore, previous relevant references will be almost mandatory to introduce new tools. The procurement process is a public tender where price and technical features are scored. Due to the internal structure, the acquisition of new assets (including SW tools) is usually very difficult so the sale of the product is better to be carried out as a service. The maintenance cost is typically the third major yearly cost of the company (after wages and energy) and usually is over 30%. A reference value of maintenance cost (including subcontracting, amortization of equipment, energy and salaries) is between 0,5M€-3M€ per million of passengers/year. For example, Metro Madrid is transporting over 580 million passengers per year, annual expenses over 1,200M€ and their maintenance expenses are over 370M€, and London Underground is transporting over 1,040 million passengers per year and their expenses are over 11,000M£ (15,000M€) and their maintenance expenses are over 3,000M€.

2.2.1.2 Infrastructure managers

They are always public companies which have the responsibility of maintaining the quality of the network above a certain level depending on the speed of the line. They are funded by track access charges and grants of the governments. Maintenance and renewal costs are typically between 40%-50% of total Life cycle costs. As an example, the renewal and maintenance average cost per kilometer is 15,000€ (SNCF) for conventional line and over 100,000€ for high speed line (ADIF). It is worth mentioning that since August 2015, EU Commission has provided a regulation that member states shall implement before end of 2018 which recommends setting track access charge as a function of the degradation the vehicles are introducing on the infrastructure. This is already implemented in the UK by Network Rail (where accurate models of the vehicle are employed to run multi-body simulations and estimate incremental damage) and SBB. This fact is expected to boost the optimization of vehicles and infrastructure maintenance and could be an important factor, which triggers in the future the sales of SIA services.

2.2.1.3 Train operators

Almost all of them are public companies which depend on the same authority of the infrastructure managers but are separated. There are also private companies mainly for rail freight transportation in Europe and the United States and some minor companies for passenger transportation (e.g. UK). For these companies, maintenance is typically around 20% of annual expenses and track access charge around 10%. The maintenance represents around 600M€ for ADIF which total budget is around 3,000M€ and transports more than 450 million passengers.

2.2.2 Input from end-users in the consortium

The end-users of the consortium are the main protagonists concerning the definition of the high-level functionality of SIA. Their role is key with regard to the following activities:

1) Analysis of the different failure mechanisms and associated maintenance actions of the assets that are relevant to the project, i.e. catenary (overhead contact line), pantograph, wheelset and rail. In addition to that, they will also provide feedback in terms of the relevant KPIs that are related to each of the identified failure modes, as well as the means of detecting such failures, e.g. visual inspections, auscultation vehicles, etc.
2) Provide feedback in the preparation of the questionnaire for surveying potential end-users external to the consortium and also answering the questionnaire
3) Drafting a set of high-level functional (and non-functional) requirements for the derivation of the high-level functionality of the four services
4) Analysis of the results and review the proposed high-level functionality
5) Contribution to the description of the use cases that will leverage the full functionality of the new services that will be validated in the last stage of the project, by means of four pilot demonstrations
6) Support the preparation of the preliminary validation plan

2.2.3 Normative / Standards

Another input to consider for establishing a set of (mostly non-functional) requirements that are relevant for the end-users is the applicable normative / standards that suits the nature SIA. The analyzed documentation is listed in the following subsections.

2.2.3.1 Catenary

- EN50119. Railway applications - Fixed installations - Electric traction overhead contact lines
- EN50345. Railway applications - Fixed installations - Electric traction - Insulating synthetic rope assemblies for support of overhead contact lines
- Railway Group Standard GL/RT1210. AC Energy Subsystem and Interfaces to Rolling Stock Subsystem
- RSSB guide GL/GN1610. Guidance on AC Energy Subsystem and Interfaces to Rolling Stock Subsystem

2.2.3.2 Pantograph

- EN50206-1. Railway applications - Rolling stock - Pantographs: Characteristics and tests -- Part 1: Pantographs for main line vehicles
- EN50206-2. Railway applications - Rolling stock - Pantographs: Characteristics and tests -- Part 2: Pantographs for metros and light rail vehicles

- EN50317. Railway applications - Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line
- EN50318. Railway applications - Current collection systems - Validation of simulation of the dynamic interaction between pantograph and overhead contact line
- EN50367. Railway applications - Current collection systems - Technical criteria for the interaction between pantograph and overhead line (to achieve free access)
- EN50405. Railway applications - Current collection systems - Pantographs, testing methods for contact strips
- Railway Group Standard GM/RT2111. Rolling Stock Subsystem and Interfaces to AC Energy Subsystem
- RSSB guide GM/GN2611Guidance on Rolling Stock Subsystem and Interfaces to AC Energy Subsystem
- Railway Group Standard RIS-1854-ENE. Rail Industry Standard for 750 V and 1500 V DC Overhead Lines and corresponding Rolling Stock requirements

2.2.3.3 Wheelset

- EN 13715. Railway applications - Wheelsets and bogies - Wheels - Tread profile
- EN15313. Railway applications - In-service wheelset operation requirements - In-service and off-vehicle wheelset maintenance
- Railway Group Standard GMRT2466. Railway Wheelsets
- Railway Group Standard RIS-2004-RST. Rail Vehicle Maintenance
- UIC 812-2 Solid wheels for tractive and trailing stock – Tolerances
- UIC 50530. Railway Application – Rolling Stock – Rolling Stock Maintenance
- ERRI B79 RP10. Catalogue of defects on the wheels of railway trailer stock
- ERRI B169 RP37. Running surface defects on wagon wheels and their impacts on the stresses exerted on running gear and the dimensioning thereof
- ERRI B169 RP43. RAMS – Guideline: Reliability, availability, maintainability, safety – Implementation of EN 50126 for Mechanical Components in Railway
- UIC 135. Atlas of wheel and rail defects
- UIC 160. A catalogue of mechanisms associated with wheel / rail contact

2.2.3.4 Rail

- ISO5003. Flat bottom (Vignole) railway rails 43 kg/m and above
- Railway Group Standard GC/RT5021. Track System Requirements
- UIC 712. Rail defects
- UIC 725. Treatment of rail defects
- ERRI C9 RP6. Worn profiles of rail heads and wheel tires
- ERRI C210 RP1. Development of methods to describe geometric track quality, with the aim of analyzing dynamic vehicle behavior – Summary Report
- ERRI D45 RP3. Collection of documentary leaflets concerning the principal rail defects
- UIC 134. An international cross reference of rail defects
- UIC 135. Atlas of wheel and rail defects

2.2.3.5 Other

- EN50126. Railway applications. The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS).
- EN50128. Railway applications - Communication, signaling and processing systems - Software for railway control and protection systems
- EN50129. Railway applications - Communication, signaling and processing systems - Safety related electronic systems for signaling
- IEC61375-2-6 T2G. Electronic railway equipment - Train communication network (TCN) - Part 2-6: On-board to ground communication
- RailTopoModel
- RSSB guide GEGN8578 Iss5. Guidance on the Use of On-Train Satellite Positioning Technology based Locator for Railway Applications
- RSSB guide GE/GN8579. Guidance on Digital Wireless Technology for Train Operators
- RSSB guide GK/GN0602. Guidance on Train Rooftop Antenna Positioning

2.2.4 Questionnaires for external end-users

Two versions of the questionnaire have been prepared in order to facilitate the input collection: an online form for a better data collection and handling (https://goo.gl/forms/wWnKyfaGGQOHW8Bf2) and a word document for convenience (see Annex 1). The content of the questionnaire is summarized here:

- Introduction of the project in order to provide a short context about SIA and the new services that will be brought to the market
- General data about the exploitation, e.g. the network length, number of passengers per year, etc.
- Defects / Failure modes: impact and frequency assessment. This section contains a set of tables based on a catalogue of the most important defects (of the catenary, pantograph, wheelset and rail) that are controlled by inspections (e.g. visual, thermographic), auscultations or otherwise, in the different types of assets, divided into systems and subsystems. To complete the questionnaire, it is necessary to fill in:
  - the “impact” on the estimated operation in case the failure occurs on a scale of 1 to 5, where 1 is "minimum impact" and 5 is "maximum impact" (circulation is halted, and an emergency maintenance operation must be performed)
  - the “frequency” of the failure mode in question on a scale of 1 to 5, where 5 stands for a very frequent condition and 1 for a very infrequent one.
- Assets / defects localization: accuracy and performance. It is important to know the localization of the different assets that are distributed throughout the network. When trying to detect faulty assets, either for corrective or predictive (preferred) actions, factors like accuracy and latency on the information become key in order to mitigate risks and reduce costs. This section looks for information related to the needs for asset and/or defects localization.
- Current maintenance operations, in order to gather data about how end-users are currently handling maintenance operations in terms of Software or otherwise.

- 4 new services: desirable features, with a specific call to action to provide the desirable features that the four new services should provide
- Other comments and suggestions

3 Current strategies for the management of the maintenance relevant to SIA

3.1 Overhead Contact Line

3.1.1 General description

The main objective of the railway electrification system is to ensure the electrical supply to the rolling stock from a safety and economy viewpoint. Starting from this concept, the Overhead Contact Line (OCL) is formed by the conductor cables that form the catenary (catenary wires, dropper, feeder and contact wires), the fastening systems and the mechanical stress compensation elements. Working together, all of them attain the objective of assuring a correct positioning of the contact wire, thus guaranteeing the quality of pantograph electrical contact and optimum wear both for the pantograph contact element and the contact wire.

Based on these criteria of safeguarding energy transport and minimizing the costs associated with construction and maintenance, the railway electrification system has a relatively fixed scheme, with repeated patterns where the different elements that make them up are simple and can be easily schematized and differentiated. In its simplest possible description, a railway electrification system is nothing more than an electrical circuit: the output from the traction substation is fed to the catenary, the train picks it up via the pantograph and the current returns via the tracks and the return wire to said traction substation.

Overhead contact lines have two sets of physical requirements: those stemming from their electrical aspects, affecting the conduction of electric current, and those deriving from the mechanical solicitations of the structure, which are responsible for a good pantograph-contact line synergy. In many ways these two set of requirements are interrelated, so they cannot be separately specified.

In Spain's Conventional Network, managed by ADIF, there are different models of catenary that have been installed throughout the years. Among then, those with CA-160 and CA-220 denominations are the most extended. Both are regulated by ADIF in descriptive specification documents. For the High-Speed Railway Network, managed by ADIF Alta Velocidad, there is no compendium standard as such, but all relevant information is collected in various technical documents.

In order to ensure the catenary service conditions, compensation, suspension and support systems are used, which together form the so-called electrification columns.

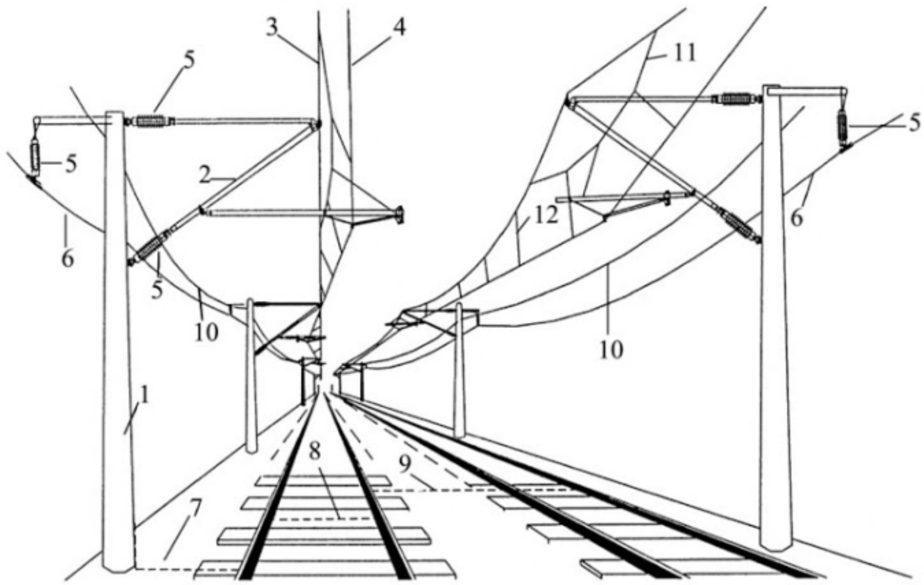


Figure 2. Single-cantilever catenary suspension overhead contact line. 1, Pole; 2, cantilever; 3, messenger wire; 4, contact wire; 5, insulator; 6, feeder; 7, pole foundation; 8, rail connection; 9, up-down track connection; 10, return wire; 11, stitch wire; 12, dropper.

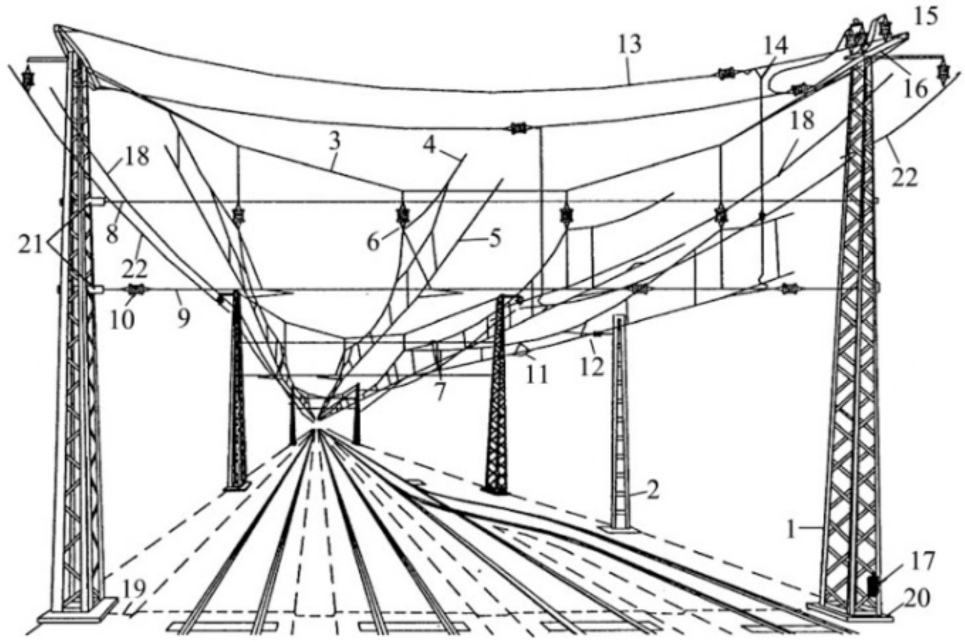


Figure 3. Head span of contact line. 1, Diagonal steel pole; 2, cross bar pole; 3, lateral messenger wire; 4, messenger wire; 5, contact wire; 6, suspension point; 7, electric connection; 8, upper safety rope; 9, lower safety rope; 10, insulator; 11, section insulator; 12, curve steady arm; 13 and 14, switch jumper; 15, isolating switch; 16, cross arm; 17, electric operating mechanism; 18, return wire; 19, pole grounding; 20, pole foundation; 21, safety rope compensation; 22, feeder.

3.1.1.1 Catenary and contact wire

The messenger cable, also known as the catenary wire, forms the catenary curve from which the contact wire hangs, held in place by the droppers. Its mission is to support the weight of the system formed by the contact wires and the droppers, as well as to maintain the whole system with a certain mechanical tension.

The droppers are a series of copper or bronze cables that connect the catenary wire with the contact wire and its mission is to maintain the electrical conduction and the contact wire (or wires) at a certain height with respect to the rolling plane. The length of these varies along the span (section between poles).

Insulators in general are elements that electrically isolate and mechanically join the bare LAC to its supports and earthing. They are made of porcelain, glass or plastic and are fastened using complementary hardware. The suspension insulator electrically separates the bracket from the suspension assembly.

The companion feeder is an element designed to help to obtain the lightness and flexibility that is expected of the catenary. If this element is not used, the equivalent section of cable necessary to carry the electric current that circulates through the lines would cause the contact wire and the catenary wire to have too large sections. The feeder is a copper cable mounted on the masthead that is connected to the catenary every certain distance, normally between 120 and 300 m. In this way it is possible to reduce the section of the catenary maintaining an equivalent electrical section and therefore making it suitable for high power consumption.

The fundamental element of the catenary is the contact wire since it is the one that is in contact with the vehicles' pantographs, ensuring the current circulation. The contact wire has lateral grooves allowing it to be supported along the span by means of the droppers.

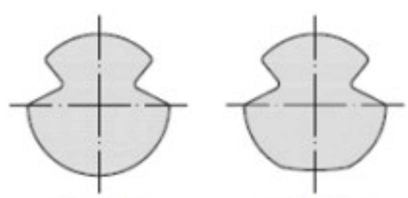


Figure 4. Contact wire typical sections.

The contact wire must have an adequate section according to the current demand and is generally made of copper. Furthermore, for the friction between the pantograph and the contact wire to be as homogeneous and uniform as possible, it is necessary that the contact wire maintains a constant height with respect to the rails (by means of the droppers). The contact wire also runs in a zig-zag path above the track to avoid wearing a groove in the pantograph. This zig-zag is usually achieved by pull-off arms attached to the cantilever masts.

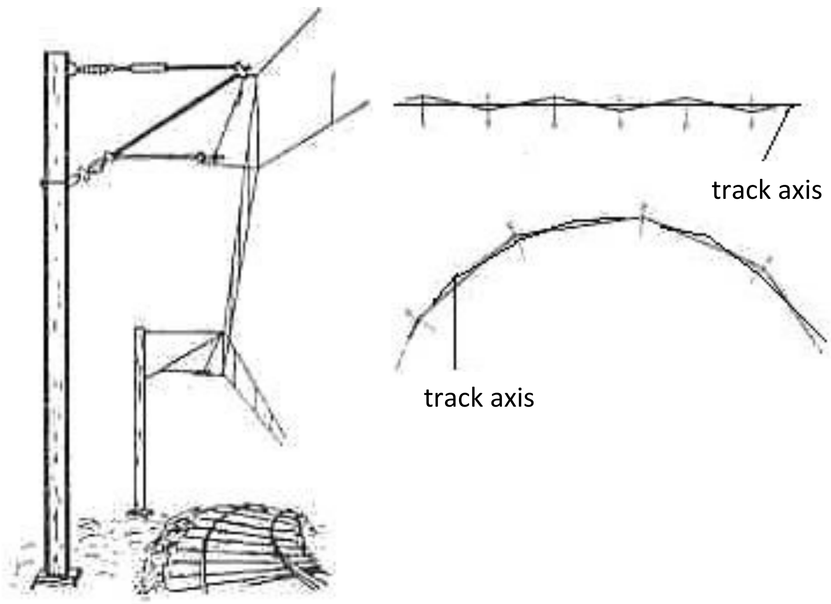


Figure 5. Typical overhead contact line layout. Straight track versus curved track.

The horizontal distance from the track axis to the position of the contact wire is referred to as stagger. This offset is measured in front of the mast and is limited by the path (straight or curved), the track width and the maximum speed. A normal value is usually 20 to 25 cm. The suspension insulator, the droppers and the steady tube must be in the same vertical plane.

In the Spanish conventional system OCL CR-160 and CR-220 supplied with 3000 V direct current, two contact wires are usually used.

3.1.1.2 Cantilevers

In main line track spans, OCL is usually supported from lineside masts using cantilevers. The catenary cable and the pull/push-off arms supporting the contact wire are attached to the ends of the cantilever. The cantilever is the element that resting on the mast allows the catenary to be placed in its proper position. There are two types of cantilever: lattice and tubular. The first are formed by U-type steel profiles (CR-160) while the second one is formed by steel or aluminum tubes (CR-220 in Spanish conventional system, and in alternate current high-speed lines).

The basic assembly difference between the two is that the tubular lattice is in electrical tension with the cables connected to it and the lattice cantilever is connected to earth and to the live cables using insulators. In addition, lattice cantilevers are standardized elements with standard measures in which the adjustment to the positioning of the contact wire is made by means of the steadiness of the cantilever and the wire itself, while for tubular cantilever the dimensions of the adaptable standardized elements that form them are modified (viz., the element itself is modified).

3.1.1.3 Masts

The masts are the structural elements in charge of supporting the catenary, as well as all the auxiliary elements that compose it. They are usually galvanized steel metal supports made up of two parallel UPN-type laminated profiles joined by diagonals (open posts) or closed with metal sheet forming a rectangular box (closed posts). Closed posts are used where the masts may be subjected to torsion loading (as is the case of semi-axes and cross-over lifts).

The masts have different heights depending on their application. In general, the height of the posts is 8.55 m, which allows a slight angle in the tie bar. For catenary anchors, for sectioning axis, cross-over elevations, connections to technical buildings and for masts that must support self-supporting rigid portal booms (without tie bars), the height of the posts will be 9.45 m. If the masts must support rigid frames with tie bars or semi portal frames, the height shall be 12.45 m long.

Masts are placed outside the running gauge. ADIF's standards specify approximately 3 meters from the axis of the track. To compensate the mechanical stresses corresponding to the elements anchored to the mast, these are placed with a small deflection (from 5 to 8 cm).

All the masts of a line are connected to each other by means of a cable (called guard cable), connected to earth every 1000 m approximately. The distance between two consecutive masts and therefore the determination of the optimum length of each span is a problem whose solution lies in technical-economic considerations.

3.1.1.4 Tensioning equipment

The tensioning mechanism is charged with the automatic regulation of the mechanical tension of the catenary. This regulation is necessary to ensure the height of the contact wire, as the conductor cables forming the catenary may be subject to length variations due to thermal expansion caused by temperature changes. This set consists of a pulley, counterweight and insulator, and is not found in all electrification columns (there is one at the beginning and end of each span).

3.1.1.5 Catenary in tunnels

The special conditions that occur in tunnels make it necessary to adopt special provisions for fastening the catenary. In tunnels the catenary is anchored to the vault of the tunnel so there are no masts and therefore foundations aren't necessary. It may be a rigid catenary or an adaptation of a cantilever-supported system.

Figure 6. Overhead contact line in tunnel using cantilevers.

Figure 7. Rigid catenary in tunnel.

3.1.1.6 Gantries

Gantries are frames (e.g. H-portals) that support the catenary of several tracks. Their use is typical in stations or track zones where there isn't enough space to mount each catenary by means of independent masts. Gantries can be flexible (funicular gantry) or rigid (rigid gantry), depending on the geometric characteristics of the track and the mechanical characteristics of the OCL.

Figure 8. Different types of catenary

The rigid gantry is a metallic structure formed by two posts and a horizontal boom transverse to the tracks that connects them, supporting the catenary loads. The mechanical independence of the different catenaries by means of a rigid gantry allows the independent compensation of each one of the tracks and prevents a mechanical incidence on one catenary from dragging all the others.

The funicular gantry suspends several catenaries from adjacent tracks mainly in stations. It consists of three cables attached to two masts located at the ends of the track bundle. The first of the cables is the funicular cable, so called because of its shape. This cable supports the loads in the vertical plane and is above the other cables. The upper transverse or suspension cable is the one in which the supporting cable is suspended. It is fastened to the funicular cable by means of steel droppers at the points where the supporting cable of each track is supported. Finally, the lower transverse cable is where the contact wire cable assemblies are fixed, and it is fastened using droppers to the upper transverse cable. Funicular gantries are being replaced by rigid ones due to their intrinsic failure propagation characteristics, whereby a failure in one of the overhead contact lines affects all the others in the same assembly

3.1.2 Overhead contact line maintenance

Every problem related to the maintenance of railway infrastructures, and more specifically in relation to the overhead contact line (hereinafter OCL), can be classified into two main groups:

1. Those related to STRUCTURES.
2. Those related to GEOMETRY.

Of these two groups, the critical is undoubtedly the GEOMETRY: to which most attention is paid at present, and therefore, to which more economic resources are allocated.

On the other hand, and in the specific case of Spain, maintenance work is clearly distinguished between conventional rail (in its Iberian and metric gauge) and high-speed rail (international gauge): it is much more exhaustive in the latter case (in terms of economic, material and human resources); whereas it is reduced to what is merely indispensable in conventional.

3.1.2.1 Problems related to structures

3.1.2.1.1 Deformations of the cantilever elements

Occasionally, elements of the cantilever assembly (e.g. the steady tube) may be deformed. Most often these problems do not occur as a result of normal ageing of the components, but due to poor initial design.

3.1.2.1.2 Corrosion of catenary poles

Especially in old lines, with painted masts; or in masts in high water table terrain, with corrosion problems at its base. Nowadays, the posts are made of galvanized steel and these problems aren't very common.

3.1.2.1.3 Inclination of the catenary masts with respect to the horizontal of the ground (collapse)

Due to the mechanical stresses to which the masts are subjected (weight of the support and contact wire(s), tensioning of the contact wire towards the anchors, weight of the bracket itself); and in some cases, due to geotechnical problems (i.e. masts grounded on slopes), the mast may lose the perpendicularity that it should maintain with respect to the ground plane. This results in incorrect work of the catenary compensation system, and changes in geometry (height and offset, see section 1.1.2.2.1).

3.1.2.2 Problems related to geometry

3.1.2.2.1 Misalignments of the height and stagger values

Contact wire heights and stagger are undoubtedly two of the most important parameters in catenary geometry. Some of the reasons why these values may change with respect to the design values and fall outside of permissible tolerances are:

- Modification of the track cant because of maintenance work on the track (correction of curves, tamping, modification of the cant on the curve). It is necessary to include the opportune correction of the catenary within these track works, thus avoiding a situation of risk in the operation of the installations.
- Modification of the radius of a curve: in this case, it is necessary to condition the staggers along the entire length of the curve, taking particular account of the stagger in the center of the span. In addition, it could happen that when the distance from the track to the mast is changed, it may be necessary to replace the cantilever or even change the location of the mast.

- Softening of the ground, with a slight inclination of the post. In this case both the height and the stagger are changed. Once this situation has been detected, the variation in height and stagger should be evaluated for immediate correction if it falls outside tolerances.
- Likewise, the evolution of the mast must be controlled to discern if the displacement has been due to a settlement of the land; or if on the contrary it is due to some hidden defect either in its piling, base or in the mast itself.
- The appropriate sensors located on the mast, or the comparison of data from a LiDAR measurement with a later one, would allow these problems to be detected more easily, and the necessary corrective actions to be taken before the influence on the geometry implies a costlier intervention.
- Other causes of gradual modification of the geometric parameters of the line, caused by sliding screws or inadequate tightening. A continuous auscultation by means of an adequate sensor, would allow detecting these problems without the need for periodic interventions (as is currently the case). Intervention would only occur if the sensors detected any variation outside of tolerances.

3.1.2.2.2 Misalignments in the dropper's assembly

Droppers hold the contact wire(s) in their correct position, keeping it (them) practically parallel and at a certain height above the rails (mechanical union with the support). In addition, the so-called "equipotential droppers" provide at the same time the adequate electrical connection between support and contact wires. In this way, the power supply assemblies between support and contact wires become unnecessary, thus avoiding the possible hard points for this reason.

In the case of using two contact wires, the same dropper can hold the two contact wires together by means of the appropriate tap. The exception are the droppers located in the vicinity of the cantilever's pull-off arm and supporting pieces, where a dropper is used for each contact wire, separated from each other by a certain distance.

Droppers can present several problems:

1. Inadequate distribution of the droppers (Figure 2.1, in green): it can give rise to an inadequate union between the catenary wire and the contact wire, causing the contact to "hang" between two consecutive droppers.
2. Dragging of droppers: for various reasons (i.e. thermal expansion and/or mechanical tension of the contact wire other than the catenary wire), the droppers can lose their verticality and decompensate the system.

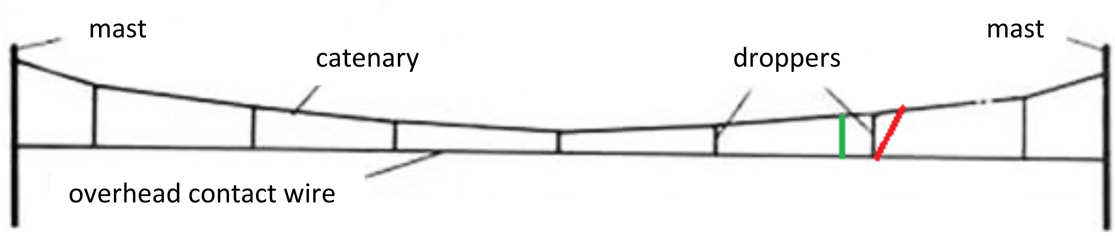


Figure 9. Changes in the geometry of droppers: out of place dropper due to a bad distribution (in green); and dragged dropper (in red).

3.1.2.2.3 Displacement and turning of the cantilevers

To counteract the effect of the expansion of the overhead contact line, the line is divided into spans between 900 and 1200 meters in length, measured from anchorage to cable anchorage. Each of these parts into which the line is divided is called a section.

In the center of each section there are cables that hold and stabilize the catenary and contact wires, preventing the whole line from moving to one side or the other. This central point is known as the Fixed Point (PF), since a mast is installed in it whose cantilever does not move/rotate, regardless of the ambient temperature or the cables. The stabilization of this cantilever is carried out by means of a steel cable, conveniently insulated, which secures the suspension assembly and through it the cantilever, the catenary and contact wires. The steel cables are fixed to the adjacent posts (APF), and to prevent them from bending, they are reinforced by a tie bar.

The section may have devices for the automatic regulation of mechanical tension or not (sections with/without automatic compensation). The most common situation is the existence of automatic compensation, that is to say, the cables are fastened to the end masts by means of a system formed by pulleys and counterweights to maintain constant the mechanical tension of the cables, independently of the variations of temperature.

In other words: both the contact wire (copper) and the catenary wire (sometimes made of copper, sometimes of steel) have an essentially linear thermal expansion, which must be considered in the installation (and maintenance).

The contact and catenary wires are in solidarity with the cantilevers, so the increases in line length produce a displacement (rotation) of the cantilever oriented towards the ends of the canton, as it is null in the PF.

This displacement is greater (a) the closer the cantilever is to the compensation equipment and (b) the higher the operating temperature of the contact wire.

The fixed-point cantilever will therefore always be perpendicular to the track, while each of the existing cantilevers from this central point to the sectioning cantilevers will move from the perpendicular position to one side or the other depending on the existing temperature. The increase in temperature over the average operating value will cause the cantilevers to turn towards the ends of the canton, and a decrease in this temperature will produce the opposite effect.

At this point the critical cantilevers are those of the sections (E, SE posts) which will have a greater turn, as the ones located at a greater distance from the central point.

In addition to supporting the larger turns, as they are double cantilevers masts (each belonging to two different cantons), their separation must be enough so that both can turn freely up to the maximum calculated displacement.

Therefore, it should be checked that (a) when the temperature decreases, they do not touch each other; and (b) when the temperature is high, the different cables do not interfere with each other, nor touch elements located at different potential (i.e. support of the collateral canton or droppers).

The design condition for each type of line is:

3. High Speed (hereinafter AV): all cantilevers are positioned in such a way that for an ambient temperature of 25ºC they remain perpendicular to the axis of the track.
4. Conventional: same criterion, but at an ambient temperature of 15ºC.

The permissible turns of each cantilever according to its distance from the PF are currently established according to values tabulated by ADIF according to these mounting temperatures.

Therefore, in overlap, the rotation of the cantilevers has a much greater influence on the geometry of the OCL than in the rest of the canton.

In addition:

5. It must be ensured that, when turning the overlap's cantilevers, a gap is maintained to ensure that the contact wires do not cross.
6. Curved sections present many more problems than straight sections, since the cantilevers in this case exert compressive forces on the mast. In this way, it can happen that the rotation does not take place in a "gradual" way with the dilation/contraction of the contact wire, but that a certain effort is accumulated that is released suddenly, making the rotation of the cantilever to be abrupt, causing greater problems in the OCL.

The objective would therefore be to know the evolution of the rotation of the cantilevers, and to guarantee that for a certain working temperature they are in the right position; paying special attention to the overlaps and, within these, to those situated on a curve.

At present, these two problems can only be solved with a "visual" maintenance: brigades that run along the section of railway line assigned to them in a maintenance vehicle and observe that these defects don't occur. It´s a very expensive method, which is why it is exhaustively carried out on High speed tracks only.

3.1.3 Failure modes

The following failure modes catalogue has been compiled taking into account TELICE's experience as maintenance provider and the standards mentioned in section 2.2.3.1.

System	Subsystem	Failure mode
Wires	Contact wire	Breakage
		Fissures
		Wear
		Roughness caused by sparkover
		Tension joints with protrusions
		Improper tension
		Wire twist
		Ice sleeves
		Improper fastening
		Incorrect height
		Incorrect stagger
		Improper wire spacing
	Catenary	Breakage
		Fissures
		Shearing
		Deformations
		Corrosion
		Joints in bad condition
		Inadequate tension
		Burned element
		Improper assembly
		Incorrect geometry
	Feeder	Breakage
		Fissures
		Incorrect geometry (isolation distances)
		Joints in bad condition
		Bending irons in bad condition
		Burned sections
		Rust
		Improper electrical continuity
		Insulator in bad condition
		Improper assembly

System	Subsystem	Failure mode
Support and sustentation	Masts and frames	Mast foundation in bad condition (cracked or bare concrete, damaged rain gutter)
		Improper geometry
		Unstable joints
		Damaged electroplating or paint job
		Bracing members in bad condition
		Rust
		Counterweight problems
		Spring tensioner faults
	Registration arms	Notable deformation
		Excessive displacement
		Rust
		Damaged electroplating or paint job
		Defective fastening
		Improper geometry
	Droppers	Breakage
		Displacement
		Defective fastening
		Incorrect alignment
		Improper geometry
		Burns
	Rigid catenary guides	Notable deformation
		Rust or corrosion
		Fastenings in bad condition
		Grease deposits
Protection equipment	Insulators	Surface contamination
		Perforations
		Improper geometry
		Vegetation-induced insulation loss
		Damaged catenary wire insulation
		Damaged overhead contact wire insulation
		Pantograph impacts
	Disconnectors	Improper electrical contact

System	Subsystem	Failure mode
		Arcing horns in bad condition
		Moving contacts in bad condition
		Improper isolation distance
		Bad electroplating
		Surface contamination
		Vegetation-induced insulation loss
		Rust
	Sections	Improper registration arms displacement
		Improper catenary separation
		Feeders in bad condition
		Improper elevation in anchoring tails.
		Vegetation-induced insulation loss
	Earth wire	Damage
		Improper electrical continuity
	Lightning conductor	Connections in bad condition
		Improper cable clamping
		Burns
	Hoods	Falling hood risk

3.1.4 Failure statistics

Currently all OCL-related inspections are performed in preventive campaigns and there is no available statistical data on the frequency of the different failure modes, due in part to the nature of the work carried out. All inspections are visual.

Inspections are carried out in two different campaign types:

- Visual inspection campaigns: they are performed each semester for high traffic track sections, and annually for the rest of the network.
- Critical subsystem checks: they are performed with different maximum schedules depending on the subsystem to be checked and varying from annual to tri-annual.

This table describes maximum frequencies for routine subsystem checks:

Subsystem	Frequency for high-traffic track	Frequency for low-traffic track
Electrical sections	1 year	2 years
Catenary points / cross-overs	1 year	2 years

Subsystem	Frequency for high-traffic track	Frequency for low-traffic track
Disconnectors	1 year	2 years
Section isolators	1 year	2 years
Contact wire (for copper pantographs, 3 kV DC)	1 year	2 years
Contact wire (for graphite pantographs, 1,5-3 kV DC)	2 years	3 years
Contact wire (for graphite pantographs, 25 kV AC)	3 years	3 years
Protection elements and earthing	3 years	3 years

All other OCL elements are subject to special revisions following criteria of responsible maintenance personnel.

3.1.5 Conclusions

While it may not be possible to eliminate the need for a visual OCL inspection, there are clearly areas where judicious technology improvements can have important impacts in the reliability of the system as a whole. The use of different measurement and inspection platforms specifically tailored to each need (i.e.: auscultation trains for high-speed measurements in main track sections, or lighter solutions amenable for OCL inspection in complex environments like stations or track spans affected by renewal or other kind of maintenance work where auscultation trains are not a practical solution) can be complemented with new, low power sensor platforms, arriving at new insights from the exploitation of the measurement data gathered using automatic pattern discovery algorithms.

Any sensor platform (i.e. wayside) taking into account weather patterns, and more particularly thermal and wind loads over the OCL system as a whole, could eventually complement the information provided by the onboard systems. Being able to monitor wire expansion via displacement of the automatic tensioning assemblies may be an interesting avenue for discussion. Sensible areas like embankments and slopes, whose displacement may affect masts, ought to be monitored for minute changes, therefore eliminating intrinsic visual inspection errors.

The contact wire is the main component of an overhead contact line. Its main function is to ensure current transmission to the train through sliding contact within pantograph strips. It is subject to two main failure modes: bad positioning and important wear. Additionally, the contact wear overhaul is the most-expensive cost of the overhead contact line maintenance budget. For that reason, the two use-cases dedicated to iCatMon will tackle these failure mechanisms.

Real-life inspection frequencies can act as a proxy for the lack of statistical data concerning catenary failures. Therefore, work should be concentrated in high-value targets that are inspected with the most frequency.

3.2 Pantograph

3.2.1 General description

Pantographs can be divided into many types. In terms of working modes of the drive system, they can be divided into spring-operated pantographs and non-spring-operated pantographs; in terms of structure of the arm lever, they can be divided into single-arm pantographs and double-arm pantographs, the latter of which can be further divided into four-cantilever diamond double-arm pantographs, double-cantilever diamond double-arm pantographs and four cantilever crossed double-arm pantographs; in terms of operation speed, they can be divided into high-speed pantographs and normal speed pantographs; in terms of application, they can be divided into DC pantographs and AC pantographs; in terms of number of layers of pantograph frame, they can be divided into single-layer pantographs and double-layer pantographs.

The pantograph type depends on operating speed, load, and contact line condition of electric trains, and may vary depending on different manufacturing experience and technical convention of each country. However, all pantographs consist of four basic parts: pantograph head, frame, base frame, and drive system. Figure 10 shows the main parts of a common single-arm pantograph.

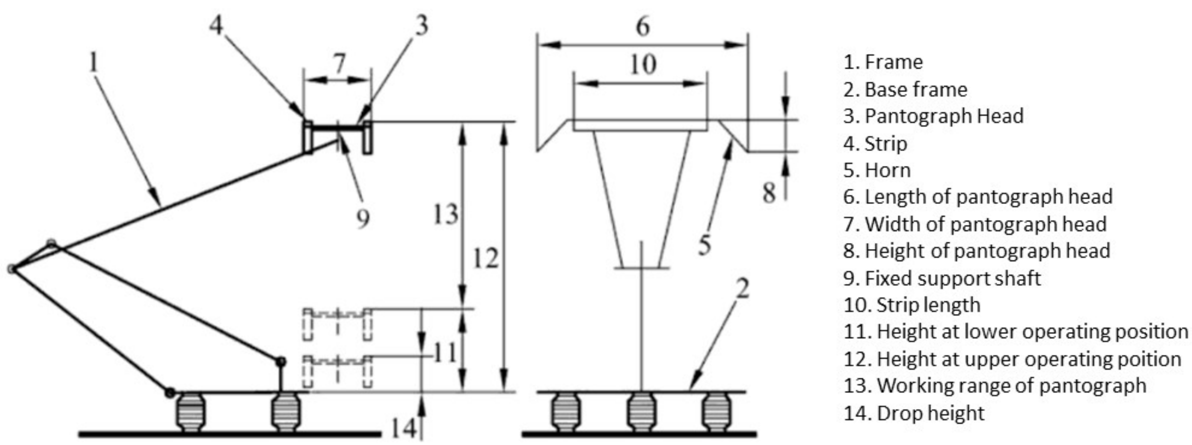


Figure 10. ***Structure of common single-arm pantograph***

The pantograph head is mounted on the top of the frame and supported by the frame. It consists of strips (also called contact strips) and horns and may contain shock absorber on the pantograph head support units. The total length of a strip, measured laterally along vehicle, is called strip length.

Horns turning downward are on both ends of pantograph heads to ensure pantographs passed through overhead crossings of contact lines smoothly.

Pantograph heads can move up and down through expansion and contraction of frames and can rotate a bit around their fixed support bearings. Horizontal dimensions of pantograph heads, measured laterally along vehicle, are called pantograph head lengths; while dimensions of pantograph heads, measured vertically along vehicles, are called pantograph head widths. Pantograph head height means the vertical distance between the lowest point of horn and the highest point of strip.

The frame is a hinge structure enabling the pantograph head to move vertically to the pantograph base frame and is used to support the weight of the pantograph head and transfer static contact force of the pantograph. The frame dimension mainly depends on the operating range of the pantograph required.

In general, the height at lower operating position means the vertical distance between the mounting surface of the pantograph on the insulator and the upper surface of the strip when the pantograph rises to the minimum design height of current collection. The height at upper operating position means the vertical distance between the mounting surface of the pantograph on insulator and the upper surface of the strip when the pantograph rises to the maximum design height of current collection. The difference between the height at the upper operating position and the height at the lower operating position is called the operating range of the pantograph.

The drop height is the vertical distance between the mounting surface of the pantograph above the insulator and the upper surface of the strip or the other higher point on the pantograph structure when the pantograph is in dropping position. The vertical distance between the charged body at the highest place of the pantograph and the charged body at the lowest place of the pantograph is called “electrical thickness” of the pantograph.

3.2.1.1 Pantograph head

Pantograph heads are the most important part of pantographs, and mainly consist of strips, horns and pantograph head supports.

<u>Pantograph strip</u>

Strips are replaceable currents collecting elements of pantographs, they contact with contact wires directly and are easy to wear. Pantographs often use integral double strips, split double strips, or single strips. Operating in extreme conditions, strips are subject to normal mechanical friction and electrical abrasion, and even possible mechanical crashes and strong heat flow erosions.

Usually pantographs are equipped with automatic dropping device that detect damage of strips, any other abnormal pantograph working or damage to drop the pantograph immediately.

Pantograph strips should have enough mechanical strength to withstand vertical vibration of pantograph and contact lines in normal operations and the impact force derived from irregular contact lines in a horizontal direction. They should have a small resistance rate to avoid overheating of contact wires due to high resistance rate of strips under larger collecting currents or avoid overheating, annealing distortion, or even partial hole burning of trip brackets. They also should have small mechanical friction, which is the main influencing factor in reducing their life cycle. contact wires require high maintenance and are difficult to replace; for that reason, the element which mostly withstands the wear is the pantograph strip. In some high speed environments, the self-lubrication is used to lower the friction between wire and strip.

They also need good heat-withstanding and arc-withstanding capability. Electrical arc is not expected to pantograph and overhead contact lines systems but is unavoidable in actual operation. Strips are also affected by weather conditions depending on its characteristics.

Strip bracket

Strip brackets are the base to mounting strips. Their mass counts most of pantograph head masses, their shape and mass have great impact on dynamic performance of pantographs, for that reason are often made of light alloy tubes.

Strip fastening

Strip fastening should be reliable, light, and easy to replace. Metal strips and powder metallurgy strips can be fixed to strip brackets directly with countersink screws or screws supplied with it. But, carbon strips are hard and fragile. Therefore, it is difficult to cut female threads on it so strips cannot be fixed to pantograph heads by screws. In general, with these strips are used nested, bolt, bond, pressing plate, or embedded methods and are assembled the entire carbon strip with metal frame. The metal frame also acts as a bracket and can be mounted to pantograph heads using bolts.

Horn

Arc-shaped horns on both sides of pantographs contact with contact wires in extreme conditions to act as a metal strips, and also enable pantograph heads to pass through overhead crossing of contact lines smoothly. When operating at the lower height under voltage, arc-shaped horns should be made of insulating material to avoid the discharging of horns against roof earthing electrodes.

Pantograph head support unit

Pantograph head support units are important components that would influence pantograph performance. In addition to reliable fastening and light weight, they should ensure smooth contact between strip and contact wire and have higher flexibility than contact wires vibrating at high frequency during sliding. Pantograph heads are often connected to frames via round strings, lea springs, or rubber.

3.2.1.2 Frame

Frames are divided into upper and lower parts, which are linked with hinges. The part above the hinges is called the upper frame and the rest is called the lower frame. There are different types of pantograph frames.

Four-cantilever diamond double-arm frames and double-cantilever double-arm frames

Each cantilever can be divided into upper cantilever and lower cantilever, which are linked with hinges and arranged symmetrically. It looks like part of a diamond, so it is called four-cantilever diamond double-arm frame, or just diamond frame. To increase the rigidity of the entire frame, some braces are often added between left and right cantilevers.

Its advantage is high rigidity but may influence pantograph performance when its mounting surface is not even, or the base is inclined and the frame itself is misaligned, according to operational and manufacturing experience. Apart from that, it is difficult to adjust after assembling.

On the basis of an ordinary diamond frame, designers created and manufactured a double-cantilever diamond double-arm frame structure. It is characterized by a lower frame consisting of front and rear cantilevers, an upper frame consisting of four cantilevers (front, rear, left and right) left and right cantilevers hinged on the top of lower cantilever in an V shape. The entire frame consists of front and rear arms that are symmetrical, looking like a diamond when viewed from the side. Compared with a traditional four-cantilever diamond double-arm frame, this frame has a simpler structure and is lighter in weight and under smaller impact of an inclined mounting face. But its rigidity is reduced more or less.

Single arm frame

A single-arm frame is equal to half of double-cantilever diamond double-arm frames. To ensure a trail of up and down motion of a pantograph, head is near vertical, and the lower frame is provided with a special strut as an auxiliary cantilever.

A single-arm frame is characterized by simple structure, small entire dimension, and light weight, which are favorable to improving dynamic performance of pantographs and reduce the impact of an inclined mounting face. However, its lateral rigidity is low.

Four-cantilever crossed double-arm frame

There is no essential difference between four-cantilever crossed double-arm frame and four-cantilever diamond frame, except for four cantilevers of lover frame, which are extended, and front and rear cantilevers on the same side, which are crossed with each other. Within identical operating range, the mounting area of such a pantograph is approximately two thirds of ordinary diamond pantograph. This can effectively reduce the roof area occupied by a pantograph.

Double-layer frame

With increasing operating speed of electric trains, the dynamic interaction between pantograph and contact lines becomes more and more complicated and requires dynamic characteristics of pantographs to be higher and higher. A double-layer frame is developed in such situations.

The basic concept is for traditional pantographs operating at high speed, change of contact wire height, change of basic waveform of contact wire caused by different elasticity of contact line, and small micro vibration at high frequency in pantograph and overhead contact line systems during high-speed current collection will influence contact quality of pantograph and contact lines. Micro vibration will offset all dynamic performance of small mass above the pantograph head spring. Frames with larger apparent masses will not follow basic waveforms of contact lines as required. Pantographs with double-layer frames can use lower-layer frames to adapt to height variations of contact wires due to different application sites. This height variation is non-periodic and often slow.

Upper-layer frames mainly compensate changes of basic waveforms caused by uneven elasticity of contact lines. A small mass above the pantograph head spring is used to compensate micro vibrations of pantograph and overhead contact line systems.

As shown by operational experience, pantographs with double-layer frame are provided with good dynamic performance and can meet the requirement of high-speed current collection. However, it is complicated in structure and expensive, and is used only in applications with very high operating speed or high operating speed and extensive current collections.

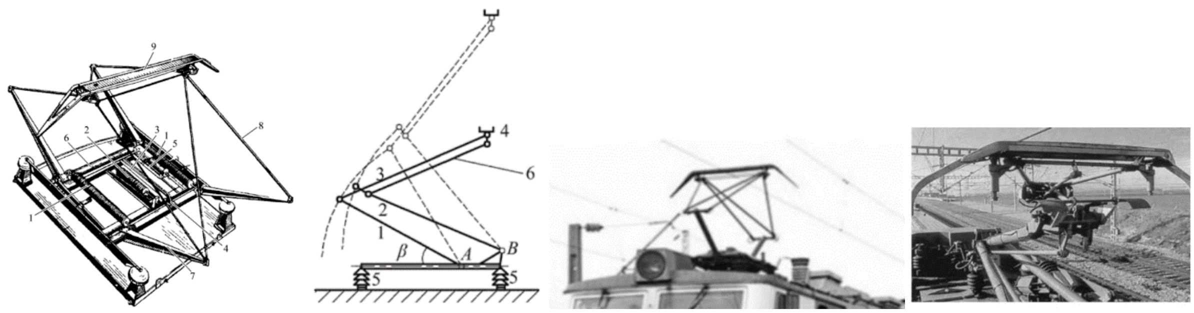


Figure 11. ***From left to right: Four-cantilever diamond double-arm frame, single arm frame, four-cantilever crossed double-arm frame, double-layer frame***

3.2.1.3 Base frame

The base frame is the base to fix pantograph frames. It supports the fixed part of the frame and is mounted on supporting insulators of pantographs.

Base frames are usually made of profile steel, plates through extrusion, or steel tubes through splicing or castings and profile steel through splicing. Base frames should have strong rigidity to avoid distortion of frames during handling and installation, which may impair pantograph performance. Base frame mass occupies a large part of the total mass of pantographs, so a lighter structure is still expected.

Base frames are usually fixed on the roof with three or four supporting insulators. In electric equipment of electric trains, supporting insulators of pantographs are subject to the most extreme operating environment. In addition to sunshine, wind, rain, and strip powder, they may be under large impact forces in case of pantograph and overhead contact line accidents.

Base frames also contain the copper braids that transmit the electricity collected with the strip to the train.

3.2.1.4 Drive System

The drive system is used to uplift or drop pantograph. The system and dropping method may include various structures in the base frame like embodiments, electric, pneumatic or hydraulic motor.

Automatic dropping device

Almost all the pantographs now are equipped with an automatic dripping device, which aim is to minimize the risk of bigger consequential damage to the overhead wire and the pantograph in case of incident.

There are different solutions for the automatic dropping for different pantographs based on air pressure solutions, mechanical bolts or wire tensions.

3.2.2 FGC Maintenance strategy for pantographs

In this section is explained in detail the maintenance done on the FGC Pantograph from train of series 113 model Schunk current collector SBE [12] where integrated and electrically insulated spindle actuator lowers the current collector, shown in Figure 12.

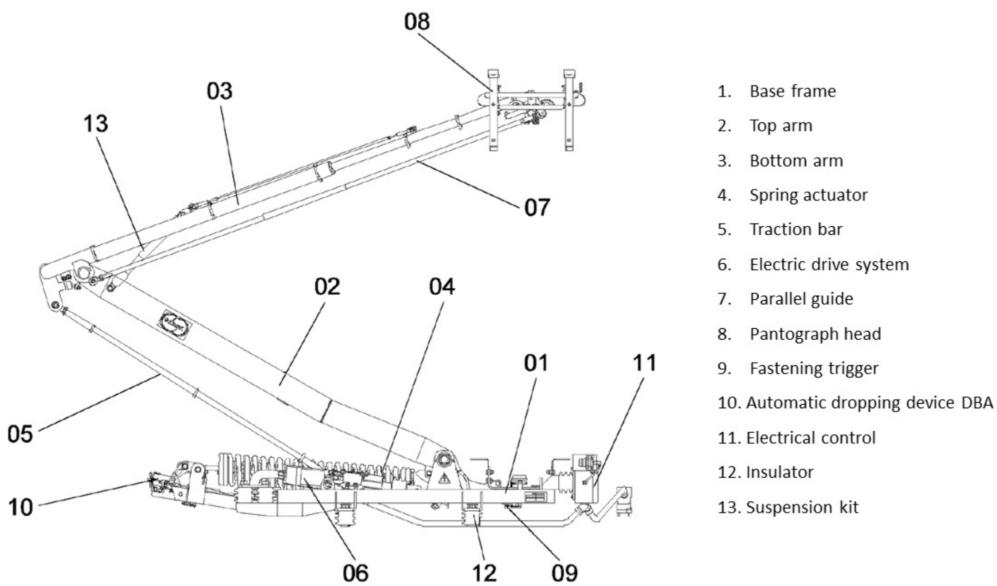


Figure 12 ***FGC Pantograph 113***

The pantograph is raised by means of a spring actuator which acts in a cable and in a curved cam over the bottom arm. The pantograph goes to the lower position by means of the electric drive system, insulated and mounted on the base frame and bottom arm. The mechanism is activated by a magneto engine permanent of continuous current with a magnetic switch.

The suspension kit dims the vibrations and ensures a continuous and uniform movement upwards and downwards, and also ensures good contact between strips and catenary.

The fastening trigger ensures that no oscillations are produced in a resting position and it is opened automatically when the electrical control starts working. The Electrical control is connected with the electric drive system and with the Rolling stock control system by means of a socket in the roof which is electrically isolated and located in the base frame. Inside the electrical control there is an electrical accumulator which allows the pantograph to drop itself in case of tension falling. The electrical control does not need any maintenance, it should not be open due to risk of an electrical discharge, and their maintenance can be only done by the manufacturer.

There are also copper braids composed by flexible copper cables which allow the transmission of current along them and not through other components of the pantograph.

There are installed an Automatic Dropping device which mission is to relax the spring actuator in case of huge forces over the pantograph head to lower the pantograph to reduce the possible damages. This is done through a mechanical process with a bolt that breaks in case of dangerous situations which in turn relaxes the spring. There are three different inspections with different periodicity where the different components are checked and changed, as summarized below:

- **Basic Inspection**
    - Visual inspection of the contact strips
    - Substitution of contact strips if needed
    - Check the performance of the electric drive system and the electrical control by elevation and dropping of pantograph
- **General inspection**
    - Check the static contact force to 80 ± 10N
    - Check the joints screwed following the corresponding tightening torques
    - Visual inspection of the spring cable and grease it
    - Visual inspection of the shock absorber regarding oil leakage
    - Visual inspection of copper braids of current
    - Clean the insulators
    - Check the smoothness of the sliding bearings
    - Check the smoothness of the strip springs
    - Check the performance of the fastening trigger
    - Check the adjustment of DBA, check the performance of the DBA and lubricate it

3.2.3 Failure modes

The following failure modes catalogue has been compiled taking into account FGC's experience as integrated operator and the standards mentioned in section 2.2.3.2. FGC has analyzed its internal maintenance procedures (not included in this document as they are confidential) and failure statistics to come up with the information provided below.

System	Subsystem	Failure mode
Pantograph head	Contact strip	Normal wear
		Asymmetric wear
		High erosion
		Cracks

System	Subsystem	Failure mode
	Horn	Scraped
	Pantograph head support unit	Damaged
		Position misadjusted
		Shock absorber misadjusted
	Other components	Damaged
Frame and base frame	Insulators	Damaged
	Junctions	High internal friction
	Operating positions	Not adjusted
	Copper braids	Damaged
	Other components	Damaged
Drive system	Automatic dropping device	Incorrect working
	Contact force regulation	Not correctly regulated
	Electrical connections	Damaged
	Other components	Damaged

3.2.4 Failures statistics FGC

Pantograph is an easy element of the train which requires little maintenance. The most demanding element is the contact strip. Failures of FGC pantograph in one year have been analyzed and the result is show in Figure 13. Replacement of contact strips is the most common action required in the pantograph and its necessity is detected in the workshop during the different revisions.

Most problematic issue are the failures produced in the drive system. Some of them are detected during operations, not all of them prevent the train unit from riding, but some of them can cause a disturbance.

Most of the important failures of the pantograph are related to the catenary, bad maintenance of one of them can damage the other, for that reason the pantograph catenary system has to be studied as a whole.

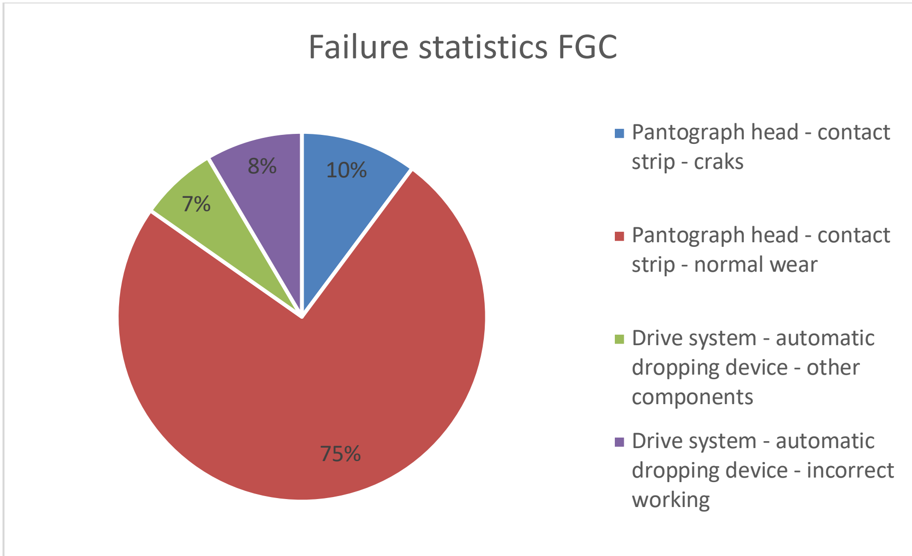


Figure 13. ***Pantograph failure statistics***

3.2.5 Conclusions

Considering coordination and conversations with catenary partners of the project we detect the need to study both pantograph and catenary together and some areas of interest are the following:

- Dynamic force of contact
- Temperature
- Dynamic behavior

3.3 Wheelset

3.3.1 General description and the main components of a wheel

The conventional railway wheelset consists of two wheels rigidly mounted on a common axle. Normally, wheels have a coned or profiled tread with a flange on the inside edge. The wheelset rests on two rails fixed to the sleepers (ties) or other support. It is divided into the main components and the other components. The main components consist of five different elements. A typical monobloc is shown in Figure 14 (left) as well as a tired wheel in Figure 14 (right).

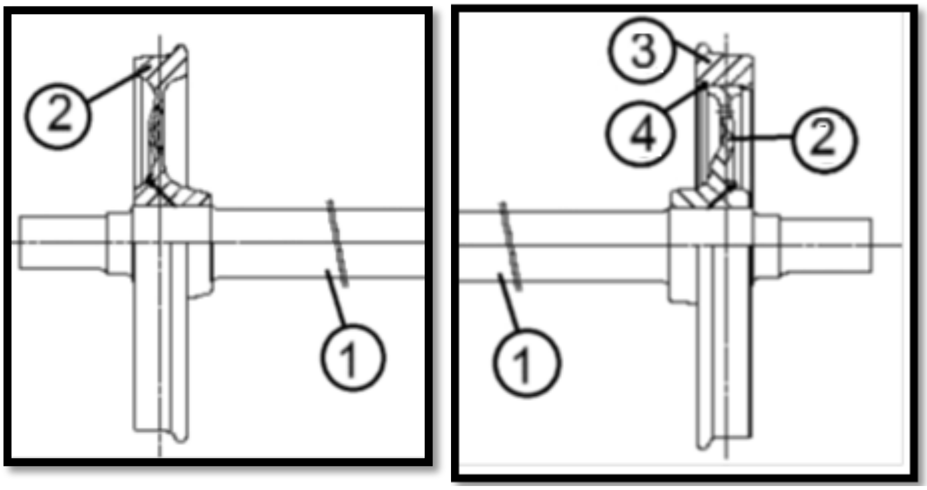


Figure 14. Monobloc wheelset (left): (1) axle, (2) monobloc wheel; tired wheelset (right): (1) axle, (2) wheel center/disc, (3) tire, (4) retaining ring

3.3.1.1 Axle

An axle is a central shaft for a rotating wheel or gear. On trains' wheels, the axle may be fixed to the wheels, rotating with them. In the former case, bearings or bushings are provided at the mounting points where the axle is supported

Straight axles are used on trains (the axle can optionally be protected and further reinforced by enclosing the length of the axle in a housing). A straight axle is a single rigid shaft connecting a wheel on the left side of the vehicle to a wheel on the right side. The axis of rotation fixed by the axle is common to both wheels. Such a design can keep the wheel positions steady under heavy stress and can therefore support heavy loads.

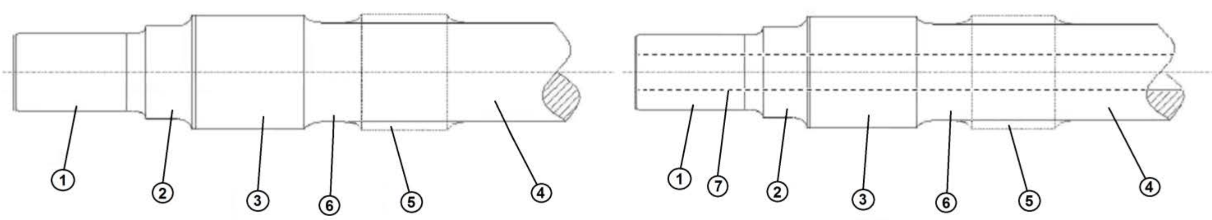


Figure 15. Wheelset axle: (1) Journal, (2) Abutment surface, (3) Wheel seat, (4) Axle body, (5) Seat for brake disc, transmission or final drive, (6) Transition zone between seats, (7) Axle bore

3.3.1.2 Monobloc Wheel

A monobloc wheel, also known as a bandless wheel, is made as a single component. The rim and hub are made as one steel component in dies on heavy presses.

This solution causes a significant increase of wheel exploitation costs. After final reeling – finishing work is performed, it is not possible to restore the appropriate parameters, which results in a need to uninstall and replace the wheel. Better safety is an advantage of such a solution, since there is no clearance between components, since the wheel is a Monobloc.

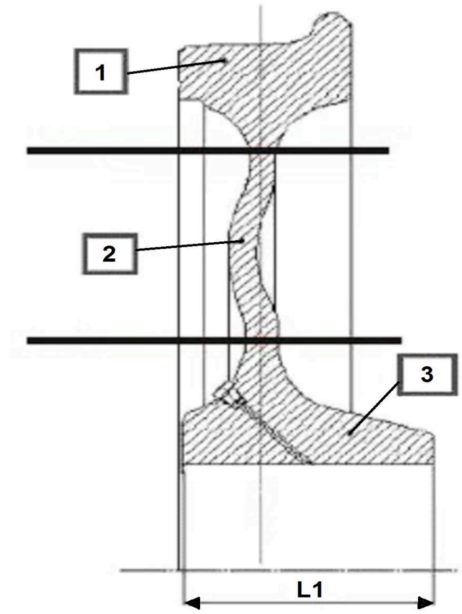


Figure 16. Wheelset. Monobloc wheel: (1) Rim, (2) Web, (3) Hub

3.3.1.3 Tire

A rail tire is usually made from steel, and is typically heated and pressed onto the wheel, where it remains firmly as it shrinks and cools. The tire is in contact with the rail, which wears out in service. The profile of the tire is significant for safe running of the trains. Taper is given on the tread to have higher diameter near the flange and lower diameter at the outer edge, to facilitate curve negotiation.

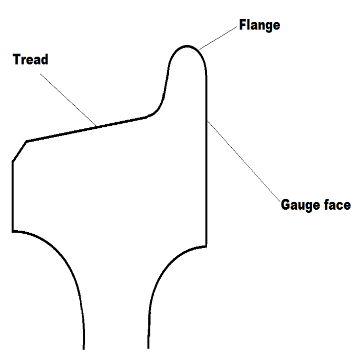


Figure 17. Wheelset profile

3.3.1.4 Wheel center/disc

The wheel center/disc is a part of the wheel between the hub and the tire. It is the thinnest component of the wheel as it does not come in contact with rail nor it is coming in contact with the axle.

3.3.1.5 Retaining ring

The retaining ring is placed on wheel to fix the tire.

3.3.1.6 Other Components

In addition to the main components listed above the wheel can be divided into the other components which consist of four different elements. A quick overview and a graphical overview of the other components:

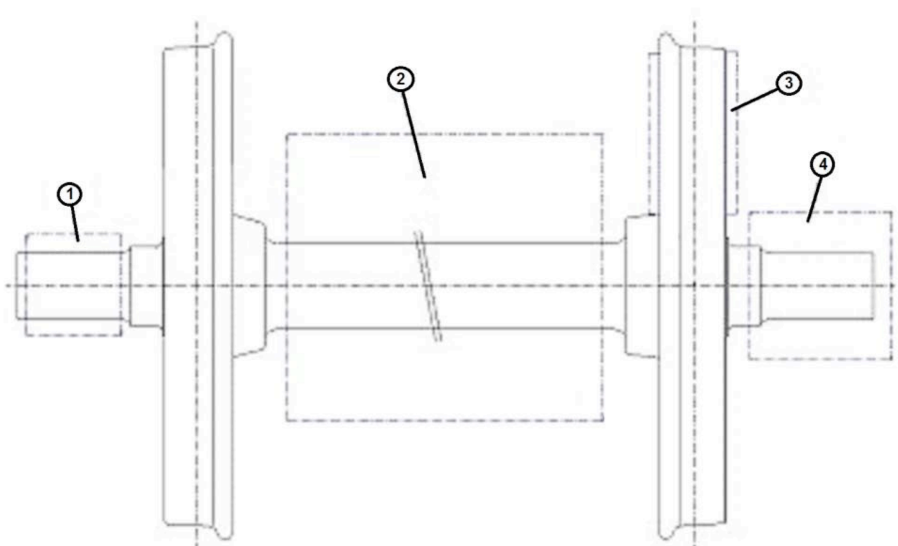


Figure 18. Wheelset. Other components: (1) Bearings, (2) Brake disc, transmission or final drive, (3) Wheel-mounted brake disc, (4) Axle box with bearings

3.3.1.7 Wheel/Rail Interaction

Wheel/rail contact physically occupies an area the size of a small coin, and such contact transfers the load from a vehicle ranging from 3.5 t (28 t lightweight passenger coach) to 17.5 t (heavy freight car of 140 t) per wheel. The material in and around the contact area is therefore highly stressed. High rates of wear might be expected from such contact but, because the load is applied and removed many times during the passage of each train, there is the added possibility of fatigue of the rail surface. The ideal material, which would have zero wear and suffer zero fatigue, and which would nevertheless be economically viable, is yet to be found.

The selection of railway wheel and rail profiles is a challenge that has faced engineers since the dawn of the railway age. From the first cylindrical wheels running on flat plates, wheels were made conical to produce better guidance, and flanges were added for safety. Modern wheels often have complex profiles based on the shape of worn wheels in an attempt to increase their life. Rails also now have complex profiles with different radii on the rail head, where the wheel tread makes contact, and on the corner, where the flange contacts. A high level of wheelset conicity allows good curving behavior even in the tightest curve, without flange contact. This can however, lead to a relatively low critical speed and possibly dangerous hunting instability. A low level of wheelset conicity on the other hand, allows stable operation at high speeds, but flangeway clearance will quickly be used up in curves, resulting in flange contact and possible flange climb derailment. Flange angle and root radius are also variables that can have a significant effect on the potential for derailment. In addition to vehicle behavior, engineers must consider stresses on both the wheel and rail.

The conventional railway wheelset consists of two wheels rigidly mounted on a common axle. Normally, wheels have a coned or profiled tread with a flange on the inside edge. The tread cone angle is about 2º, while the flange cone angle is about 70º. The wheelset rests on two rails fixed to the sleepers (ties) or other support (e.g., embedded rail). A typical wheelset on rails is shown in Figure 19. A wheelset runs on rails normally inclined (canted) at 1 in 40 (1 in 20), see Figure 20. The gap between the flange of the wheel and the gauge side of the rail is such that it allows about 9 mm lateral wheelset displacement before flange contact occurs.

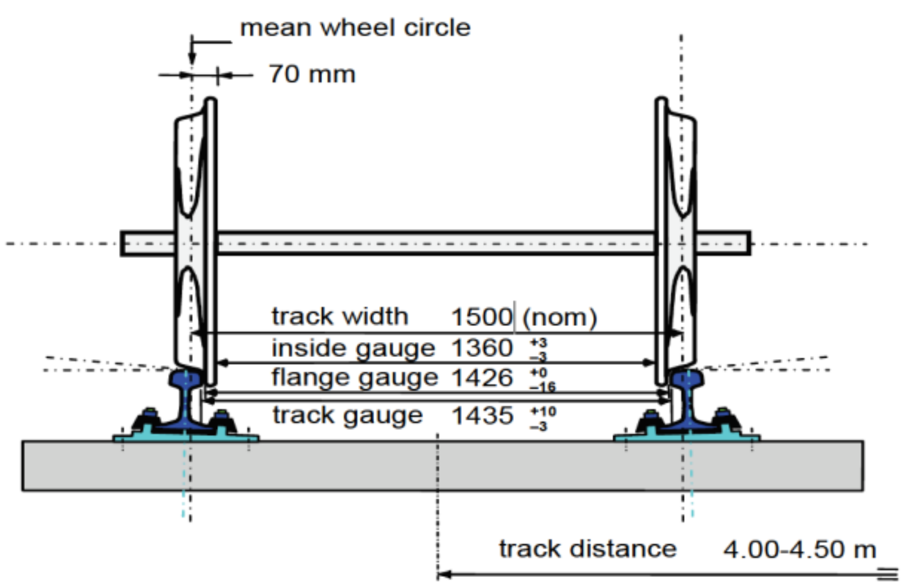


Figure 19. Wheels on rails

The shapes of wheel/rail are important to vehicle stability, wheel/rail interaction forces, contact stresses, and wear characteristics. Vehicle dynamic response, wheel/rail contact forces and positions, and track dynamic response can be derived from vehicle/track dynamic simulation. Normally, vehicle and track dynamics models are considered separately, due to complicity of the models, and limitations on computer recourses.

Vehicle and track dynamics systems interact via wheel/rail interface, using output from one model as input for another, and vice-versa. For example, track irregularities can be used as an input for wheel/rail contact, causing disturbances in contact forces, which in turn will be used as an input for the vehicle model. To determine forces in wheel/rail contact, values of creepage and spin are required, which can be obtained from analysis of geometric contact between wheelset and track.

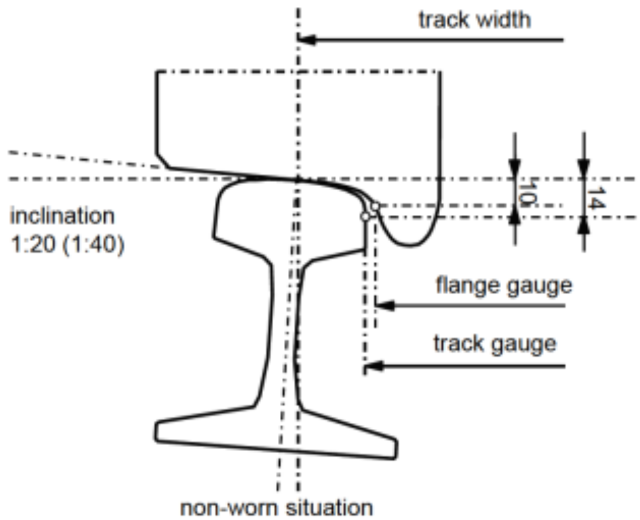


Figure 20. Wheels on rails (detail)

3.3.2 Maintenance of the wheelset

In this section it is explained in detail the maintenance that should be done on all types of trains. The maintenance of the wheelset involves the following points below:

a) maintenance of in-service wheelsets/axle boxes
b) maintenance of off-vehicle wheelsets/axle boxes
c) special maintenance attention after in-service incidents (e.g. overloads, hot axle box detection, wheelset
d) bearings subject to water ingress, etc.)

An in-service wheelset shall be maintained by a maintenance undertaking qualified in this type of wheelset.

For maintenance of wheelsets, as a minimum, the following shall be utilized:

e) a maintenance plan
f) service experience
g) an organization for component and production management
h) specific wheelset maintenance tools
i) qualified staff for non-destructive testing and welding

3.3.2.1 Maintenance organization plan

The general maintenance of the wheelset is organized as shown in Figure 21.

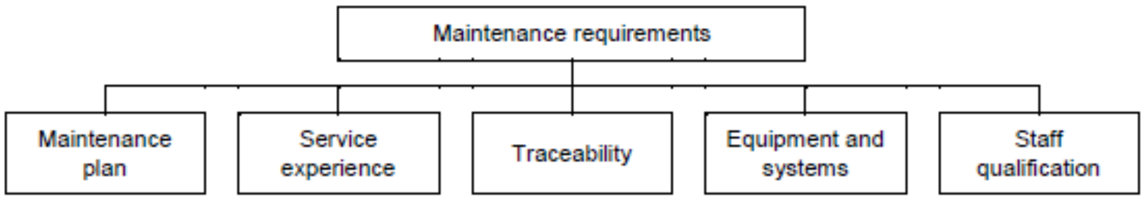


Figure 21. Wheelset maintenance organization

For wheelset maintenance, it is necessary to have a maintenance plan for the wheelsets when in-service and off-vehicle. The maintenance plan shall specify:

j) The actions to be performed to meet the requirements and mandatory operations listed in this standard
k) The maintenance intervals
l) Any specific measures to be implemented

The maintenance plan shall be written by a competent technical department in the railway field and approved by the technical expert for the owner undertaking.

3.3.2.2 Off-vehicle maintenance

Maintenance plan

The maintenance plan shall specify:

a) Qualified procedures and intervals for non-destructive tests
b) Any special procedures (e.g. demagnetization of the bearings, etc.)
c) Cleaning instructions
d) Criteria for the rejection of the bearings and their protection after the overhaul
e) Approval criteria for different constituent parts (e.g. dimensions, etc.)
f) List of work to be carried out to restore the wheelset to comply with the requirements of this standard
g) List of tests to be carried out
h) Specific values resulting from service experience

Key operations for off-vehicle wheelset maintenance

The key operations are as follows:

a) Wheelset cleaning with protection of the individual component, if required;
b) General inspection
c) Complete inspection of the wheelset components (e.g. axle, wheel, bearing, axle box, lubrication, etc.);
d) Overhaul of the axle boxes (e.g. dimensions manganese wear plate, etc.)
e) Reprofiling, if required
f) Assembly of wheels, if required, according to EN 13260

g) Assembly of bearings, if required: only processes qualified by the technical expert of the owner
h) Undertaking shall be used
i) Protection against corrosion
j) Final check for conformity of the wheelset to the requirements of this standard
k) Drafting of a report to ensure traceability of all the operations and including the wheel assembly press-fit
l) force displacement diagrams (cold assembly) or mechanical resistance test confirmation following shrink fitting (hot assembly)

Off-vehicle wheelset cleaning

The maintenance plan shall specify the requirements associated with the cleaning of wheelsets and their components.

The following cleaning procedures can be used:

a) High-pressure water jet
b) Brushing
c) Mechanical scouring (e.g. plastic shot blasting, etc.) provided it does not change the fatigue limit characteristics of the components (e.g. axle, etc.) and does not risk concealing any cracks by deforming the component surfaces

Any other cleaning method shall be defined in the maintenance plan. The axle box protection shall be specified in the maintenance plan.

3.3.2.3 In-service wheelset maintenance

The maintenance plan shall include:

1. The periodicity of and criteria for dimensional checks;
2. The periodicity of and criteria for non-destructive tests;
3. The periodicity and criteria for the mandatory in-service maintenance operations;
4. Any periodicity and criteria and specifics for equipment not subject to Directive 2008/57/EC.

3.3.3 Failure modes

The following failure catalogue has been elaborated taking into account references [4] and [5], as well as the standards mentioned in section 2.2.3.3.

System	**Subsystem**	**Failure mode**
Wheels	All types of wheels	Wheel flat
		Metal build-up

System	Subsystem	Failure mode
		Shelling, cavities
		Scaling
		Tread indentation
		Isolated traverse cracking
		Circularity defect (local tread collapse; periodic or stochastic out of round)
		Spalling (thermal effects due to tread braking)
		Thermal crack
		Wheel tread roll-over
		Damage to chamfered corner
		Wheel tread – grooves and channels
		False flange
		Damage on the flange
		Sharp-edged radial marks and radial defects on the internal face of the rim
		Damage resulting from identification markings
		Damage from lathe driving tools
		Sharp-edged circumferential defects on the web or wheel centre
		Sharp-edged radial defect on the web
		Wheel web hole defects
		Cracks in the wheel hub
	Monobloc wheels	Deep sub-surface tread

System	Subsystem	Failure mode
		Wheel web (Defects on the web of a wheel used as braking surface; Overheating affecting the wheel rim/web transition)
		Exceptional thermomechanical stressing in tired wheels
	Axle	Corrosion
		Axle protection defect – Damage on the painting/coating
		Defects Around the whole circumference
		Circumferential defects (on a singular zone; around the whole circumference)
		Notches and impact damage
		Longitudinal defects
		Damage in the interference fit zones
	Axle Box	Axle box body (cracking or failure)
		Thermal damage to the axle box
		Damage at the weld seams of the manganese wear plates
		The state of the bearing housing bore
		Out-of-roundness of the bore of the wheelset bearing housing
		Damage allowing water or dust to penetrate
		Missing or loose locking pieces
		Missing or loose locking and mounting bolts
		Excessive wear of the bearing housing
		Axial and radial clearance depending on the axle box type
		Internal damage (for example due to running noise

System	Subsystem	Failure mode
		Disconnected, missing or damaged constituent elements or cables
		Disconnected, missing or damaged wheelset guidance elements
		Traces of lost grease/oil projected regularly over the entire circumference of the central portion of the wheel
	Wheelset	Wheel distortion
		In service axial or angular movement of a wheel or of one of the other components (Axial movement; angular movement)

3.3.4 Conclusions

Taking into account coordination and conversations of the project we detect the need to study both wheel and track together and some areas of interest are the following:

- On board monitoring to detect track (wheel) defects.
- Condition of the axle bearings.
- Detect the condition of the wheels profile and the instability of the train.
- Collect data about detached tires.

3.4 Rail

3.4.1 General description

The rails, along the history and development of the railroad, have been evolving their section until being classified in tree main groups:

- **Double Headed Rail.** Both the upper and lower tables were identical, and they were introduced with the hope of doubling the life of rails. When the upper table is worn out then the rails can be placed upside down reversed on the chair and so the lower table can be brought into use. Therefore, this type of rail is practically out of use.
- **Bull Headed Rails.** These rails were made of steel. The head is of larger size than foot and the foot is designed only to hold up properly the wooden keys with which rails are secured. Thus, the foot is designed only to furnish necessary strength and stiffness to rails
- **Flat Footed Rails.** These rails were first of all invented by Charles Vignoles in 1836 and hence these rails are also called vignols rails. It consists of three parts. The foot is spread

out to form a base. This form of rail has become so much popular that about 90% of railway tracks in the world are laid with this form of rails.

Figure 22. Types of rails

We are going to focus on the third one: flat-footed rails. The functions that the rail must play in the railroad are:

- Resist the efforts introduced by the passage of vehicles and transmitted to the rest of the elements of the track. The efforts can be of several types:
    - Vertical efforts due to the weight of the train
    - Lateral forces due to loop movement and unbalanced transverse acceleration
    - Longitudinal efforts due to temperature variations, and to the traction and braking of the vehicle
- Guided the wheels, achieving the greatest possible smoothness
- Transmit the electricity needed for traction, on electrified lines (return currents) and signaling circuit currents

The rail consists of three parts, as illustrated in Figure 23:

- **The Head**: used for supporting and guiding the wheels of trains
- **The Web**: intermediate zone of small thickness that serves to join the head with the lower part of the lane. It transmits the charges of the head.
- **The Foot:** allows good support on the sleeper, conferring high degree of stability without the need of special devices.

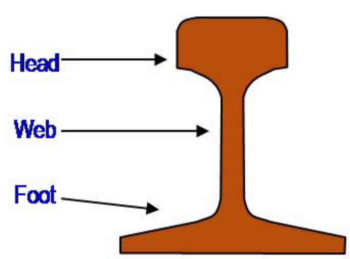
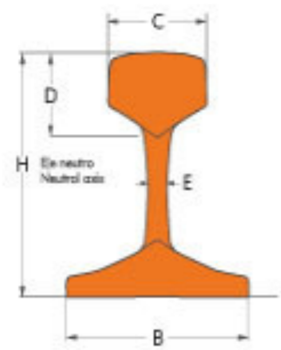


Figure 23. Parts of the rail

There are different kinds of rails according different standards, we are going to focus on the European ones.



Type of Rail	Standard	Dimensions mm					Section S	Mass m
		H	B	C	D	E	cm²	kg/m
European standards								
RN 45	UNE 25122	142,00	130,00	66,00	40,50	15,00	57,05	44,79
45E1 (BS 90A)	EN 13674 - 4	142,80	127,00	66,60	46,00	13,80	57,45	45,10
46E2 (U33)	EN 13674 - 1	145,00	134,00	62,00	47,00	15,00	58,04	46,27
49E1 (S49)	EN 13674 - 1	149,00	125,00	67,00	51,50	14,00	62,92	49,39
49E5	DBS 918 254-1	149,00	125,00	67,00	51,50	14,00	62,59	49,13
50E6 (U50)	EN 13674 - 1	153,00	140,00	65,00	49,00	15,50	64,84	50,90
54E1 (UIC54)	EN 13674 - 1	159,00	140,00	70,00	49,40	16,00	69,77	54,77
54E2 (UIC54E)	EN 13674 - 1	161,00	125,00	67,00	51,40	16,00	68,56	53,82
54E3 (S54)	EN 13674 - 1	154,00	125,00	67,00	55,00	16,00	69,52	54,57
54E4	DBS 918 254-1	154,00	125,00	67,00	55,00	16,00	69,19	54,31
60E1 (UIC60)	EN 13674 - 1	172,00	150,00	72,00	51,00	16,50	76,70	60,21
60E2	EN 13674 - 1	172,00	150,00	72,00	51,00	16,50	76,48	60,03

Figure 24. Types of Rail, Europen Standars

In order to define and locate the failures on the rail it is mandatory to define the parts/sides of the rail that are affected by the rolling stock and the directions and plane of the rail.

3.4.1.1 Terminology used for rail locations

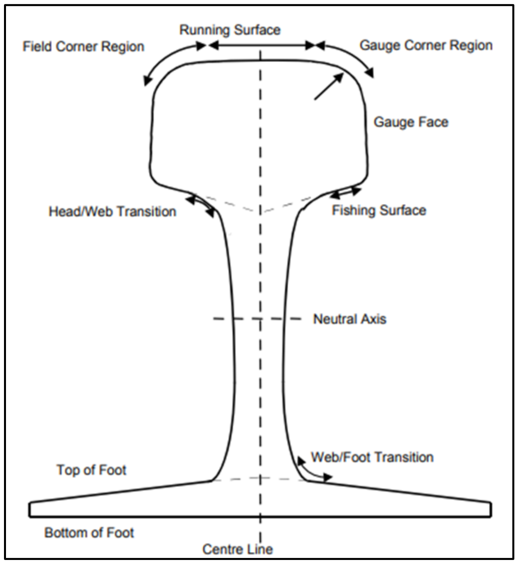


Figure 25. Rail locations

- ***Running Surface***: The zone on top of the rail head, which makes contact with the wheel tread. In tangent and low rails this region can range in width from very narrow to very wide depending on the wheel and rail profiles.
- ***Gauge Corner Region***: The top corner on the gauge side of the rail, which makes contact with the wheel throat region.
- ***Gauge Corner***: The single point in the gauge corner region, the tangent of which is at 45° to the horizontal (with or without cant).
- ***Field Corner Region***: The top corner on the field side of the rail. Contact can occur in this region depending on the wheel and rail profiles.
- ***Fishing Surface***: The region at the bottom of the rail head, which makes contact with fish plates.
- ***Rail Centre Line***: The vertical center of the rail section.
- ***Rail Head***: The region of the rail that is above the extensions of the fishing surfaces to the rail center line.
- ***Rail Foot***: The region of the rail that is below the extensions of the top of foot surfaces to the rail center line.
- ***Rail Web***: The region of the rail that is between the rail head and the rail foot.
- ***Head/Web Transition***: The transition region between the rail head and web sections.
- ***Neutral Axis***: The vertical distance of the rail at which the Second Moment of area of the section above is the same as the section below. This is the point at which, in bending, there is no tension or compression.
- ***Web/Foot Transition***: The transition region between the rail web and foot sections.

- ***Top of Rail Foot***: The region on top of the rail foot, which makes contact with rail fasteners or insulating biscuits.
- ***Bottom of Rail Foot***: The region on the bottom of the rail foot, which makes contact with sleeper plates or rail pads.
- ***Toe of Foot***: The edge region of the rail foot.

3.4.1.2 Terminology used for directions and planes for rails:

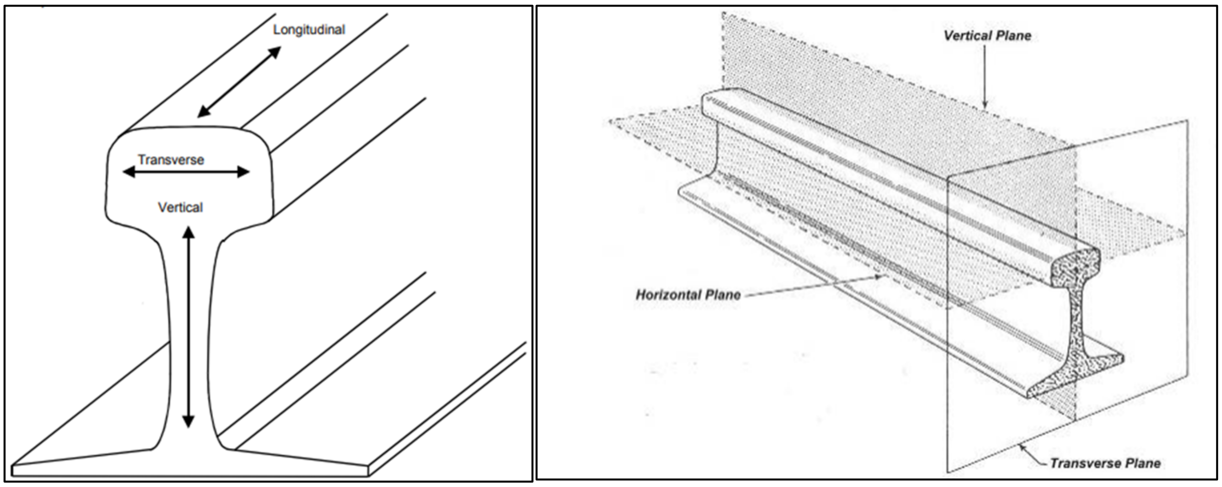


Figure 26. Rails, planes and directions

- **Longitudinal direction**: along the rail
- **Transverse direction**: across the rail
- **Vertical direction**: normal to the rail
- **Vertical plane**: vertical along the rail
- **Horizontal plane**: horizontal along the rail
- **Transverse plane:** transverse across the rail

Another classification also considers the fact that defects may be located at the rail ends, away from the rail ends or in welding zones.

- **Rail end**: The part of the rail located at the level of the fishplates.
- **Zone away from rail end**: Zone comprising all parts of the rail located away from the rail ends and from the welding zones.
- **Welding zone**: The welding zone stretches 10 cm to either side of the centre-line of rail welds, in other words 20 cm in all. Any defect of internal origin occurring in the zone shall be classified as a welding defect. Defects of external origin shall be classified according to their own specific codes.

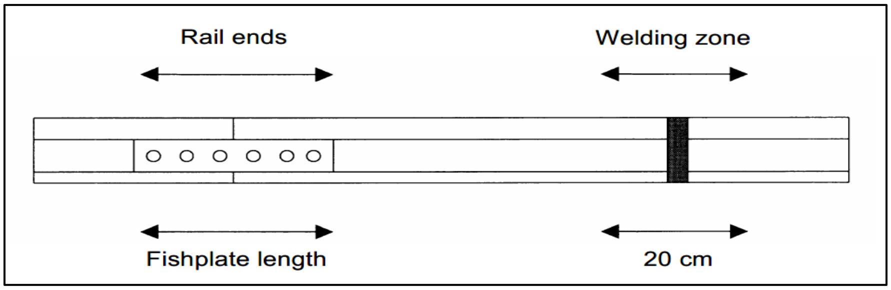


Figure 27. Rail locations

3.4.2 Maintenance of the rail

The rail is subjected to different actions from the rolling stock that causes wear and faults. Generally, there are three main types of rail wear, that is, side wear, vertical wear, corrugation wear.

Side wear

Is the one that occurs at the side of head of rails caused by the train wheels because of the interaction, causing the change of rail profile. The side wear almost occurs on small radius curves or in a track that is not straight, because the gauge is longer than the proper one causing a snake movement of the train.

Figure 28. Side wear

Vertical wear

Is the wear that occurs at the top of head of rails. The top of the rail head is worn out and damaged in the vertical direction. The main caused of this wear is the excessive load of the track

Figure 29. Vertical wear

Corrugation wear

On the top surface of rails, there occurs uneven but regular corrugation shape of wear, which can be generally divided into long corrugation wear and short corrugation wear. It is thought that it can be caused by a faulty contact force between the rail and the wheel because of a reduction of the rail´s stiffness.

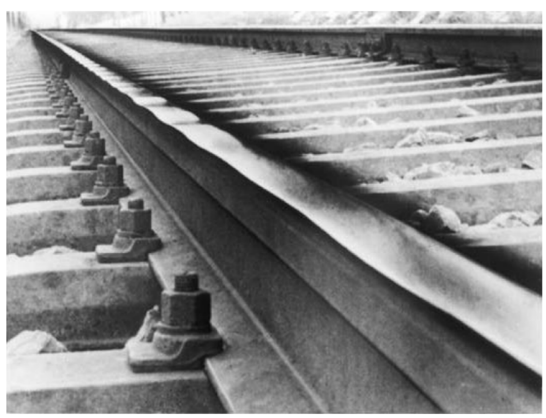


Figure 30. Corrugation wear

3.4.2.1 Rail inspections techniques

Visual inspections/ testing

Visual inspections are an integral component of non-destructive rail testing: With the naked eye and aided by mirrors, a magnifying glass and artificial light.

Metallic hammer

Is used to detect external discontinuities that can´t be detected in a visual inspection or when the discontinuities are internal. The inspection is done by hitting the rail with a 0.5 kg weigh hammer. It is very important to detect the sound this crash made and the rejection that the rail does. A hollow sound and a less extensive rejection mean a discontinuity.

Liquid Penetrant Examination

Liquid penetrant examination is one of the most popular Nondestructive Examination (NDE) methods in the industry. Liquid penetrant exams check for material flaws open to the surface by flowing very thin liquid into the flaw and then drawing the liquid out with a chalk-like developer.

In particular, the working principle of LPI (liquid penetrant inspection) operations is based on a low-tension liquid substance and with high wetting power capable of penetrating into very fine surface discontinuities. The surface defects absorb the liquid by capillarity and not by gravity, such main characteristic, which is the basis of all testing methods, makes it easy to check surfaces difficult to access regardless of their position.

A second substance (detector) highlights the capillary rise, forming visual indications to the naked eye at the same level of the defect. The indications obtained must be observed and evaluated under white light."

Ultrasonic inspections

Ultrasonic testing is the most widely used method for examining rails for flaws and irregularities in the metal. The rail's susceptible areas are examined using nine transducers set at angles of 0, 40 and 70 degrees. All rail defects in the rail head, web and base can be seen in real time. The data collected during the test, e.g. B-scans, permanently document the rail's condition at the time of inspection. Besides recording any irregularities, the inspection also easily recognizes squats, deep head checks and corrosion on the rail base. Audible and visual signals reveal exactly where a flaw in the rail is located. The user can set the threshold values and all the parameters such as fault length, depth and amplitude are recorded and saved. The findings can be sent directly to the office via the internet.

Figure 31. Ultrasonic inspection devices

Pulse magnetic Flux leak / Magnetic particle testing

It is a technique for crack detection and characterization, the presence of a crack on a magnetized sample will disturb the initial flow of flux, since the permeability of the defective part will be lower than that of the non-defective parts, resulting in an increase in the magnetic reluctance

Eddy current

One established method for detecting surface defects is eddy current testing. Network operators use this method to detect and evaluate surface defects with depths of between 0.1 and 2.7 mm that are caused mainly by rolling contact fatigue. Four eddy current probes are deployed per rail and these probes can be used on all the common rail profiles like S 49, UIC 54 or UIC 60. They are set at different angles relative to the rail‘s running edge. By exploiting the probe‘s optimum depth range, we can quantitatively determine the crack length and crack depth of head checks more precisely. Eddy current testing examines the rail‘s running surface and running edge and records both the defect frequency per meter and damage depths of up to 2.7 mm below the running surface. The method is also suitable for inspecting the flexible area on the switch points.

3.4.2.2 Rail maintenance operations

Repair of the rolling surface by electric arc welding

The method of repair defects of the running surface of the rails consists in eliminating the faulty zones by replacing the lack of material with a filler steel with equivalent mechanical properties of hardness to wear to avoid altering its structure or causing cracks in the repaired area.

This metal comes from the fusion of a welding rod constituted by an electrode, a metal tubular wire or any other element that is suitable to originate it under the required conditions. Their deposit on Rail is achieved by attaching both to an electrical power source and blowing up an arch between them when approaching them at a certain distance but, for this deposit to be correct, the rail must stay at a certain temperature for the entire duration of the operation.

Figure 32. Area repaired by arc welding

The electric arc produced reaches a temperature of around 3,300 ° C and, when it is created, it forms a point of liquid steel in the base metal that receives the name of "fusion bath". It melts, too, the extreme of the rod and the tiny drops that originate from filler metal fall into the bath giving place a mixture between the two steels and causing, when falling, short circuits between the rod and the rail that decrease the tension of the electric arch until it almost annuls it, although primes again by the action of the electric current facilitated by the ionization of the column of hot metallic vapor created by the arc between the welding rod and the rail.

The displacement of the welding rod causes new melting baths and new deposits of metal contribution, giving rise to the so-called laces of the recharge that provide the repair of the rail.

Grinding

Grinding is a maintenance operation used to restore the profile or remove irregularities from the rail head in order to extend its useful life. Rail grinding can be broken down into three different types: initial, preventive and corrective.

- Initial grinding is performed on rails that are freshly laid during new construction or after re-railing. Initial grindings correct construction damage and adds the final touch to optimal opening conditions. Experience has shown that grinding new rails retards the onset of track deterioration. Initial Grinding for new rails: the start of corrugation is delayed, improve the lifecycle of the rail
- Preventive grinding involves intervening before data has matured. The idea is to treat the rail when damage is at the embryonic stage. This approach is based upon cyclical timing. The grinding campaigns are steered in accordance with cumulative track loading, Preventive Grinding, eliminates vibrations on the rolling surface plane, leads to significant savings in replacement and maintenance costs
- Corrective grinding is based on symptom-related interventions. Campaigns are directed by monitoring damage against preset levels, such as removing short pitch corrugation once it reaches 0.05 mm depth. Corrective Grinding improve the lifecycle of the rail.

There are other kinds of grinding that could maybe be included in the previous one, but are worth mentioning separately:

- Asymmetric Grinding: improve (25% 80%) the lifecycle of the rail installed in curves
- Acoustic Grinding: reduce the noise between the wheel and the rail
- Anti-head check Grinding: prevent the rail contact fatigue
- Grinding for gauge repair: to prevent the instability of the rolling stock

Figure 33. Rail Grinder

Railway replacement operations

Consist on replace the non-useful rail by a new one, if there are a lot of faults in the same area it should be studied by the experts if the replacing of the rail is cheaper than the resurfacing or the grinding or if a maintenance operation is effective. We can find to different kinds of tracks:

The one that is composed of rails connected with rail joint bars and the ones that are constructed by long-welded rails.

In the long-welded rail tracks the rail is replaced by a continuous welded rail stressing process with the limitation of the length of the rail that is going to be welded, it has to be less than 18 m, between 18 and 72 m or longer than 72 m.

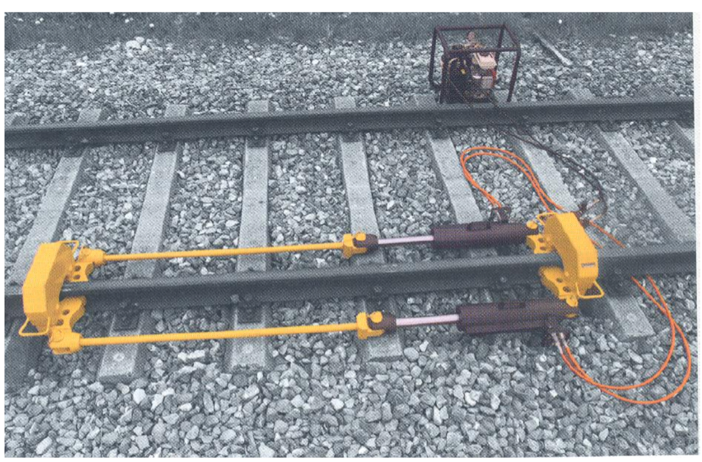


Figure 34. Stressing jack

3.4.3 Failure modes

The failure catalogue compiled in this section has taken into account the UIC 712 leaflet [6] and the standards mentioned in section 2.2.3.4.

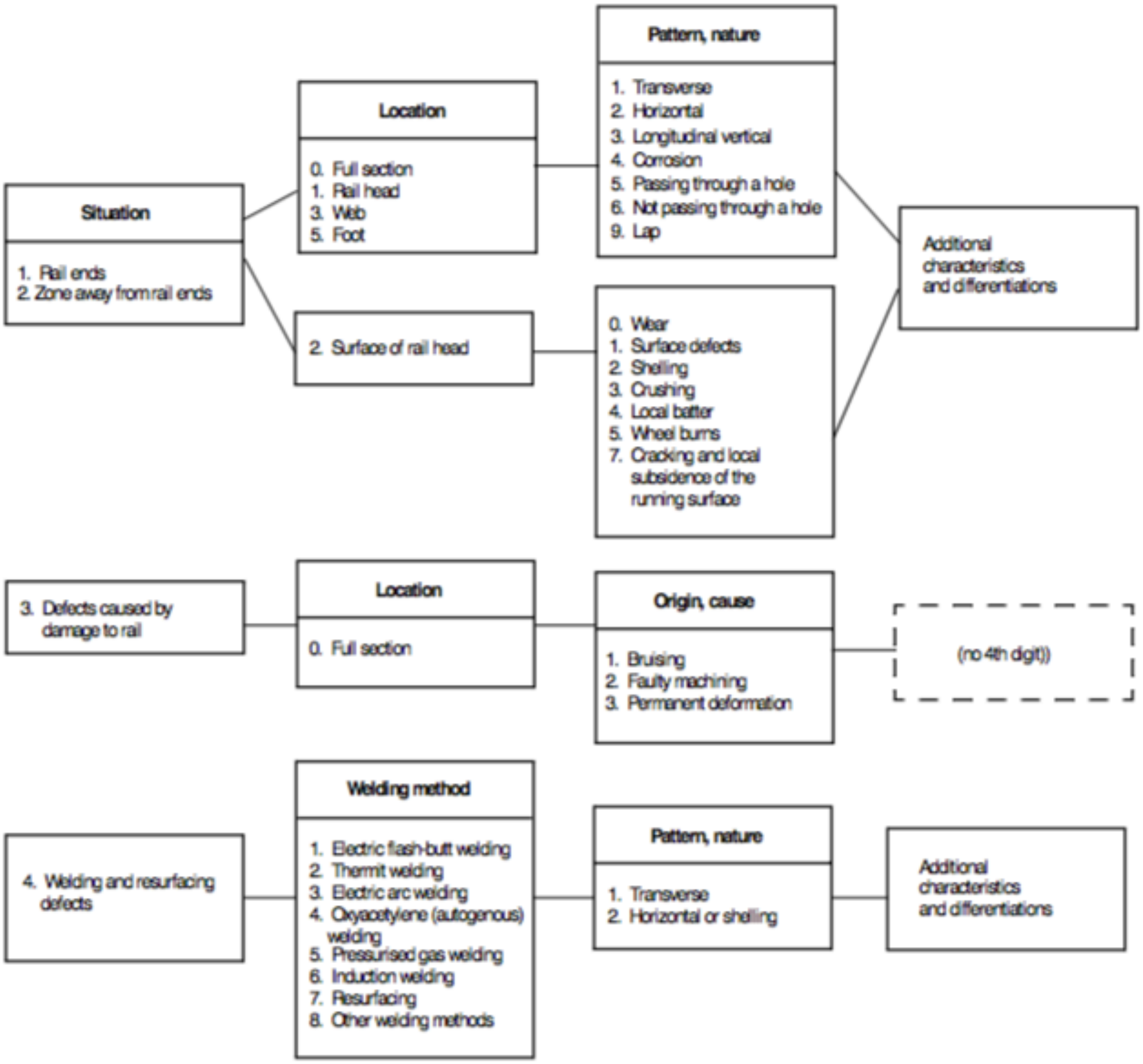


Figure 35. Rail defects according to UIC 712 leaflet

System	Subsystem	Failure mode
Defects in rail ends	Full section	Transverse break without apparent origin
	Head	Progressive Transverse Cracking (kidney-shaped fatigue crack)

System	Subsystem	Failure mode
		Horizontal cracking
		Longitudinal vertical cracking
		Surface defects
		Shelling of running surface
		Crushing
		Local batter of running surface
		Wheel burns
	Web	horizontal cracking at the web-head fillet radius
		horizontal cracking at the web-foot fillet radius
		longitudinal vertical cracking in the web (piping)
		corrosion
		Star cracking of fishbolt holes
		Lap
	Foot	Longitudinal vertical cracking
		Corrosion
Defects away from rail ends	Full section	Transverse break without apparent origin
	Head	Progressive Transverse Cracking (kidney-shaped fatigue crack)
		Longitudinal vertical cracking
		Short pitch corrugation
		Long pitch corrugation

System	Subsystem	Failure mode
		Lateral wear
		Abnormal lateral wear
		Shelling of the running surface
		Shelling of the gauge corner
		Head checking/fissuring/Scaling at the gauge corner
		Crushing
		Local butter of running surface
		Isolated wheel burn
		Repeated wheel burn
		Squats/Cracking and local depression of the running surface
	Web	horizontal cracking at the web - head fillet radius
		horizontal cracking at the web - foot fillet radius
		Longitudinal vertical cracking (piping)
		Corrosion
		Cracking around holes other than fishbolt holes
		Diagonal cracking away from any hole
		Lap
	Foot	Longitudinal vertical cracking
		Corrosion

System	Subsystem	Failure mode
Defects caused by damages to the rail	Full section	Bruising
		Faulty machining
		Permanent deformation (warped rail)
Welding and resurfacing defects	Electric flash-butt welding	Transverse cracking of the profile
		Horizontal cracking of the web
	Thermite welding	Transverse cracking of the profile
		Horizontal cracking of the web
	Electric arc welding	Transverse cracking of the profile
		Horizontal cracking of the web
	Oxyacetylene welding	
	Pressurised gas welding	
	Induction welding	
	Resurfacing	Transverse cracking of the head
		Detachment or shelling of the resurfaced portion
	Other welding methods	Transverse cracking under electrical connection

3.4.4 Conclusions

Rail maintenance is a challenging task due to the variety of failure modes, which need specific maintenance operations and inspection techniques. Traditionally, inspection is carried out by walking the track (e.g. visual inspection) or by dedicated measurement equipment. These techniques can be very precise, but are time consuming, require the closure of the track and are hence expensive. For these reasons they can only be conducted in defined time intervals. To enable predictive maintenance schemes, which could significantly reduce maintenance costs, a quasi-continuous inspection is required as provided by the SIA service iRailMon. Different use cases of the SIA services will be described in the following chapter.

4 Definition of Use Cases

Chapter 3 has compiled a detailed set of failure modes and degradation mechanisms related to the assets relevant to SIA, as well as the associated maintenance actions. This set of failure modes implies many different means of detection and handling of information. Therefore, it is not feasible to tackle them all in this project.

For that reason, a set of use cases have been selected in terms of

- Their impact in the operations and frequency of appearance
- The technical feasibility of their detection by means of low-cost sensors[1]
- The feasibility of predicting the evolution of the damage in terms of physical modeling
- The interests and feedback from end-users of the consortium

Even though a significant set of the failure modes presented in chapter 3 will be eventually managed within SIA services (i.e. in terms of management of data and visualization of information), just the following set of use cases will exploit the full functionality of SIA:

- **iCatMon.** The contact wire is the main component of an overhead contact line. Its main function is to ensure current transmission to the train through sliding contact within pantograph strips. It is subject to two main failure modes: bad positioning and important wear. Additionally, the contact wear overhaul is the most-expensive cost of the overhead contact line maintenance budget. For that reason, the two use-cases dedicated to iCatMon will tackle these failure mechanisms.
    - **Use case #1**: contact wire wear
    - **Use case #2**: contact wire incorrect height & stagger
- **iPantMon.** The interaction between the pantograph and OCL takes place between the OCW and the pantograph's contact strips. Failures associated to contact strips account for more than 75% of defects in the pantograph (see 3.2.4). Currently at FGC, the means of inspection to detect wear on the contact strips is based on visual inspection when the train enters the workshop. A degraded (i.e. weared) pantograph has a direct impact on the wear pattern of the OCW which, as said above, is the the most important component of the catenary. Therefore, this failure mechanism will be tackled as use case within the project.
    - **Use case #3**: contact strip normal wear (normal / asymmetric)
- **iWheelMon.** Out-of-roundness defects on the wheelset are the most important of this component, due to two important reasons. On the one hand, polygonization defects could seriously compromise the safety of operation by increasing the probability of derailment [7]. On the other hand, they can seriously damage the track quality. Wheel flats may have a critical importance in the track geometry degradation, which accounts for the greatest costs in terms of maintenance. A way of predicting these defects could potentially benefit the leverage of CBM mechanisms to address track access charges by IMs to TOCs [8].

[1] According to the end-users of the consortium, a low-cost sensor is any sensor that can reliably operate within an in-service train, and not just in a measurement vehicle. Price sensitivity is relative.

  - **Use case #4**: wheel flats and polygonization wear
- **iRailMon.** In addition to track geometry-related defects, those on the rail account for the gratest contribution in the LCC of railway infrastructure. Among the failure mechanisms described in section 3.4, rail corrugations and short-wave irregularities have the greatest impact on noise emissions [9] and safety [10]. For these reasons, the following use cases will be tackled by the project.
  - **Use case #5**: Rail corrugations
  - **Use case #6**: Short-wave irregularities

All these use cases will be described in the following subsections. The actors that will participate in each of the use cases will be listed for each of them. Nevertheless, all of them will be summarized and detailed in section 5.2.

4.1 Use Case #1. Contact wire wear

4.1.1 SIA service

iCatMon

4.1.2 Description

The interaction of the pantograph collector strips and the contact wires is maintained by the pressure applied by the pantographs. This friction inevitably leads to the wear and tear of both the interfacing materials. Replacement of the pantograph collector strips is performed in the train maintenance facility whereas the replacement of the contact wires can be done during the limited non-train running periods normally at night or planned system shutdowns. The railway operator has to plan in advance the replacement of the contact wire, before the cross-sectional area is worn below the point where, it infringes on either the electrical or mechanical limits. If the contact wire is worn below its limit, then the electrical resistance may result in a voltage drop becoming too high and train motors may stall and burn out. If the contact wire fails mechanically i.e. below the minimum tensile strength, then it may break due to tension on the wire.

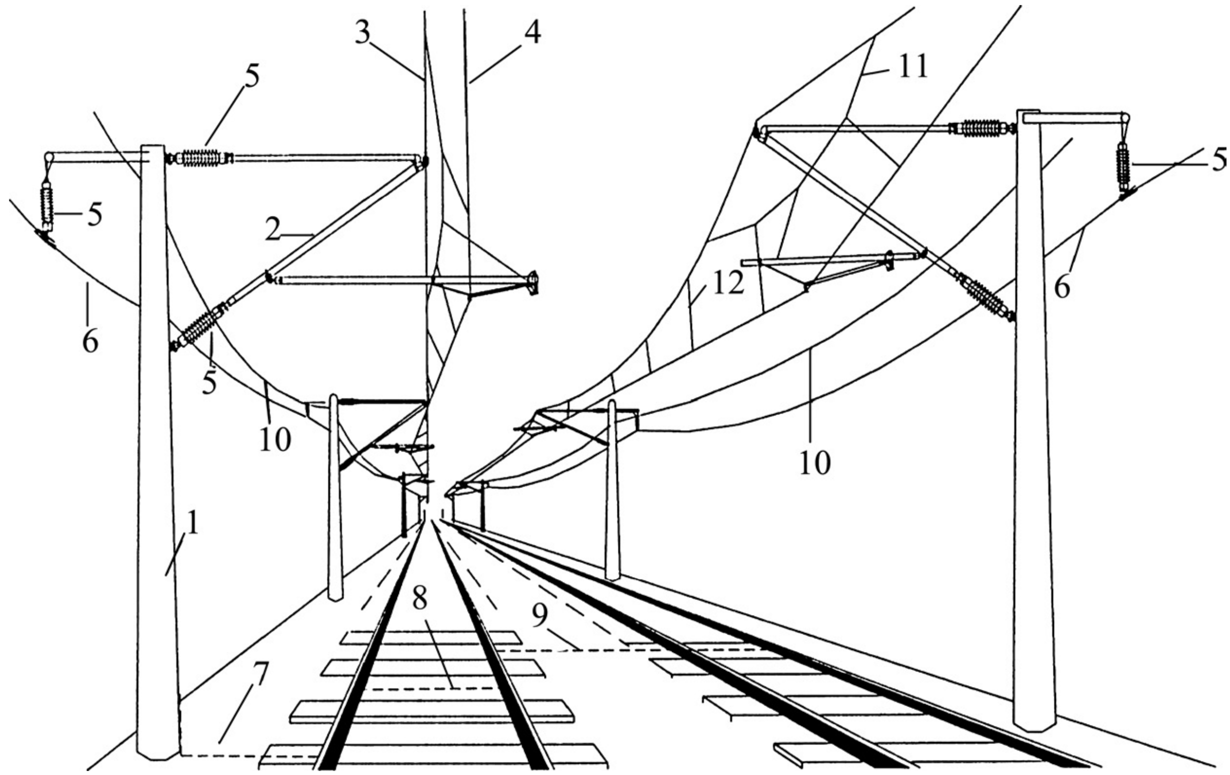


Figure 36. Single-cantilever catenary suspension overhead contact line. (1) pole, (2) cantilever, (3) messenger wire, i.e. catenary, (4) contact wire, (5) insulator, (6) feeder, (7) pole foundation, (8) rail connection, (9) up-down track connection, (10) return wire, (11) stitch wire, (12) dropper

During its life cycle, the contact wire is subject to wear due to environmental or operational parameters such as overheat, arcs, exceeding contact force and more generally the pantograph-catenary interaction. The CW wear estimation is done by the calculation of the ratio between the original section and the worn area of the CW. The threshold for its overhaul is fixed at 80% of the original CW section. Furthermore, it has been shown that the wear mechanism is due to the combination of three physical phenomena:

- Electrical contribution to wear. It is due to the current flow at the contact between the CW and collector strips. The power dissipation at the contact point involves wear of both strips and CW. This contribution depends on strips materials, and current levels and voltage.
- The mechanical wear is generated by the friction and shocks caused during the interaction. This contribution depends on the hardness of collector strips, surface condition, contact force, train speed, and weather conditions.
- Electrical arcs are generated during a loss of contact between the CW and the pantograph. This power dissipation may cause an electrical erosion and fusion for both CW and pan-head strips.

The wear of the contact wire is considered as a geometrical parameter. The wear measurement aims to plan preventive maintenance tasks to ensure homogeneous wear of the wires until they reach their limit.

In this use case, iCatMon will bring the following functionality:

- Configuration of the service and Installation of the necessary on-board systems
- Allow the introduction of inspection / auscultation data, either from electronic forms and/or digital raw data
- Inform about the historic health status (i.e. wear) of the overhead contact wire with the relevant KPIs
- Inform about the current health status (i.e. wear) of the overhead contact wire with the relevant KPIs
- Inform about early detection of failures due to the presence of wear in the overhead contact wire (e.g. when the relevant KPIs surpass a given threshold)
- Propose maintenance recommendations that mitigate this failure mechanism based on the early detection information.

4.1.3 Actors

- Installer/ Configurator
- Infrastructure auscultation systems that provide KPIs related to the status of the overhead contact line
- EGNSS systems to synchronize wear-related KPIs with their localization along the overhead contact line
- Infrastructure maintenance manager that will be informed about past, present and future status of the overhead contact line concerning the apparition and evolution of wear
- Infrastructure maintenance operator that input relevant info to the system (e.g. visual inspection questionnaires)
- Ambient (i.e. pantograph to catenary contact) from which onboard sensors will extract physical magnitudes (e.g. electric signals) to be processed by iCatMon and converted in the relevant KPIs for the analysis of wear in the overhead contact line
- Other IT systems (e.g. asset management) that will be interfaced with iCatMon so this service can share information with them

4.2 Use Case #2. Contact wire incorrect height & stagger

4.2.1 SIA service

iCatMon

4.2.2 Description

Geometry data are related to components positioning regarding design definition. The aim is to measure some lengths in order to detect and correctly assess any deviation from the safety limits and design definition. The main geometry parameters of the overhead contact wire are height, stagger, and sag. These values are measured relatively to track position, and can be achieved in a static way (without pantograph interaction), or dynamically (pantograph-catenary interaction).

The height of the conductor depends on the force between pantograph and catenary, that produces the uplift of the contact wires under the pushing of the pantograph. The knowledge of this force is therefore very important to evaluate the uplift expected and the consequent difference between the dynamic and static values. On the other hand, the stagger of each conductor is given by the distance between the axis of the track and the middle line of the worn out surface.

An excessive stagger or sag of the CW can lead to a pantograph dewirement (pantograph comes off the contact wire) which can result in the OCL destruction. A bad position of the CW can be caused by extreme weather conditions or bad equipment installation. Consequently, for safety reasons, infrastructure maintainers organize regular inspections to measure the height and the stagger of the CW.

The height value is checked regarding to a threshold value defined by standards that allow the trains to reach the desired speed. The stagger shall not exceed a limit value defined during the design in order to avoid pantograph dewirement and cross-wind effect.

As the sag of the conductors (and consequently their height) depends also on temperature, it is useful to record it using a thermometer outside the cabin to consider the climatic conditions during the inspections.

In this use case, iCatMon will bring the following functionality:

- Configuration of the service and installation of the necessary on-board systems
- Allow the introduction of inspection / auscultation data, either from electronic forms and/or digital raw data
- Inform about the historic health status (i.e. height and stagger) of the overhead contact wire with the relevant KPIs
- Inform about the current health status (i.e. height and stagger) of the overhead contact wire with the relevant KPIs
- Inform about early detection of failures due to an incorrect height and/or stagger of the overhead contact wire (e.g. when the relevant KPIs surpass a given threshold)
- Propose maintenance recommendations that mitigate this failure mechanism based on the early detection information.

4.2.3 Actors

- Installer / Configurator
- Infrastructure auscultation systems that provide KPIs related to the status of the overhead contact line
- EGNSS systems to synchronize height and stagger-related KPIs with their localization along the overhead contact line
- Infrastructure maintenance manager that will be informed about past, present and future status of the overhead contact line concerning the evolution of its height and stagger

- Infrastructure maintenance operator that input relevant info to the system (e.g. visual inspection questionnaires)
- Ambient (i.e. pantograph to catenary contact) from which onboard sensors will extract physical magnitudes (e.g. electric signals) to be processed by iCatMon and converted in the relevant KPIs for the analysis the height and stagger of the overhead contact line
- Other IT systems (e.g. asset management) that will be interfaced with iCatMon so this service can share information with them

4.3 Use Case #3. Contact strip wear (normal / asymmetric)

4.3.1 SIA service

iPantMon

4.3.2 Description

Wear modes of current collecting materials were empirically classified into mechanical wear and electrical wear modes. The mechanical wear mode is thought to be caused by adhesive and abrasive wear under high contact load conditions, whereas the electrical wear mode is thought to be caused by electric arcs under contact loss conditions. The wear rate of current collecting materials increases significantly due to electric arcs. Wear reduction measures have therefore been proposed to prevent contact loss by improving dynamic interaction between the catenary and the pantograph.

In order to model pantograph wear is necessary to use an equation that include the contribution to the rate of wear both of the contact force, electric current and the appearance of electric arcs, but at the same time taking into consideration the influence that each of these phenomena performs on each other.

Mechanically, the pantograph on the locomotive and the overhead current supply system on the track are two dynamic systems that interact with each other through the contact force acting on a collector strip of the pantograph head. This gives a force moving along the contact wire and, because of the staggered alignment of the contact wire, the contact force is moving (sideways) on the collector strip as well. Owing to geometrical and other irregularities in the track and in the catenary system, the contact force will be irregular in time, causing dynamic excitation of the pantograph and the catenary system.

When the collector strip slides along the contact wire, the pantograph will perceive an irregular stiffness (in the vertical direction) from the contact wire. The irregular stiffness is caused by the droppers and by the sagging of the contact wire between the droppers. The droppers (with their fastenings) also induce an irregular mass distribution along the contact wire. This generates variations of the contact force and vibrations in the two systems. Variations in the contact force between the pantograph and the contact wire create problems. If the contact force goes down to zero, electromagnetic disturbances due to sparkling appear. If the contact force is too large, the contact wire uplift may exceed allowable limits and may even be torn down. Also, the wear of the contact wire and the collector strip(s) is influenced by the contact force. Thus, to avoid excessive wire uplift and wear (due to friction), the contact force should be small, but to avoid electromagnetic disturbances, the contact force should be large. As seen, these requirements are conflicting.

In this use case, iPantMon will bring the following functionality:

- Configuration of the service and installation of the necessary on-board systems
- Allow the introduction of inspection / auscultation data, either from electronic forms and/or digital raw data
- Inform about the historic health status (i.e. wear) of the pantograph's contact strip with the relevant KPIs
- Inform about the current health status (i.e. wear) of the pantograph's contact strip with the relevant KPIs
- Inform about early detection of failures due to contact strip wear (e.g. when the relevant KPIs surpass a given threshold)
- Propose maintenance recommendations that mitigate this failure mechanism based on the early detection information.

4.3.3 Actors

- Installer / Configurator
- Vehicle auscultation systems that provide KPIs related to the status of the pantograph's strip
- EGNSS systems to synchronize wear-related KPIs and/or failure events with their localization along the line
- Vehicle maintenance manager that will be informed about past, present and future status of the pantograph concerning the apparition and evolution of wear
- Vehicle maintenance operator that input relevant info to the system (e.g. visual inspection questionnaires)
- Ambient (i.e. pantograph to catenary contact) from which onboard sensors will extract physical magnitudes (e.g. electric signals) to be processed by iPantMon and converted in the relevant KPIs for the analysis of wear in the pantograph
- Other IT systems (e.g. asset management) that will be interfaced with iPantMon so this service can share information with them

4.4 Use case #4: Wheel flats and polygonization wear

4.4.1 SIA service

iWheelMon

4.4.2 Description

Wheel flats are singular local defects at the tread surface of a railway wheel [13] and a special type of wheel out-of-roundness [16]. They appear as result of unintended sliding on the track, for example due to defective brakes [38][24]. High temperatures during the sliding period and subsequent sudden cooling lead to a material transformation and cause a flat spot on the running surface [36]. The formation of wheel flats is often accompanied by creation of martensite which can lead to cracks [24][19] and spalling [24][36]. Wheel flats tend to grow from an initial small flat with sharp edges to a large one with rounded edges [13][36][17].

Having several and diverse negative effects, wheel flats constitute a serious problem for rail traffic. Besides from producing environmental impacts, such as increased rolling noise of trains[13][38][17][37] and ground vibrations [13][36][37], they cause high impact loads, which can lead to various severe damages at rail, wheel or other rail and vehicle components such as sleepers or ballast. Examples for wheel flat induced component degradation are initiation or growth of cracks in rails [34][15] and wheels [36] or rail breaks [38]. The deviations of the wheel-rail contact force from normal interaction depend on the train speed: Below a critical speed, oscillations of the impact loads are observed [34], whereas above the critical speed a loss of contact between wheel and rail occurs, followed by a high force when the wheel impacts on the track [13][18], which in turn provokes a high frequency response of the track [35]. At very high speeds, even a bouncing of the wheel is possible. The value of the critical speed is determined by the flat size and position.

Polygonization represents another type of wheel wear leading to unroundness of the wheels. These deviations from ideal roundness are periodic and span around the whole circumference of the wheel having a large wavelength (14 cm to one circumference, often from 1 to 5 harmonics, [38][37][32]. In contrast to a wheel flat, polygonization is a global defect of the wheel. As rail and wheel corrugation, the formation of polygonal wheels is explained by a combination of a wavelength-fixing and a damage mechanism [26].

As wheel flats, polygonal wheels increase noise and vibration loads and may lead to deterioration of infrastructure and rolling stock. Depending on train speed and wavelength of the wheel deformation, polygonal wheels induce periodically increased vertical wheel-rail contact forces.

To avoid further damages on other components and thus to reduce repair and maintenance costs, early detection and removal or reprofiling of defective wheels is important. Removal criteria can be the length and depth of a wheel flat or the exceedance of an impact load threshold. Besides from visual inspection, which is time and cost intensive for wheel flats and mostly fails to successfully detect polygonal wheels, it is possible to measure impact loads by installing accelerometers on the rail, strain gauges on rail web, wheel web or wheelset axle, or by using wheel impact load detectors to detect wheel flats and polygonal wheels.

Our objective is to collect axle box acceleration data using the ABA system developed within SIA. The ABA data contain information on both the vehicle and track vibrations and thus will reflect the varying impact loads induced by wheel flats and polygonal wheels. In contrast to track irregularities, wheel defects, such as wheel flats and polygonization, generate vibrations that are not bound to specific track segments but occur rather continuously. The data will be analyzed using, e.g. frequency and Cepstrum analyses to identify specific frequency modes of the different wheel defects. Predictive analytics in combination with physical degradation models will be analyzed to predict the development of wheel defects and hence will help to schedule maintenance actions.

In this use case, iWheelMon will bring the following functionality:

- Configuration of the service and Installation of the necessary on-board systems
- Allow the introduction of inspection / auscultation data, either from electronic forms and/or digital raw data
- Inform about the historic health status (i.e. flats and polygonization wear) of the wheelset's wheels with the relevant KPIs
- Inform about the current health status (i.e. flats and polygonization wear) of the wheelset's wheels with the relevant KPIs
- Inform about early detection of failures due to wheel flats and polygonization wear (e.g. when the relevant KPIs surpass a given threshold)
- Propose maintenance recommendations that mitigate this failure mechanism based on the early detection information.

4.4.3 Actors

- Installer / Configurator
- Vehicle auscultation systems that provide KPIs related to the status of the wheels
- EGNSS systems to synchronize wheel flats and polygonization wear related KPIs and/or failure events with their localization along the line
- Vehicle maintenance manager that will be informed about past, present and future status of the wheels concerning the apparition and evolution of flats and polygonization wear
- Vehicle maintenance operator that input relevant info to the system (e.g. visual inspection questionnaires)
- Ambient (i.e. wheel to rail contact) from which onboard sensors will extract physical magnitudes (e.g. electric signals) to be processed by iWheelMon and converted in the relevant KPIs for the analysis of wheel flats and polygonization wear
- Other IT systems (e.g. asset management) that will be interfaced with iWheelMon so this service can share information with them

4.5 Use case #5: Rail corrugation

4.5.1 SIA service

iRailMon

4.5.2 Description

Rail corrugation is a periodic irregularity on the track surface with small wavelength (< 1m). Different types of corrugation can be distinguished, depending on its formation process (wavelength-fixing mechanism), kind of damage progression (damage mechanism), location (e.g., in curves, on low or high rail) or typical frequency of the wavelength fixing mechanism. Frequent damage mechanisms for rail corrugation are wear and plastic deformations [20][22]. Typical frequencies range from 50 to 1200 Hz, examples for wavelength-fixing mechanisms are the second torsional resonance of wheelsets or the resonance of unsprung masses of the vehicle on the track stiffness [21]. The wavelength of the resulting corrugation is determined by both the frequency of the wavelength-fixing mechanism and train speed and equal to the speed-frequency-fraction. The initial rail surface is a crucial factor for the position and wavelength of corrugation.

Rail corrugation is responsible for severe problems: Depending on its wavelength, it can cause high and annoying rolling noise levels [20][22][29] and vibrations of ground [22] and train. Furthermore, by increasing the rail-wheel contact forces it can lead to damages on other track and vehicle components.

Several authors combine physical models of the dynamic train-track interactions and simulations to predict corrugation growth rates (e.g., [45]). These models involve a large number of track, train and traffic characteristic parameters, e.g., train speed, axle load, support stiffness, stiffness and spacing of sleepers, stiffness, spacing and damping of railpads, stiffness and damping of ballast, vertical/lateral bending stiffness of the rail, rail mass, wheel radius, wheel mass and wheel load [35][21][29][45][16][23].

Influencing factors on corrugation growth have been examined by Meehan et al. in [25][30]. Besides dynamical factors having a large influence on the corrugation growth rate (e.g., the friction/traction ratio), they found a high correlation between variation on daily rainfall and corrugation growth.

Corrugation is removed by expensively grinding the rail surface. Further treatments and preventive measures are hardening of rails, variation of traffic speed, friction control or removal of track irregularities that can initiate corrugation. Preventive grinding is commonly carried out in fixed time intervals and metal removal rates without detailed knowledge of quantity and quality of corrugation. This is mainly due to the lack of continuous track inspection.

A commonly used instrument for measuring rail corrugation is the corrugation analysis trolley (CAT) [20], which allows to operate at walking speed. The vibrations induced by corrugation can be measured by accelerometers placed on the track where corrugation has been detected [45].

The aforementioned monitoring methods are either non- continuous and/or only carried out within a restricted track segment and therefore do not provide enough information for condition based maintenance.

In this project the SIA-ABA-System will be used to quasi-continuously monitor the health status of the rail by measuring the vibrations generated by the unevenness of the rail. The acceleration data gathered in this way will be analyzed. Features will be extracted in different domains (e.g. frequency-and wavenumber-domain) and subsequent pattern recognition algorithms will be applied to identify typical vibration signatures of rail corrugation. Finally, the future trend of corrugation severity will be estimated by means of predictive analytics and physical degradation models. The early detection of rail corrugation and the prediction of the rail health status can be used to plan grinding actions and hence reduce maintenance cost.

In this use case, iRailMon will bring the following functionality:

- Configuration of the service and Installation of the necessary on-board systems
- Allow the introduction of inspection / auscultation data, either from electronic forms and/or digital raw data
- Inform about the historic health status (i.e. corrugation) of the rail with the relevant KPIs
- Inform about the current health status (i.e. corrugation) of rail with the relevant KPIs
- Inform about early detection of failures due to rail corrugation (e.g. when the relevant KPIs surpass a given threshold)
- Propose maintenance recommendations that mitigate this failure mechanism based on the early detection information.

4.5.3 Actors

- Installer / Configurator
- Infrastructure auscultation systems that provide KPIs related to the status of the rail
- EGNSS systems to synchronize corrugation-related KPIs with their localization along the rail
- Infrastructure maintenance manager that will be informed about past, present and future status of the rail concerning the apparition and evolution of corrugation
- Infrastructure maintenance operator that input relevant info to the system (e.g. visual inspection questionnaires)
- Ambient (i.e. wheel to rail contact) from which onboard sensors will extract physical magnitudes (e.g. electric signals) to be processed by iRailMon and converted in the relevant KPIs for the analysis of corrugation on the rail
- Other IT systems (e.g. asset management) that will be interfaced with iRailMon so this service can share information with them

4.6 Use case #6: Short-wave irregularities

4.6.1 SIA service

iRailMon

4.6.2 Description

Short rail track irregularities, such as rail-joints, welds, squats etc. are, in contrast to track corrugation, non-periodic isolated track deformations. They can excite high dynamic forces at the wheel-rail interface which results in track and vehicle damage and deterioration, high noise levels and ground vibrations.

Since the continuously welded rail (CWR) became the standard modern railway track, joints mainly occur in the form of insulated rail joints (IRJ) for the purpose of safe signal control. IRJs are weak points in railway tracks because of the subsequent material deterioration caused by high dynamic wheel-rail contact forces at the discontinuity between rail ends [39]. The resulting defects can lead to derailment or dysfunction of the signalling system.

In this regard, the CWR is a significant improvement. However, welds are still geometrical disturbances along the wheel-rail interface and therefore prone to damages [43]. The form and cause of weld damages is described in [44] and weld inspection methods are introduced in [42].

Squats are a different type of track irregularities. They are generally initiated at the surface due to rolling contact fatigue [41]. Squats lead to increased noise and vibration levels significantly decreasing the ride comfort. Furthermore, if allowed to develop squats will grow under the surface and can lead to rail degradation and even fracture.

In general, short rail track irregularities reduce the ride comfort and quality of life of residents along the track through noise and vibrations. Additionally, they can lead to dysfunction of safety-critical systems and cause high maintenance costs. In order to tackle these issues, the early detection and appropriate diagnosis of the current and future severity of these defects is fundamental. Traditional track inspection methods as summarised in [40] do not provide that.

Therefore, ABA from in-service trains have been recently investigated to indicate short track-irregularities, specifically, damaged rail joints [39], weld irregularities [14] and squats [33].

In this project the SIA-ABA-System will be used to measure vibrations excited at the wheel-rail interface due to short track irregularities. Data analyses will be carried out to identify the form and evaluate the severity of the defects. Here, auxiliary data and the experience in construction and maintenance from the infrastructure operators will be used to link the ABA data with the component health status and to develop degradation predictive algorithms.

In this use case, iRailMon will bring the following functionality:

- Configuration of the service and installation of the necessary on-board systems
- Allow the introduction of inspection / auscultation data, either from electronic forms and/or digital raw data
- Inform about the historic health status (i.e. short-wave irregularities) of the rail with the relevant KPIs
- Inform about the current health status (i.e. short-wave irregularities) of rail with the relevant KPIs
- Inform about early detection of failures due to short-wave irregularities on the rail (e.g. when the relevant KPIs surpass a given threshold)
- Propose maintenance recommendations that mitigate this failure mechanism based on the early detection information.

4.6.3 Actors

- Installer / Configurator
- Infrastructure auscultation systems that provide KPIs related to the status of the rail

- EGNSS systems to synchronize short-wave irregularities-related KPIs with their localization along the rail
- Infrastructure maintenance manager that will be informed about past, present and future status of the rail concerning the apparition and evolution of short-wave irregularities
- Infrastructure maintenance operator that input relevant info to the system (e.g. visual inspection questionnaires)
- Ambient (i.e. wheel to rail contact) from which onboard sensors will extract physical magnitudes (e.g. electric signals) to be processed by iRailMon and converted in the relevant KPIs for the analysis of short-wave irregularities on the rail
- Other IT systems (e.g. asset management) that will be interfaced with iRailMon so this service can share information with them

5 Functional requirements of SIA

5.1 High-level functionality

REQ. SIA must have the following high-level functionality:

- F1. Configuration and Installation
- F2. Introduction of inspection data
- F3. Introduction of auscultation data
- F4. Inform about the historic health status of assets
- F5. Inform about the current health status of assets
- F6. Inform about early detection of failures
- F7. Propose maintenance recommendations

The high-level functionality of SIA is detailed below:

- **F1. Configuration / Installation**

  INFO. Installation of the HW components of SIA, as well as the SW applications and the required (if any) IT infrastructure. Also, the configuration of the SW for the particularities of end-users.

  SIA_F1_001. SIA shall allow setting configuration parameters of the different services with their corresponding screens:

  - iCatMon (screen P1.1)
  - iPantMon (screen P1.2)
  - iWheelMon (screen P1.3)
  - iRailMon (screen P1.4)

  SIA_F1_002. The Firmware of the on-board electronic equipment shall allow initial configuration by means of the necessary port(s), that will not be accessible once they are installed on-board.

- **F2. Introduction of inspection data**

  INFO. Understanding "inspection" as all diagnostic events that don't imply any contact (e.g. visual inspections). This functionality allows introducing inspections-related information to SIA (e.g. formularies, reports, etc.) and its digitalization in order to be used by the different modules of SIA.

  SIA_F2_001. SIA shall allow introducing the inspection data of assets with the required electronic forms and visualize the inspection information with the correspondent screens:

  - Catenary (screen P2.1)
  - Pantograph (screen P2.2)
  - Wheelset (screen P2.3)
  - Rail (screen P2.4)

- **F3. Introduction of auscultation data**

INFO. Understanding "auscultation" as all diagnostic events that imply contact (e.g. auscultation train). This functionality allows introducing auscultation-related information to SIA (e.g. raw data coming from auscultation devices, etc.) and its digitalization in order to be used by the different modules of SIA.

SIA_F3_001. SIA shall allow introducing the auscultation data of assets with the required electronic file format and visualize the auscultation information with the correspondent screens:

- Catenary (screen P3.1)
- Pantograph (screen P3.2)
- Wheelset (screen P3.3)
- Rail (screen P3.4)

- **F4. Inform about historic health status**

INFO. This functionality will combine inspection and auscultation data in order to visualize the historic evolution of the health status of assets with the relevant KPIs that are relevant to each asset.

SIA_F4_001. SIA shall inform about historic health status of components in the time range [-t, t0], where

- t can be up to 10 years
- t0 is the present day

SIA_F4_002. The historic health status of components shall be visualized by means of the time representation of the evolution of their relevant KPIs.

SIA_F4_003. The historic health status of components shall be assessed by combining information from their related auscultation and/or inspection data and the associated maintenance actions.

SIA_F4_004. SIA shall inform about historic health status of the different assets by displaying information in the corresponding screens:

- Catenary (screen P4.1)
- Pantograph (screen P4.2)
- Wheelset (screen P4.3)
- Rail (screen P4.4)

- **F5. Inform about current health status**

INFO. This functionality will combine inspection and auscultation data with the information coming from SIA's on-board equipment in order to visualize the current health status of assets with the relevant KPIs that are relevant to each asset.

SIA_F5_001. The current health status of components shall be visualized by means of the representation of their relevant KPIs.

SIA_F5_002. The current health status of components shall be assessed by combining information from their historic health status with the information provided by SIA's on-board systems.

SIA_F5_003. SIA shall inform current historic health status of the different assets by displaying information in the corresponding screens:

- Catenary (screen P5.1)
- Pantograph (screen P5.2)
- Wheelset (screen P5.3)
- Rail (screen P5.4)

- **F6. Inform about early detected failures**

INFO. This functionality will combine inspection and auscultation data with the information coming from SIA's on-board equipment and the components' degradation models in order to visualize the predicted (i.e. future) health status of assets with the relevant KPIs that are relevant to each asset.

SIA_F6_001. SIA shall inform about future health status of components in the time range [t0, +t], where

- t can be up to 2 years
- t0 is the present day

SIA_F6_002. The early detected failures of components shall be visualized by means of

- the representation of their relevant KPIs
- a warning message describing the potential failure

SIA_F6_003. The detection of future (i.e. potential) failures shall be based on the future (i.e. predicted) evolution of the components' relevant KPIs. It will be assessed by combining (whenever possible) two sources of information:

- Statistical analysis of current and past data
- Simulations based on physical degradation models

SIA_F6_004. SIA shall inform about the future health status of the different assets by displaying information in the corresponding screens:

- Catenary (screen P6.1.1)
- Pantograph (screen P6.1.2)
- Wheelset (screen P6.1.3)
- Rail (screen P6.1.4)

SIA_F6_005. When an early failure is detected, a warning message (i.e. pop-up window) shall appear on the corresponding screen.

- Catenary (screen P6.2.1)
- Pantograph (screen P6.2.2)

- Wheelset (screen P6.2.3)
- Rail (screen P6.2.4)

- **F7. Propose maintenance recommendations**

  INFO. This functionality will consider the different failure mechanisms of a given asset, their location and their severity and will suggest the related maintenance actions that lead to failure correction.

  SIA_F7_001. When a potential failure is detected, SIA shall propose a set of (related) maintenance actions recommendations through the correspondent screen:

  - Catenary (screen P5.1)
  - Pantograph (screen P5.2)
  - Wheelset (screen P5.3)
  - Rail (screen P5.4)

5.2 Actors / Context

The context diagram with which SIA will operate is shown in Figure 37. The system will interact with the following actors:

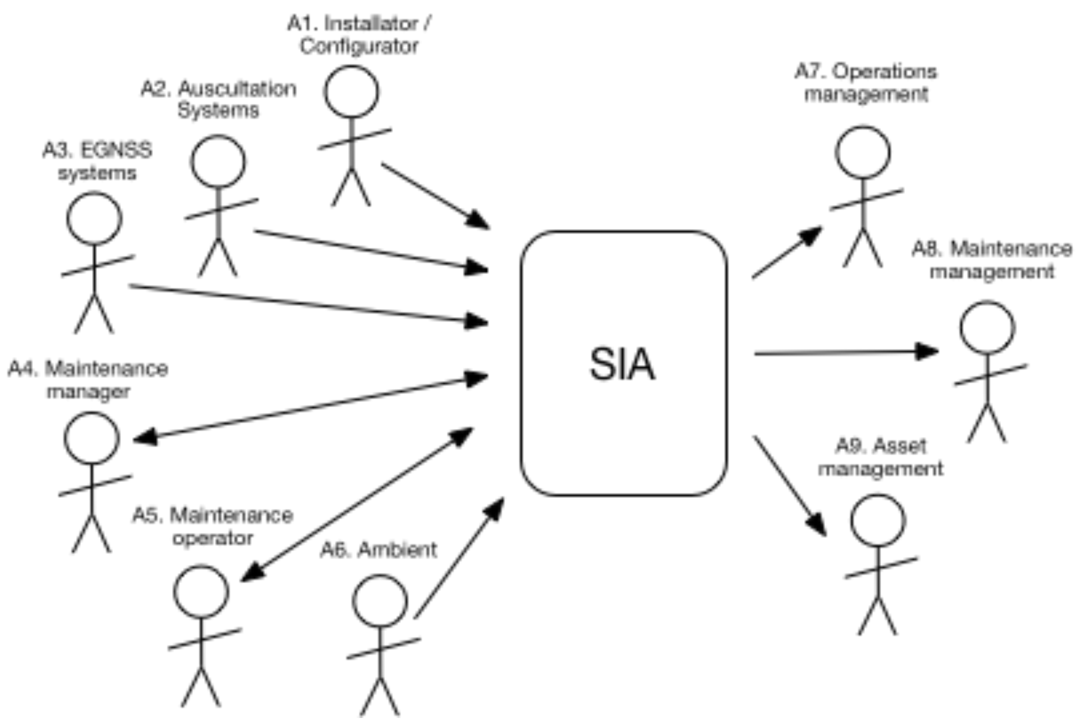


Figure 37. SIA context diagram

- **A1. Installer / Configurator**. This actor installs and configures the HW and SW of SIA's services.

- **A2. Auscultation systems**. This actor comprises all auscultation systems that provide information (either in raw form or processed-KPI) to SIA (a distinction between infrastructure and vehicle is made).
  - **A2.1. Infrastructure**.
  - **A2.1. Vehicle**.
- **A3. EGNSS systems**. This actor is referred to the Electro Magnetic environment in which the EGNSS signals are received.
- **A4. Maintenance manager**. This actor is the maintenance manager (a distinction between infrastructure and vehicle is made), and will interact with the outputs provided by SIA (i.e. visualization)
  - **A4.1. Infrastructure**.
  - **A4.2. Vehicle**.
- **A5. Maintenance operator**. This actor is the maintenance operator (a distinction between infrastructure and vehicle is made) and will interact with SIA by providing it with input data (in the form of non-digital inspection and/or auscultation information).
  - **A5.1. Infrastructure**.
  - **A5.2. Vehicle**.
- **A6. Ambient**. This actor is referred to the different ambient in which the on-board system will work, in order to gather data (i.e. sensors) and supply the electronic circuits with the required electrical energy (i.e. energy harvesters).
  - **A6.1. Catenary-Pantograph contact**. SIA will sense the necessary physical magnitudes of the catenary-pantograph contact to infer the health status of the catenary and pantograph (according to the use cases – see section 4). SIA will also obtain the required electrical power supply for the sensors from the ambient surrounding the catenary-pantograph contact.
  - **A6.2. Wheel-Rail contact**. SIA will sense the necessary physical magnitudes of the wheel-rail contact to infer the health status of the wheelset and rail (according to the use cases – see section 4). SIA will also obtain the required electrical power supply for the sensors from the ambient surrounding the wheel-rail contact.
- **A7. Operations management IT systems**. SIA will interact with operations management IT systems to provide information (as an output) about early-detected failures.
- **A8. Maintenance management IT systems**. SIA will interact with maintenance management IT systems to provide information (as an output) about the proposed maintenance recommendations.

- **A9. Asset management IT systems**. SIA will interact with asset management IT systems in order to provide information (as an output) of the current health status about assets (according to the use cases of section 4).

REQ. SIA system must have the necessary interfaces to interact with the following actors:

- A1. Installer / Configurator
- A2. Auscultation systems
- A3. EGNSS systems
- A4. Maintenance manager
- A5. Maintenance operator
- A6. Ambient
- A7. Operations management IT systems
- A8. Maintenance management IT systems
- A9. Asset management IT systems

The following figures illustrate the context in which the different services will operate.

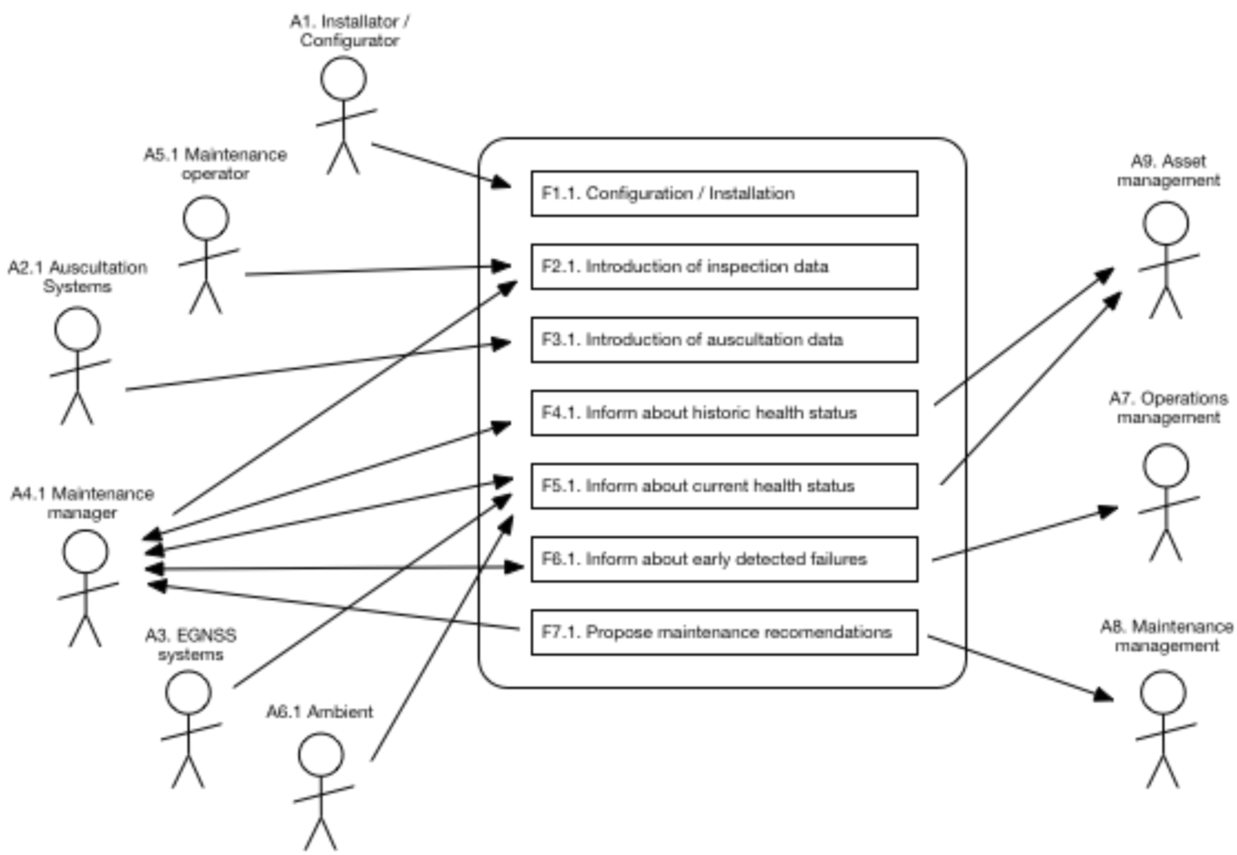


Figure 38. iCatMon & iRailMon context diagram

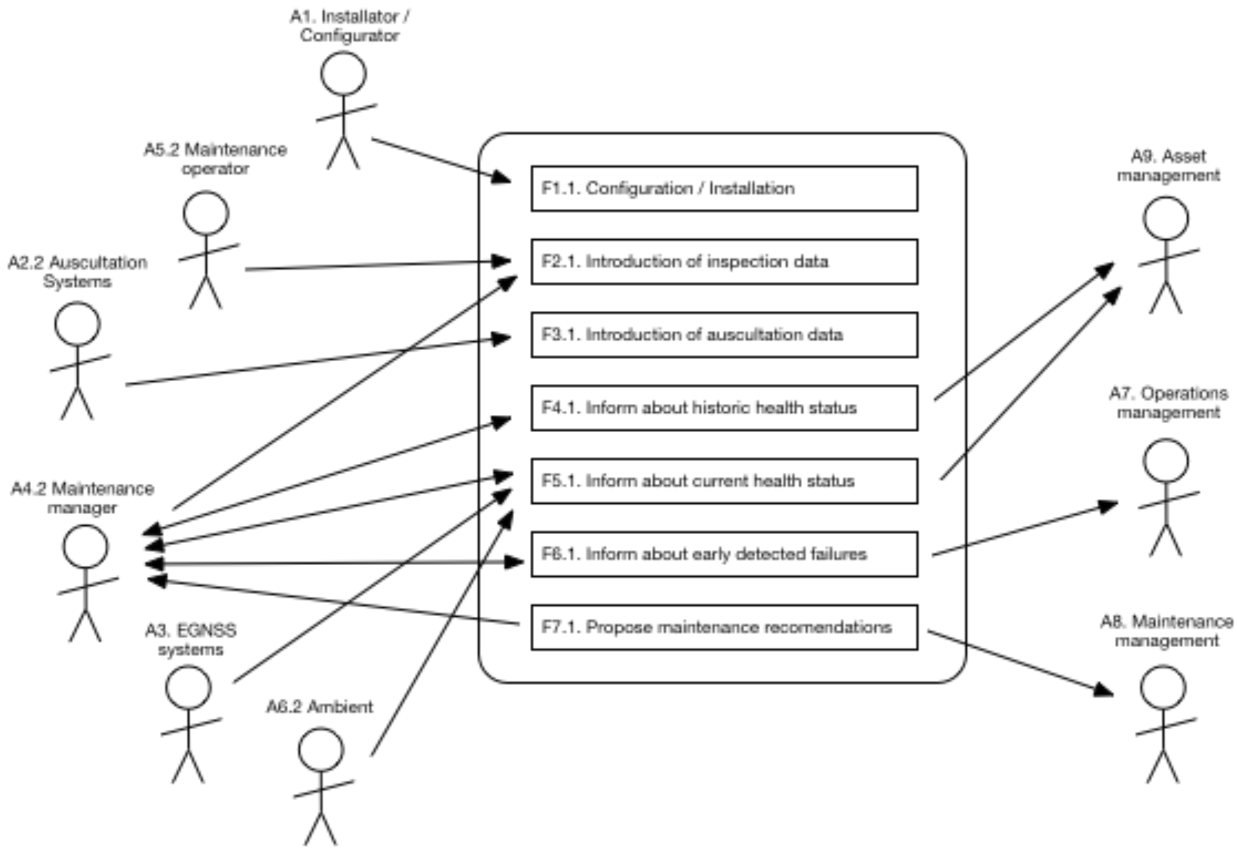


Figure 39. iPantMon & iRailMon context diagram

5.3 Interfaces

This section describes the external interfaces with which SIA will interact with the actors described in section 5.2. A first overview of the external interfaces of SIA is shown in Figure 40.

REQ. SIA must receive input information through the following interfaces:

- IF0. Configuration
- IF1. Operations data
- IF2. Maintenance procedures
- IF3. Auscultation data
- IF4. Inspection data
- IF5. Ambient
- IF6. EGNSS system

REQ. SIA must output information through the following interfaces:

- IF7. Asset status
- IF8. Early detection of component failure

- IF9. Maintenance recommendations
- IF10. External interfaces

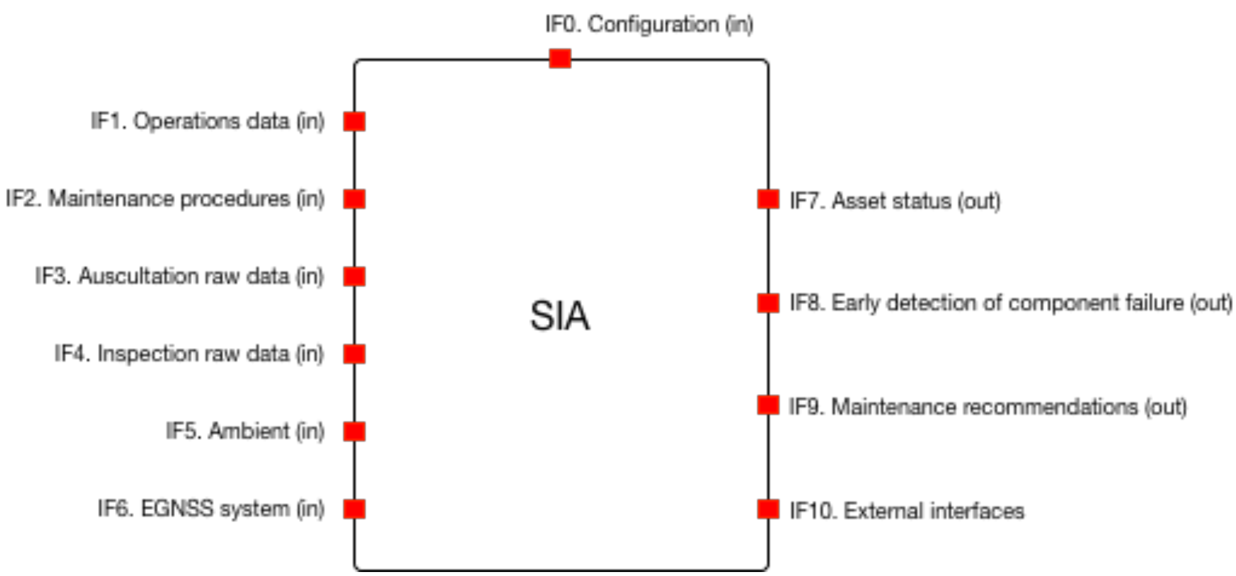


Figure 40. SIA high-level interfaces

5.3.1 High-level requirements of input interfaces

5.3.1.1 Requirements of Interface IF0. Configuration (in)

SIA_IF_001. SIA shall configure the following subsystems (IF9)

- IF0.1. Network of sensors
- IF0.2. Data hub
- IF0.3. Positioning system
- IF0.4. Visualization platform

5.3.1.2 Requirements of Interface IF1. Operations data (in)

SIA_IF_002. SIA shall process the following information related to Operations Data (IF1):

- IF1.1. Infrastructure characteristics
  - IF1.1.1. GIS map of the line(s)
  - IF1.1.2. Composition of the infrastructure (e.g. sections, curvature, switches and crossings, tunnels, components, materials, etc.)
- IF1.2. Vehicle characteristics
  - IF1.2.1. Vehicle Multibody models (Simpack - http://www.simpack.com)
  - IF1.2.2. Parameters of Multibody (Simpack) models

- IF1.3. Service and operational characteristics
    - IF1.3.1. List of vehicles with unique ID code
    - IF1.3.2. Relation between ID and Multibody model
    - IF1.3.3. Operations table (e.g. timetables, acceleration data, speed profiles, loading curves, etc.)

5.3.1.3 Requirements of Interface IF2. Maintenance procedures (in)

SIA_IF_003. SIA shall process the following information related to Maintenance procedures (IF2):

- IF2.1. Component defect/failure catalogue
    - IF2.1.1. Catenary
    - IF2.1.2. Pantograph
    - IF2.1.3. Wheelset
    - IF2.1.4. Rail
- IF2.2. KPIs associated to components' defects/failures
    - IF2.1.1. Catenary
    - IF2.1.2. Pantograph
    - IF2.1.3. Wheelset
    - IF2.1.4. Rail
- IF2.3. Limits / Thresholds of component defects/failures
    - IF2.2.1. Catenary
    - IF2.2.2. Pantograph
    - IF2.2.3. Wheelset
    - IF2.2.4. Rail
- IF2.4. Maintenance actions
    - IF2.3.1. Catenary
    - IF2.3.2. Pantograph
    - IF2.3.3. Wheelset
    - IF2.3.4. Rail

5.3.1.4 Requirements of Interface IF3. Auscultation raw data (in)

SIA_IF_004. SIA shall process the following information related to Auscultation raw data (IF3):

- IF3.1. Catenary

- IF3.2. Pantograph
- IF3.3. Wheelset
- IF3.4. Rail

***NOTE**. It is understood by auscultation any means of raw data collection (i.e. digital data) that implies physical contact, e.g. auscultation trains, handheld trolleys, etc.*

5.3.1.5 Requirements of Interface IF4. Inspection raw data (in)

SIA_IF_005. SIA shall process the following information related to Inspection raw data (IF4):

- IF4.1. Catenary
- IF4.2. Pantograph
- IF4.3. Wheelset
- IF4.4. Rail

***NOTE**. It is understood by inspection any means of input data collection other than auscultation e.g. inspection forms, thermographic inspections, etc.*

5.3.1.6 Requirements of Interface IF5. Ambient (in)

SIA_IF_006. SIA shall process the following information related to Ambient (IF5):

- IF5.1. Catenary-Pantograph contact, i.e. physical magnitudes (e.g. accelerations) that will be processed in order to assess the health status of both catenary and pantograph
- IF5.2. Wheel-Rail contact, i.e. physical magnitudes (e.g. accelerations) that will be processed in order to assess the health status of both catenary and pantograph
- IF5.3. Electric power supply

5.3.1.7 Requirements of Interface IF6. EGNSS systems (in)

SIA_IF_007. SIA shall process the following information related to EGNSS (IF6)

- IF6.1. GNSS signals
- IF6.2. Inertial signals
- IF6.3. Digital map

5.3.2 High-level requirements of output interfaces

5.3.2.1 Requirements of Interface IF7. Asset status (out)

SIA_IF_008. SIA shall process and visualize the following information related to Asset status (IF7):

- IF7.1. Historic auscultation data
    - IF7.1.1. Catenary

    - IF7.1.2. Pantograph
    - IF7.1.3. Wheelset
    - IF7.1.4. Rail
- IF7.2. Historic inspection data
    - IF7.2.1. Catenary
    - IF7.2.2. Pantograph
    - IF7.2.3. Wheelset
    - IF7.2.4. Rail
- IF7.3. Current status of components
    - IF7.3.1. Catenary
    - IF7.3.2. Pantograph
    - IF7.3.3. Wheelset
    - IF7.3.4. Rail
- IF7.4. Predicted status of components
    - IF7.4.1. Catenary
    - IF7.4.2. Pantograph
    - IF7.4.3. Wheelset
    - IF7.4.4. Rail

5.3.2.2 Requirements of Interface IF8. Early detection of component failure (out)

SIA_IF_009. SIA shall process and visualize the following information related to early detection of component failure (IF8):

- IF8.1. Catenary
- IF8.2. Pantograph
- IF8.3. Wheelset
- IF8.4. Rail

5.3.2.3 Requirements of Interface IF9. Maintenance recommendations (out)

SIA_IF_010. SIA shall process and visualize the following information related to maintenance recommendations (IF9):

- IF9.1. Catenary
- IF9.2. Pantograph
- IF9.3. Wheelset

- IF9.4. Rail

5.3.2.4 Requirements of Interface IF10. External interfaces (out)

SIA_IF_011. SIA shall process and communicate a summary of the current state of assets, the early detection of component failure and the associated maintenance recommendations to the following external interfaces (IF10):

- IF10.1. Asset management
- IF10.2. Operations management
- IF10.3. Maintenance management

6 Non-functional requirements of SIA

6.1 Hardware requirements

SIA_HW_001. The electrical power supply port shall comply with EN50155 [46], in terms of

- Service's electrical conditions (section 5)
- Reduction of the supply voltage (section 7.2.5)
- Reverse polarity (section 7.2.6)
- Inrush currents (section 7.2.7)

SIA_HW_002. All the electronic circuits of the on-board systems must be implemented in any standard PCB, as long as all the vias and through-hole connection pads are metallized.

SIA_HW_003. The layout of the PCBs of the on-board systems shall be designed according to EN62326 [56].

SIA_HW_004. The on-board system must include some means of data storage with a capacity of 16Gb.

SIA_HW_005. It is suggested that the Hardware of SIA shall be documented according to the checklist of EN50155 (section 11.2.1).

SIA_HW_006. The GNSS antenna size and location must be according to the Guidance on Train Rooftop Antenna Positioning document [54].

6.2 Software requirements

SIA_SW_001. The Software shall be coded following the recommendations of EN50128 [55].

SIA_SW_002. The Software shall be documented according to the recommendations of EN50128.

6.3 Performance requirements

SIA_PF_001. SIA must guarantee its functionality with a train velocity up to 100 km/h.

SIA_PF_002. Electromagnetic Compatibility. According to what is stablished by EN50155, the on-board equipment of SIA shall be protected against both radiated and conducted interferences according to EN50121-3-2 requirements [47]:

- Enclosure port (radiofrequency, electrostatic discharge).
- Power supply port (bursts, surges, conducted RF, voltage variations and interruptions).
- Wired communication ports (bursts, conducted RF).

SIA_PF_003. Electromagnetic Compatibility. According to what is stablished by EN50155, the radiated emissions of the on-board equipment of SIA shall be below the limits stablished in EN50121-3-2:

- Enclosure port.
- Telecommunications ports.
- Power supply port.

SIA_PF_004. The emissions through the Wireless telecommunications ports (e.g. WiFi) shall comply with the requirements set by the correspondent ETSI standard.

> ***INFO****. The correspondent ETSI standard will depend on the design of the different modules of the subsystems foreseen in the architecture definition, for both internal communications (i.e. on-board) and external (i.e. train-to-ground).*

SIA_PF_005. The accuracy requirements of the positioning subsystem shall comply with deci-meter horizontal positioning in the railway environment in post-processing mode (back office) for physical degradation modelling.

SIA_PF_006. The accuracy requirements of the positioning subsystem shall comply with sub-20m horizontal positioning for the localization of failures on infrastructures assets.

6.4 Supportability requirements

SIA_SP_001. All the on-board equipment shall be protected against the correspondent ambient with a proper enclosure.

SIA_SP_002. The on-board equipment shall guarantee its functionality against eventual impacts of ballast or other objects according to the shock criteria described in section 6.6.

SIA_SP_003. The enclosure(s) of the on-board equipment shall provide the required IP protection.

SIA_SP_004. The enclosure(s) of the on-board equipment shall allow its disassembling to access (their) content.

SIA_SP_005. All the antennas required for the wireless telecommunications ports shall include the necessary mechanical protection.

SIA_SP_006. The on-board electronic equipment must by composed by modules

SIA_SP_007. The modules of the on-board electronic equipment shall be interchangeable in case of malfunction.

SIA_SP_008. The on-board electronic equipment must not count with wired terminals, unless they are conveniently crimped (according to EN60352-1 [48]) or an ancillary PCB is used with the components conveniently identified.

SIA_SP_009. The electrical / electronic components that do not have specific fixation mechanisms must be secured to the PCB.

SIA_SP_010. The electrical / electronic components that do not have specific fixation shall allow their replacement without damaging the PCB.

SIA_SP_011. The installation of the on-board equipment shall not require any modification of the existing wiring or components of the vehicle.

6.5 Maintainability

SIA_MT_001. The on-board equipment shall include some means of testing mechanism (i.e. port) in order to detect its malfunction with a suitable portable device.

SIA_MT_002. In case the on-board equipment includes any primary battery (i.e. non-rechargeable), it shall be substituted every 2 years.

SIA_MT_003. In case the on-board equipment includes any secondary battery (i.e. rechargeable), it must be necessary to stablish a periodic recharge operation that guarantees the continuous operation of the electronic systems.

SIA_MT_004. When the use of other operation settings is required (different from factory settings), the mechanisms that will allow changing these settings must not be accessible when the system is under normal operation.

6.6 Operability

SIA_OP_001. Pressure. The on-board equipment shall be functional for altitudes between -120m (below sea level) and +2000m (above sea level), what translates into an approximate pressure range from 101.3kPa to 79.5kPa (EN 50125-1 [49], 4.2).

SIA_OP_002. Temperature. The on-board equipment shall be functional for the following temperature conditions, according to EN50155, section 4.1.2:

- Ambient (i.e. air) temperature: -40ºC to +50ºC
- Temperature inside the enclosure: -40ºC to +70ºC
- Contact temperature (i.e. air with PCB): -40ºC to +85ºC

SIA_OP_003. Relative humidity. The on-board equipment shall be functional with the following ambient conditions about relative humidity, according to EN50155:

- Annual average ≤ 75%
- 30 consecutive days at 95%

SIA_OP_004. Vibrations. The on-board equipment must cope with vibrations (i.e. continuous sinusoidal stress) in the three axis, according to EN61373 [50]:

- Mass of equipment: No limit
- Frequency range: 5 – 10 Hz
- Cross-over frequency: 20.5 Hz
- Displacement amplitude below cross-over frequency: 12 mm
- Acceleration amplitude above cross-over frequency: 200 m/s2

SIA_OP_005. Shocks. The on-board equipment must endure with shocks according to EN61373:

- Vertical: 100g / 6ms
- Transversal: 100g / 6ms
- Longitudinal: 100g / 6ms

SIA_OP_006. Acceleration. The on-board equipment shall be functional under accelerations due to both inclination and centrifugal forces according to EN61373.

> ***NOTE**. The maximum equivalent transversal acceleration values applied to the carbody for verification shall be $4m/s^2$ (duration below 50ms) or $2m/s^2$ (duration exciding 50ms).*

SIA_OP_007. Acceleration. During traction and braking operations, the on-board equipment shall be functional for longitudinal accelerations up to $7m/s^2$ with a minimum duration of 50ms, according to EN61373.

SIA_OP_008. Solar radiation. The on-board equipment shall be functional under solar radiation up to 5K3 (1120 W/m2), according to EN-50125-1, 4.9.

SIA_OP_009. Wind. The on-board equipment shall be functional under cross-winds up to 35m/s.

SIA_OP_010. Wind. The on-board equipment shall be functional under gusts of cross-wind up to 50m/s during a maximum time of one second.

SIA_OP_011. Precipitation. The on-board equipment shall be functional under any precipitation condition (rain, snow, hail), according to IEC721 [51]:

- Water and precipitation: 5K4
- Precipitation: 15mm/min
- Water and other sources different than rain: 3m/s
- Low-temperature rain: N/A

SIA_OP_012. The minimum required protection shall be IP66 according to IEC529 [52].

6.7 Security & safety requirements

INFO. The services that will be developed within SIA, as well as the specific on-board equipment, are not safety-related applications. However, the standard EN 50126 [53] shall be eventually utilized as a guideline for the design of the different subsystems according to the architecture definition [11].

7 Preliminary validation plan

7.1 Methodology

The validation of the high-level functionality of SIA will be carried out by the end-users of the consortium, by means of two different demonstrations in two pilot scenarios:

- Scenario 1, with a few representative sections of the Wien-Graz line, coordinated by OBB.
- Scenario 2, with a few representative sections of the Barcelona-Vallés line, coordinated by FGC.

During the last stage of the project, the on-board systems developed during the project will be installed in regular service trains, and the four services will be fully functional for 9 months (starting in M27-June2020 and finishing in M36-February2021 of the project) . In this period, the end-users will validate the functionality of the services according to the test-cases defined in section 7.3.

In addition to that, as originally stated in the DoA, the objectives claimed by SIA will be validated with the following criteria:

- For the validation of component degradation models, it is planned to use historical records of both inspection and maintenance actions from the two reference scenarios. These sets of data will be used with two purposes:
    - the first part, corresponding to the older data from the dataset will be used as the “guiding samples” to adjust and calibrate the degradation models, and
    - the second part, corresponding to the newer data from the dataset that will act as the “control samples” to check the accuracy of the predictions.
    - Moreover, the analysis of the results of the last 9 months during the field testing in the pilot scenarios, where real time information will be used in combination with the degradation models, will also be verified by means of the traditional inspection procedures.
- To validate the potential reduction of maintenance cost thanks to the use of the new services (iWheelMon, iRailMon, iPantMon and iCAtMon), it is planned to compare historical records of maintenance costs of FGC and OBB with those that would results from using the provided information to avoid unscheduled events and optimizing maintenance with the knowledge of prognostic health status in different periods.
- To validate the business plan, it is foreseen the specific presentation of the new services (iWheelMon, iRailMon, iPantMon and iCAtMon) to at least 20 possible clients and to update with their feedback key issues such as willingness to pay, perceived value, commercial tools, and commercial networks.

7.2 Description of scenarios

7.2.1 Scenario 1: Wien-Graz

Scenario 1 will host two pilot projects:

- Pilot project 1 – new end-to-end service iWheelMon involving end user OBB and UIC perspective
- Pilot project 3– new end-to-end service iRailMon involving end user OBB, VIAS and UIC perspective

The two largest cities of Austria the capital Vienna and Graz are connected via a 235-km-long section of the Austrian southern line (Figure 41) that is one of the major lines in the country.

Figure 41. Map of the Austrian Southern Line (https://commons.wikimedia.org/wiki/File:S%C3%BCdbahn.png)

This line is being used today by over 20 trains of mixed traffic and over 120M passengers per year. Main operating vehicles are Siemens types ES64U2 and ES64U4. The construction of sections of the Austrian southern line started in the 1830s with major milestones of finished sections in the 1840s. The end-to-end railway connection from Vienna to Triest across the Austrian southern line was established in 1857. One of the in all aspects most challenging sections is the "Semmeringbahn", an about 42-km-long mountain railway line opened in 1848, which starts at Gloggnitz and leads over the mount Semmering to Mürzzuschlag by 14 tunnels, 16 viaducts and about 100 bridges. About half of the track is in curves. Some of the narrow curves have radii of about 180 m. Due to the geographic characteristics, the used rail is mainly UIC60 and UIC 54 over the mountain Semmering with a track gauge of 1,435 mm. The line Vienna-Graz holds diverse challenges in terms of maintenance: On the one hand, the line comprises high speed sections with operating speeds of 160 km/h and on the other hand, the Semmering railway is characterised by difficult terrain, considerable differences in altitude and narrow curves.

This table summarizes the scenario line details:

Line identification	Wien-Graz (Vienna-Graz)
No. of Km	235 km
Number of passengers per year	Aprox. 120M passengers per year
Number of trains per day	More than 20 (mixed traffic)
Type of catenary	Conventional catenary, 15 kV/16,7 Hz AC
Type of rails	Usual UIC 60 (UIC 54 over the mountain Semmering)
Gauge	1,435 mm
Speed of the line	Up to 160km/h
Number of maintenance actions per year	More than 8,000
Cost of maintenance and renewal per year	120M€
Records of maintenance since 2010	3 Tb maintenance and renewal of tracks
Records of inspection since 2010	20 Tb of information including dynamic inspections, ultrasonic inspection, etc.

7.2.2 Scenario 2: Barcelona-Vallés

Among other railway related activities, FGC has two main lines in Catalonia, whose names are Barcelona – Vallès and Llobregat – Anoia, in orange and yellow respectively depicted in Figure 42, where the different FGC infrastructure can be seen inside Catalonia Map.

Figure 42. FGC railway lines.

Llobregat – Anoia line has a historical origin in the freight transport. It was constructed to transport mining products from Súria mines and textile products from the Llobregat and Anoia basins. First section of this line was constructed in 1893 and due to this origin it has metric track gauge 1.000 mm. Over the years, some updating of this line has been done maintaining 1.000 mm of track gauge. Nowadays the line has mixed traffic of passengers and different freights, among them cars, car pieces or salt. Along the line there are different train services, some metro services inside Barcelona, some suburban services connecting Barcelona and surrounding areas and some commuter trains which connect more distant areas of Catalonia.

- Nº of km: This line has a total of 140 km with 27 km of double track and 113 km of single track where 40 km of they are freight braches.
- Nº of pax per year: 22 million pax data from 2017.
- Nº trains per day: 439 circulations per day.
- Type of catenary: Flexible.
- Speed of the line: up to 90 km/h.

Barcelona - Vallès line has its origins in 1863, as a railway line that connected Barcelona with surrounding villages that nowadays are part of Barcelona. This line, with international track gauge of 1.435 mm, has evolved from this old rail line and has grown during the years to the current configuration, with his last extension finished on 2017. The line has some suburban services connecting Barcelona and surrounding areas and other services of metro inside Barcelona city.

Nowadays Barcelona - Vallès is one of the lines with most demand among other metro lines of Metro de Barcelona.

- Nº of km: This line has a total of 52,5 km of double track.
- Nº of pax per year: 62 million pax data from 2017.
- Nº trains per day: 1.301 circulations per day.
- Type of catenary: Flexible and Rigid depending on the section.
- Speed of the line: up to 90 km/h.

Figure 43. Llobregat – Anoia line details

Figure 44. Barcelona – Vallès line details

7.3 Description of test cases

The validation plan of SIA will gravitate towards the **functional requirements**. The non-functional set of requirements described in section 6 will not be subjected to validation, but verification, as will be described in the deliverable [11], where the architecture design will be documented along with the system verification plan.

The validation process will be coordinated and assessed by the end-users of the consortium, by checking the fulfillment of the high-functionality requirements (section 5.1) related to the use cases defined in section 4. The results will be recorded with the following information:

- Service Functionality

- ID of the corresponding requirement
- Associated use case
- Validation successful?
- Validation notes

The following sections include the tables that will be used for the validation for each of the four services.

7.3.1 iCatMon

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
SIA_F1_001	iCatMon allows setting configuration parameters	1, 2	Y / N	
SIA_F1_002	The onboard equipment related to iCatMon allows the initial configuration of the firmware by means of the necessary port(s)	1, 2	Y / N	
SIA_F2_001	iCatMon allows the introduction of inspection data related to the catenary with the associated electronics forms	1, 2	Y / N	
SIA_F3_001	iCatMon allows the introduction of auscultation data (if any) related to the catenary	1, 2	Y / N	
SIA_F4_001 SIA_F5_002 SIA_F5_003 SIA_F5_004	iCatMon informs about the historic health status of the catenary, by integrating data from inspections, and auscultations. The historic health status of the catenary is visualized by means of a time representation of its relevant KPIs	1, 2	Y / N	
SIA_F5_001 SIA_F5_002 SIA_F5_003	iCatMon informs about the current health status of the catenary, by integrating data from historic health status and from onboard systems. The current health status of the catenary is visualized by means of a time representation of its relevant KPIs	1, 2	Y / N	
SIA_F6_001 SIA_F6_002 SIA_F6_003	iCatMon visualizes the future (i.e. predicted) status of the overhead contact wire in terms of its wear, height and stagger with their relevant KPIs	1, 2	Y / N	

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
SIA_F6_004				
SIA_F6_005	iCatMon displays a warning message if a failure related to wear, height and/or stagger of the overhead contact wire is detected	1, 2	Y / N	
SIA_F7_001	iCatMon proposes a set of related maintenance actions recommendations when a failure related to wear, height and/or stagger of the overhead contact wire is detected	1, 2	Y / N	

7.3.2 iPantMon

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
SIA_F1_001	iPantMon allows setting configuration parameters	3	Y / N	
SIA_F1_002	The onboard equipment related to iPantMon allows the initial configuration of the firmware by means of the necessary port(s)	3	Y / N	
SIA_F2_001	iPantMon allows the introduction of inspection data related to the pantograph with the associated electronics forms	3	Y / N	
SIA_F3_001	iPantMon allows the introduction of auscultation data (if any) related to the pantograph	3	Y / N	
SIA_F4_001 SIA_F5_002 SIA_F5_003 SIA_F5_004	iPantMon informs about the historic health status of the pantograph, by integrating data from inspections, and auscultations. The historic health status of the pantograph is visualized by means of a time representation of its relevant KPIs	3	Y / N	
SIA_F5_001 SIA_F5_002	iPantMon informs about the current health status of the pantograph, by integrating data from historic health status and	3	Y / N	

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
SIA_F5_003	from onboard systems. The current health status of the pantograph is visualized by means of a time representation of its relevant KPIs			
SIA_F6_001	iPantMon visualizes the future (i.e. predicted) status of the pantograph in terms of its wear, with the relevant KPIs	3	Y / N	
SIA_F6_002				
SIA_F6_003				
SIA_F6_004				
SIA_F6_005	iPantMon displays a warning message if a failure related to the wear of the pantograph contact strips is detected	3	Y / N	
SIA_F7_001	iPantMon proposes a set of related maintenance actions recommendations when a failure related to wear of the contact strips is detected	3	Y / N	

7.3.3 iWheelMon

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
SIA_F1_001	iWheelMon allows setting configuration parameters	4	Y / N	
SIA_F1_002	The onboard equipment related to iWheelMon allows the initial configuration of the firmware by means of the necessary port(s)	4	Y / N	
SIA_F2_001	iWheelMon allows the introduction of inspection data related to the wheelset with the associated electronics forms	4	Y / N	
SIA_F3_001	iWheelMon allows the introduction of auscultation data (if any) related to the wheelset	4	Y / N	
SIA_F4_001		4	Y / N	

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
SIA_F5_002 SIA_F5_003 SIA_F5_004	iWheelMon informs about the historic health status of the wheelset, by integrating data from inspections, and auscultations. The historic health status of the wheelset is visualized by means of a time representation of its relevant KPIs			
SIA_F5_001 SIA_F5_002 SIA_F5_003	iWheelMon informs about the current health status of the wheelset, by integrating data from historic health status and from onboard systems. The current health status of the wheelset is visualized by means of a time representation of its relevant KPIs	4	Y / N	
SIA_F6_001 SIA_F6_002 SIA_F6_003 SIA_F6_004	iWheelMon visualizes the future (i.e. predicted) status of the wheelset in terms of the apparition of wheel flats and polygonization wear, with the relevant KPIs	4	Y / N	
SIA_F6_005	iWheelMon displays a warning message if a failure related to wheel flats and polygonization wear of the wheelset is detected	4	Y / N	
SIA_F7_001	iWheelMon proposes a set of related maintenance actions recommendations when a failure related to wheel flats and polygonization wear of the wheelset is detected	4	Y / N	

7.3.4 iRailMon

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
SIA_F1_001	iRailMon allows setting configuration parameters	5,6	Y / N	
SIA_F1_002	The onboard equipment related to iRailMon allows the initial	5,6	Y / N	

Req_ID	Functionality description	Use case no.	Validation successful	Validation notes
	configuration of the firmware by means of the necessary port(s)			
SIA_F2_001	iRailMon allows the introduction of inspection data related to the rail with the associated electronics forms	5,6	Y / N	
SIA_F3_001	iRailMon allows the introduction of auscultation data related to the rail	5,6	Y / N	
SIA_F4_001 SIA_F4_002 SIA_F4_003 SIA_F4_004	iRailMon informs about the historic health status of the rail, by integrating data from inspections, and auscultations. The historic health status of the rail is visualized by means of a time representation of its relevant KPIs	5,6	Y / N	
SIA_F5_001 SIA_F5_002 SIA_F5_003	iRailMon informs about the current health status of the rail, by integrating data from historic health status and from onboard systems. The current health status of the rail is visualized by means of a time representation of its relevant KPIs	1, 2	Y / N	
SIA_F6_001 SIA_F6_002 SIA_F6_003 SIA_F6_004	iRailMon visualizes the future (i.e. predicted) status of the rail in terms of the apparition of corrugation and short-wave irregularities, with the relevant KPIs	5,6	Y / N	
SIA_F6_005	iRailMon displays a warning message if a failure related to corrugation and short-wave defects of the rail is detected	5,6	Y / N	
SIA_F7_001	iRailMon proposes a set of related maintenance actions recommendations when a failure related to corrugation and short-wave defects of the rail is detected	5,6	Y / N	

8 Conclusions

The aim of this report has been to provide the **high-level requirements** associated to the functionality of the four services to be developed within SIA project. The main conclusions are summarized below.

- Concerning the methodology for the elaboration of the high-level functionality of SIA, the participation of the end-users present in the consortium has been key. In addition to that, the participation of external (potential) end-users has been fostered by means of the circulation of a questionnaire.
- A deep analysis and an exhaustive compilation of failure mechanisms and associated maintenance actions have been described for the assets that are relevant to SIA's services (catenary, pantograph, wheelset and rail). The nature of these failure mechanisms is very wide, and their early detection via on-board low-cost systems is non-viable. For that reason, some of them have been targeted for the full functionality of SIA and described as use cases.
- The selection of the relevant use cases has been made consider the impact of the different failure modes in the operations of the end-users, and also in terms of the technological feasibility of the predictive capabilities of the services. These are the use cases that will be validated:
    - iCatMon: wear, incorrect height and/or stagger of the overhead contact wire
    - iPantMon: wear of the pantograph's carbon strips
    - iWheelMon: wheel flats and polygonization wear
    - iRailMon: rail corrugation and short-wave defects
- The main functionality of the four systems that SIA will bring to market has been established, and the external interfaces with which SIA will interact with its context have been described. The high-level functionality can be summarized through the following functions:
    - F1. Configuration and Installation
    - F2. Introduction of inspection data
    - F3. Introduction of auscultation data
    - F4. Inform about the historic health status of assets
    - F5. Inform about the current health status of assets
    - F6. Inform about early detection of failures
    - F7. Propose maintenance recommendations
- Non-functional requirements have also been established and will mainly impact the requirements of the on-board subsystems of SIA
- The preliminary validation plan of iCatMon, iPantMon, iWheelMon and iRailMon has been also described. The end-users will validate the high-level functionality particularized for the use cases by means of four pilot demonstrations in two different scenarios, by the assessment of the completion of the high-level requirements.

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Appendix A: Questionnaire for potential end-users

From the questionnaire only four (4) online responses have been obtained. We eventually find out that the reason could be due to the complexity and detail of the questions. The questionnaire has been online since August 2018 and it is expected to be online until the end of the project (February 2021) as the feedback obtained will also be helpful for the exploitation plan down the road. However, the questionnaire has been used as a guideline to obtain feedback from potential end-users in informal (no minutes and/or proof material available) interviews that CEIT held during Innotrans fair, as SIA was present at the CEIT's stand. The same actuation is foreseen in future fairs (e.g. RailLive 2019 & 2020, Innotrans 2020).

Intro / Context

SIA Project (https://siaproject.eu) has the objective of developing 4 ready-to-use new services (iWheelMon, iRailMon, iPantMon and iCatMon) to provide prognostic information about the health status of the railway's most demanding assets in terms of maintenance costs (wheel, rail, pantograph and catenary).

These new services will help to reduce the 15% of railway maintenance costs, 25% of maintenance unscheduled events and 15% of derailments associated to the rail-wheel interface. These new end-to-end services are supported by a system that will adapt and integrate existing products (TR9) and technologies (TRL5-TRL7) as STEREO®, WINDSepe® and ERSAT_CPS® among others, brought by the consortium.

The features of the services rely on an accurate and available positioning that will be achieved thanks to the distinguished characteristics for the railway environment of the EGNOS and Galileo multi-frequency multi-constellation signals (e.g. E5 wideband signal with Altboc modulation has high code range precision through reduced code noise and multipath).

SIA will build on existing EGNSS based pilot projects such as H2020-ERSAT EAV and H2020-FR8RAIL within the context of Shift2Rail. SIA will also build on standards and best practice guides (e.g. GEGN8578, IEC613735-2-6, RailTopoModel among others), which will foster EGNSS adoption in the railway environment.

Complementary, and with the same importance level to the technical development, SIA has the objective of paving the way for the market uptake of the new services. With this regard, 4 pilot projects have been planned to validate the performance of the new services in fully operational scenarios and to be used as a commercial platform for potential end-users.

The preliminary business plan reveals a very promising business potential with a ROI of 126%, an accumulated turn-over of 34M€ in 5 years and acquired income rights of another 58M€ for the 5th year. Three high-tech SMEs are leading the project representing approximately 40% of the project effort.

1) General data about the exploitation

Please complete this section with general data of your exploitation. Whenever possible, be specific in the answers by providing accurate numbers.

a. Type of **exploitation**
   i. Tram
   ii. Metro
   iii. Regional / Metropolitan
   iv. Intercity
   v. High-speed
   vi. Freight
   vii. Other (please state): ______________________________
b. Network **length** (total)
   i. < 10km
   ii. < 100 km
   iii. < 1000 km
   iv. Other (please state): ______________________________
c. Years in **service**
   i. < 10 years
   ii. < 50 years
   iii. < 100 years
   iv. Other (please state): ______________________________
d. **No. passengers** per year
   i. < 10 Million
   ii. < 100 Million
   iii. < 100 Million
   iv. < 1000 Million
   v. Other (please state): ______________________________
e. **Maintenance costs** per year
   i. < 1 M€
   ii. < 10 M€
   iii. < 100 M€
   iv. Other (please state): ______________________________
f. **No. trains** in simultaneous operation
   i. < 10
   ii. < 50
   iii. < 100
   iv. < 500
   v. Other (please state): ______________________________
g. Mean **time between trains**
   i. < 5 min
   ii. < 10 min
   iii. < 30 min
   iv. Other (please state): ______________________________

2) Defects / Failure modes: impact and frequency

This section contains a set of tables based on a **catalogue of the most important defects** that are controlled by inspections (e.g. visual, thermographic), auscultations or otherwise, in the different types of assets, divided into systems and subsystems. To complete the questionnaire, it is necessary to fill in:

- the “**impact**” on the estimated operation in case the failure occurs on a scale of 1 to 5, where 1 is "minimum impact" and 5 is "maximum impact" (circulation is halted, and an emergency maintenance operation must be performed)
- the “**frequency**” of the failure mode in question on a scale of 1 to 5, where 5 stands for a very frequent condition and 1 for a very infrequent one.

2.1) Catenary Failure Modes

System	Subsystem	Failure mode	Impact	Frequency
Wires	Contact wire	Breakage		
		Cracks		
		Wear		
		Roughness caused by sparkover		
		Tension joints with protrusions		
		Improper tension		
		Wire twist		
		Ice sleeves		
		Improper fastening		
		Incorrect height		
		Incorrect stagger		
		Improper wire spacing		
	Catenary	Breakage		
		Cracks		
		Shearing		
		Deformations		
		Corrosion		
		Joints in bad condition		
		Inadequate tension		
		Burned element		
		Improper assembly		
		Incorrect geometry		
	Feeder	Breakage		
		Cracks		
		Incorrect geometry (isolation distances)		

System	Subsystem	Failure mode	Impact	Frequency
		Joints in bad condition		
		Bending irons in bad condition		
		Burned sections		
		Rust		
		Improper electrical continuity		
		Insulator in bad condition		
		Improper assembly		
Support and sustentation	Masts and gantries	Mast foundation in bad condition (cracked or bare concrete, damaged rain gutter)		
		Improper geometry		
		Unstable joints		
		Damaged electroplating or paint job		
		Anchor points in bad condition		
		Rust		
	Registration arms	Notable deformation		
		Excessive displacement		
		Rust		
		Damaged electroplating or paint job		
		Defective fastening		
		Improper geometry		
	Droppers	Breakage		
		Displacement		
		Defective fastening		
		Incorrect alignment		
		Improper geometry		
		Burns		
	Rigid catenary guides	Notable deformation		
		Rust or corrosion		
		Fastenings in bad condition		
		Grease deposits		
Protection equipment	Insulators	Surface contamination		
		Perforations		
		Improper geometry		
		Vegetation-induced insulation loss		
		Damaged catenary wire insulation		

System	Subsystem	Failure mode	Impact	Frequency
		Damaged overhead contact wire insulation		
		Pantograph impacts		
	Disconnectors	Improper electrical contact		
		Arcing horns in bad condition		
		Moving contacts in bad condition		
		Improper isolation distance		
		Bad electroplating		
		Surface contamination		
		Vegetation-induced insulation loss		
		Rust		
	Sections	Improper registration arms displacement		
		Improper catenary separation		
		Feeders in bad condition		
		Improper elevation in anchoring tails.		
		Vegetation-induced insulation loss		
	Earth wire	Damage		
		Improper electrical continuity		
	Lightning conductor	Connections in bad condition		
		Improper cable clamping		
		Burns		
	Hoods	Falling hood risk		

2.2) Pantograph Failure Modes

System	Subsystem	Failure mode	Impact	Frequency
Pantograph head	Contact strip	Normal wear		
		Asymmetric wear		
		High erosion		
		Cracks		
	Horn	Scraped		
		Damaged		

System	Subsystem	Failure mode	Impact	Frequency
	Pantograph head support unit	Position misadjusted		
		Suspension misadjusted		
	Other components	Damaged		
Frame and base frame	Insulators	Damaged		
	Junctions	High internal friction		
	Operating positions	Not adjusted		
	Electrical connections	Damaged		
	Other components	Damaged		
Drive system	Automatic dropping device	Incorrect working		
		Other components		
	Contact force regulation	Not correctly regulated		
	Other components	Damaged		

2.3) Wheelset Failure Modes

System	Subsystem	Failure mode	Impact	Frequency
Wheel	All types of wheels	Wheel flat		
		Metal build-up		
		Shelling, cavities		
		Scaling		
		Tread indentation		
		Isolated traverse cracking		
		Circularity defect (local tread collapse; periodic or stochastic out of round)		
		Spalling (thermal effects due to tread braking)		
		Thermal crack		
		Wheel tread roll-over		
		Damage to chamfered corner		
		Wheel tread – grooves and channels		

System	Subsystem	Failure mode	Impact	Frequency
		False flange		
		Damage on the flange		
		Sharp-edged radial marks and radial defects on the internal face of the rim		
		Damage resulting from identification markings		
		Damage from lathe driving tools		
		Sharp-edged circumferential defects on the web or wheel centre		
		Sharp-edged radial defect on the web		
		Wheel web hole defects		
		Cracks in the wheel hub		
	Monoblock wheels	Deep sub-surface tread		
		Wheel web (Defects on the web of a wheel used as braking surface; Overheating affecting the wheel rim/web transition)		
		Exceptional thermomechanical stressing in tired wheels		
Axle		Corrosion		
		Axle protection defect – Damage on the painting/coating		
		Defects Around the whole circumference		
		Circumferential defects (on a singular zone; around the whole circumference)		
		Notches and impact damage		
		Longitudinal defects		
		Damage in the interference fit zones		
Axle box		Axle box body (cracking or failure)		
		Thermal damage to the axle box		
		Damage at the weld seams of the manganese wear plates		
		The state of the bearing housing bore		

System	Subsystem	Failure mode	Impact	Frequency
		Out-of-roundness of the bore of the wheelset bearing housing		
		Damage allowing water or dust to penetrate		
		Missing or loose locking pieces		
		Missing or loose locking and mounting bolts		
		Excessive wear of the bearing housing		
		Axial and radial clearance depending on the axle box type		
		Internal damage (for example due to running noise		
		Disconnected, missing or damaged constituent elements or cables		
		Disconnected, missing or damaged wheelset guidance elements		
		Traces of lost grease/oil projected regularly over the entire circumference of the central portion of the wheel		
Wheelset		Wheel distortion		
		In service axial or angular movement of a wheel or of one of the other components (Axial movement; angular movement)		

2.4) Rail Failure Modes

System	Subsystem	Failure mode	Impact	Frequency
Defects in rail ends	Full section	Transverse break without apparent origin		
	Head	Progressive Transverse Cracking (kidney-shaped fatigue crack)		
		Horizontal cracking		
		Longitudinal vertical cracking		
		Surface defects		
		Shelling of running surface		
		Crushing		

System	Subsystem	Failure mode	Impact	Frequency
		Local batter of running surface		
		Wheel burns		
	Web	horizontal cracking at the web-head fillet radius		
		horizontal cracking at the web-foot fillet radius		
		longitudinal vertical cracking in the web (piping)		
		corrosion		
		Star cracking of fishbolt holes		
		Lap		
	Foot	Longitudinal vertical cracking		
		Corrosion		
Defects away from rail ends	Full section	Transverse break without apparent origin		
	Head	Progressive Transverse Cracking (kidney-shaped fatigue crack)		
		Longitudinal vertical cracking		
		Short pitch corrugation		
		Long pitch corrugation		
		Lateral wear		
		Abnormal lateral wear		
		Shelling of the running surface		
		Shelling of the gauge corner		
		Head checking/fissuring/Scaling at the gauge corner		
		Crushing		
		Local butter of running surface		
		Isolated wheel burn		
		Repeated wheel burn		
		Squats/Cracking and local depression of the running surface		
	Web	horizontal cracking at the web - head fillet radius		
		horizontal cracking at the web - foot fillet radius		
		Longitudinal vertical cracking (piping)		
		Corrosion		

System	Subsystem	Failure mode	Impact	Frequency
		Cracking around holes other than fishbolt holes		
		Diagonal cracking away from any hole		
		Lap		
	Foot	Longitudinal vertical cracking		
		Corrosion		
Defects caused by damages to the rail	Full section	Bruising		
		Faulty machining		
		Permanent deformation (warped rail)		
Welding and resurfacing defects	Electric flash-butt welding	Transverse cracking of the profile		
		Horizontal cracking of the web		
	Thermite welding	Transverse cracking of the profile		
		Horizontal cracking of the web		
	Electric arc welding	Transverse cracking of the profile		
		Horizontal cracking of the web		
	Oxyacetylene welding			
	Pressurised gas welding			
	Induction welding			
	Resurfacing	Transverse cracking of the head		
		Detachment or shelling of the resurfaced portion		
	Other welding methods	Transverse cracking under electrical connection		

3) Assets / defects localization: accuracy & performance

It is important to know the localization of the different assets that are distributed throughout the network. When trying to detect faulty assets, either for corrective or predictive (preferred) actions, factors like accuracy and latency on the information become key in order to mitigate risks and reduce costs. This section looks for information related to the needs for asset and/or defects localization.

a. For the provision of **location information** (e.g. that associated with a detected point of failure), what form do you require this to be provided in?
  - i. Geospatial coordinates (e.g. Lat, Lon)
    - 1. If yes, which of the following do you require?
      - a. 2-dimensional horizontal coordinates only
      - b. 3-dimensional coordinates
  - ii. Distance along-track from a reference point (railway linear system of reference)
    - 1. If yes, could you provide some information about the required system of reference? ______________________________
  - iii. Don't know
  - iv. Other (please state): ______________________________

b. Approximately how **accurate** do you require location information to be, where A=accuracy?
  - i. A<10cm
  - ii. 10cm<A<1m
  - iii. 1m<A<10m
  - iv. 10m<A
  - v. Don't know
  - vi. Other (please state): ______________________________

c. What would be an acceptable **latency** between the detection of an asset fault and the delivery of the associated information, where L=latency?
  - i. L<1sec
  - ii. 1sec<L<10sec
  - iii. 10sec<L<1min
  - iv. 1min<L<5min
  - v. Don't know
  - vi. Other (please state)

4) Current maintenance operations

We would like to know how you are currently managing your maintenance-related activities, in terms of Software you are using or otherwise.

a. Which specific Software are you currently using to manage the maintenance activities?
    i. General purpose CMMS
        Supplier: ______________________________
    ii. Railway specific CMMS
        Supplier: ______________________________
    iii. Own development
    iv. Other (please state): ______________________________
b. What are its three main features? List in order of importance
    i. Feature 1: ______________________________
    ii. Feature 2: ______________________________
    iii. Feature 3: ______________________________
c. What do you miss from it? List in order of importance
    i. Desired feature 1: ______________________________
    ii. Desired feature 2: ______________________________
    iii. Desired feature 3: ______________________________
d. What do you find most frustrating about it? List in order of importance
    i. Feature 1: ______________________________
    ii. Feature 2: ______________________________
    iii. Feature 3: ______________________________

5) 4 new services: desirable features

SIA project's main goal (www.siaproject.eu) is to develop four ready-to-use new services to provide prognostic information about the health status of the railway's most demanding assets in terms of maintenance costs, at the points of the interaction between the vehicle and the infrastructure:

- *iCatMon* for the catenary
- *iPantMon* for the pantograph
- *iWheelMon* for the wheelset
- *iRailMon* for the rail

We would like to hear your opinion about **which features should these new services provide**, in terms of functionality, appearance (i.e. visualization), installation, integration of datasources, etc., taking into account that they will be based on these common features:

- Plug-in SW based on Web App
- Real-Time info about assets' status
- Prognostic health status assessment
- Integration with other IT systems

a. iCatMon (catenary)
   i. Feature 1: ____________________
   ii. Feature 2: ____________________
   iii. Feature 3: ____________________
b. iPantMon (pantograph)
   i. Feature 1: ____________________
   ii. Feature 2: ____________________
   iii. Feature 3: ____________________
c. iWheelMon (wheelset)
   i. Feature 1: ____________________
   ii. Feature 2: ____________________
   iii. Feature 3: ____________________
d. iRailMon (Rail)
   i. Feature 1: ____________________
   ii. Feature 2: ____________________
   iii. Feature 3: ____________________
e. Other general features (please elaborate)

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6) OTHER COMMENTS AND SUGGESTIONS