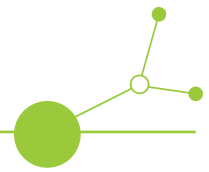


# Annex 1 to Deliverable D3.1.2

## Report on development of joint digital solutions to enable and accelerate circularity in public transport



Version 2  
03 2026

1.A Modules for predictive maintenance of  
infrastructure and rolling stock - LVB







# DELIVERABLE D.3.1.2

Solutions O3.2 - Modules for predictive maintenance of infrastructure and rolling stock and O3.4 Circular business planning tool for electrified public transport fleets and infrastructure

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# 1. Objectives

## Primary objective

The primary objective of the Leipzig predictive maintenance solution is to transform LVB’s current reactive and interval-based maintenance approach into a continuous, data-driven and predictive maintenance model. By using vehicle-based sensing, edge computing and AI-supported analytics, the solution enables continuous assessment of track, trackbed and overhead line (OHL) condition, early identification of degradation patterns, and targeted integration of findings into maintenance workflows. This reduces failures, enhances operational reliability and extends the lifetime of key infrastructure assets.

## Circular economy objective

The solution aims to significantly improve resource and energy efficiency and material use in public transport infrastructure. By identifying wear and emerging faults at an early stage, the solution helps to avoid late, material-intensive interventions, extend asset lifecycles, and reduce waste. By identifying energy losses, e.g. in breaking resistors, it helps to show potential for using less energy and recovering more energy by recuperation. It thus directly supports CE4CE’s overarching goal of increasing circularity and creating value through prolonged asset life in the public transport sector.

## Strategic objective

The pilot forms the foundation for the future development of a scenario-based and parameter-supported planning and decision-making model within LVB’s asset management. This model is intended to support objective prioritisation, investment planning and budget steering. Its development and institutionalisation are part of the Action Plan, not the outcome of the pilot itself.

## Scalability and replicability objective

The solution is designed to be scalable and transferable through its modular architecture, clear interface separation, and compliance with relevant rail standards (e.g. EN 50155, EN 45545).



The pilot validates the core system components, while wide-scale adoption and long-term institutionalisation will be achieved after the pilot as part of the Action Plan.

## 2. Target groups

The Leipzig predictive maintenance solution addresses several core user and stakeholder groups within LVB and the wider ecosystem. The grouping follows the roles, responsibilities and interactions that were defined and practiced during the pilot implementation.

### 2.1. Primary target groups

#### Asset management (LVB)

- Central consumer of continuously generated condition data and AI-supported findings
- Responsible for **prioritisation, maintenance planning, budget preparation** and **decision support**
- Uses the solution to transition from reactive to predictive maintenance and to inform strategic steering

#### Infrastructure maintenance / IFTEC

- Operational user of track, track bed and OHL detection results
- Responsible for **on-site validation**, targeted interventions and structured feedback loops
- Benefits from increased efficiency in resource allocation and precise localisation of hotspots

#### Digital systems / IT / Data platform teams (LVB)

- Ensure integration with existing systems (MR.pro®, GIS, data platforms)
- Maintain data sovereignty, interfaces, metadata, object IDs, and georeferencing
- Operate the data pipelines and provide visualisation for internal processes

#### Operations / Control room / Drivers

- Provide feedback on ride quality, irregularities and operational anomalies
- Benefit from early warnings about potential disruptions
- Are informed about planned interventions or operational impacts

### 2.2. Secondary target groups (indirect users and stakeholders)

#### Controlling and Investment Planning (LVB)

- Use condition and prioritisation data to support budget and investment decisions
- Gain improved transparency and more objective inputs for risk-based planning



### City of Leipzig and municipal infrastructure partners

(e.g., water utilities, electricity grid operators, road authorities)

- Can use georeferenced condition insights for coordinated planning of multi-stakeholder street interventions
- Benefit from early identification of critical sections during joint construction planning processes

### Research and industry partners (e.g., HTWK Leipzig, Goldschmidt, and other technology providers)

- Support technical evaluation and method development
- Use the data for scientific analysis, algorithm refinement and innovation

## 2.3. Transfer and replication target groups

### Public transport operators, infrastructure owners, transport authorities in Europe

- Can adopt the modular architecture (sensing → edge → analytics → integration)
- Benefit from standards compliance (EN 50155 / EN 45545) and transferable processes
- Preconditions: object IDs, georeferencing, interfaces to AM/GIS systems

### Technology providers and system integrators

- Can connect to the solution, extend modules or integrate alternative components
- Are supported by the clear separation of data acquisition and analytics (avoiding vendor lock-in)

## 3. The solution concept

The solution developed in the Leipzig CE4CE pilot is a modular, vehicle-based predictive maintenance system that continuously assesses the condition of urban rail infrastructure and translates raw measurement data into actionable operational and strategic insights. It integrates on-train sensing, edge computing, AI-supported analytics, georeferencing, and interactive dashboards into a coherent, end-to-end monitoring chain.



Figure 1 The solution vision prepared by LVB

### 3.1. Short summary of the pilot action (what was tested and why)

During the pilot, selected tram vehicles were equipped with modular sensor units that collected:

1. vibration data for track and track bed condition,
2. vibration-, camera- and profilometry data for overhead line inspection,
3. positional and object-reference data for spatial accuracy.

The aim was to replace missing continuous condition information and establish a reliable basis for early detection of degradation patterns across the network.

In addition to continuous monitoring, the pilot also explored the potential for partially complementing or extending traditional periodic infrastructure measurement campaigns. Public transport operators typically rely on specialised external inspection services carried out at defined intervals. Through continuous vehicle-based monitoring, the system provides additional information between such inspections and may contribute to reducing their frequency or increasing the interval between campaigns, subject to regulatory approval and certification of measurement accuracy.

### 3.2. Definition and design of the solution

The solution represents an end-to-end digital monitoring system that:

1. continuously captures infrastructure condition,
2. automatically identifies anomalies through AI,



3. displays all findings in a fully georeferenced manner,
4. supports prioritisation of interventions,
5. and integrates seamlessly into existing asset management workflows.

In essence, the solution acts as an early-warning system for infrastructure risks, enabling more objective, data-driven maintenance decisions and providing the foundation for predictive maintenance strategies.

### 3.3. Solution concept and structure

#### 3.3.1. Modular on-train sensing

The system is based on the principle of collecting high-quality data during regular vehicle operation. Modules include:

- vibration sensors (track & trackbed),
- vibration sensors, camera and laser units (overhead line & pantograph interaction),
- georeferencing and object-ID mapping for precise localization,
- existing data from standard on-board systems.

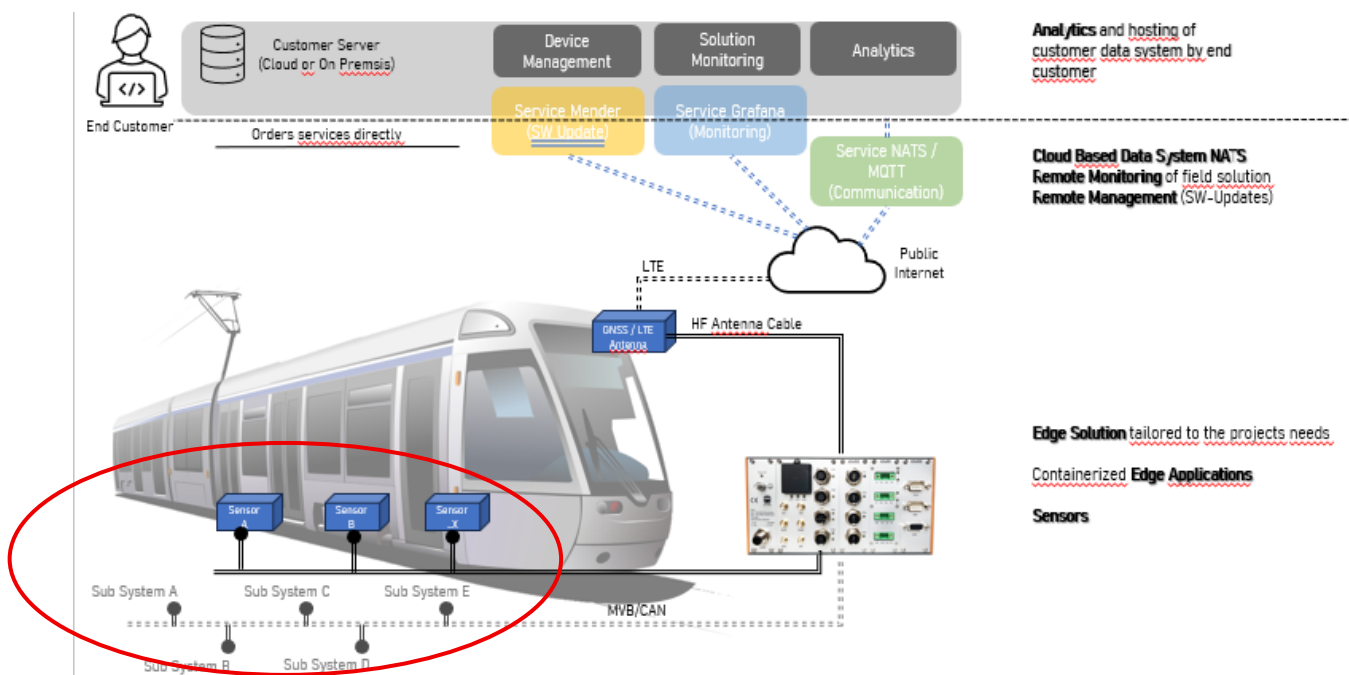


Figure 2 Solution visual conceptualisation: the modular approach to on-train sensing

The modular approach allows operators to adapt the sensing setup to their fleet, network characteristics, or regulatory requirements.



### 3.3.2. Edge computing and stable data pipeline

An on-board edge computing device (CI4RAIL) performs:

- preprocessing and filtering,
- buffering of data,
- quality assurance under varying connectivity conditions.

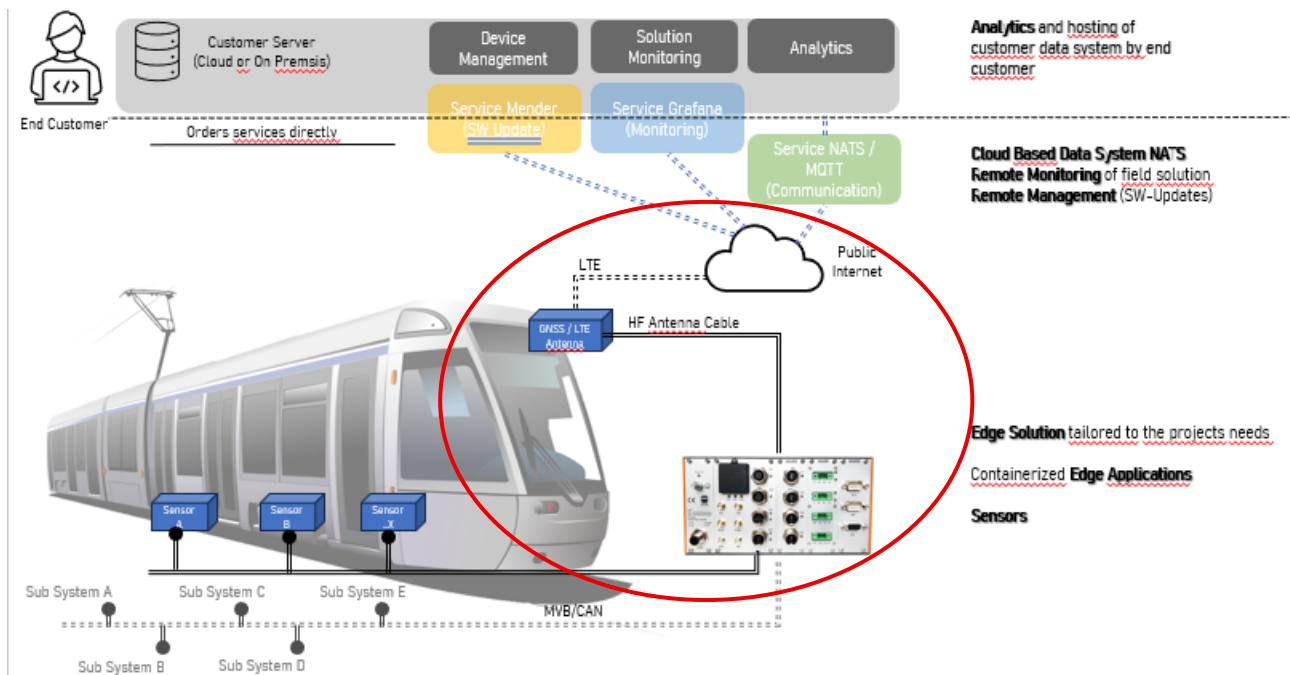


Figure 3 The data pipeline

This ensures a robust, resilient data pipeline, which is essential for large-scale predictive maintenance systems.

### 3.3.3. AI-supported analytics platforms

The solution uses multiple specialised analytics modules:

- CEMIT OnTrack → detection and classification of track and trackbed defects, hotspot identification, heatmaps
- PantoHealth → detection of OHL hardpoints, faulty section insulators, stagger deviations, contact wire height misadjustment, contact wire critical thickness, contact anomalies
- KRUCH RAILWAY INNOVATIONS - analyzation of various sensor and on-board data sets for complex monitoring and optimisation

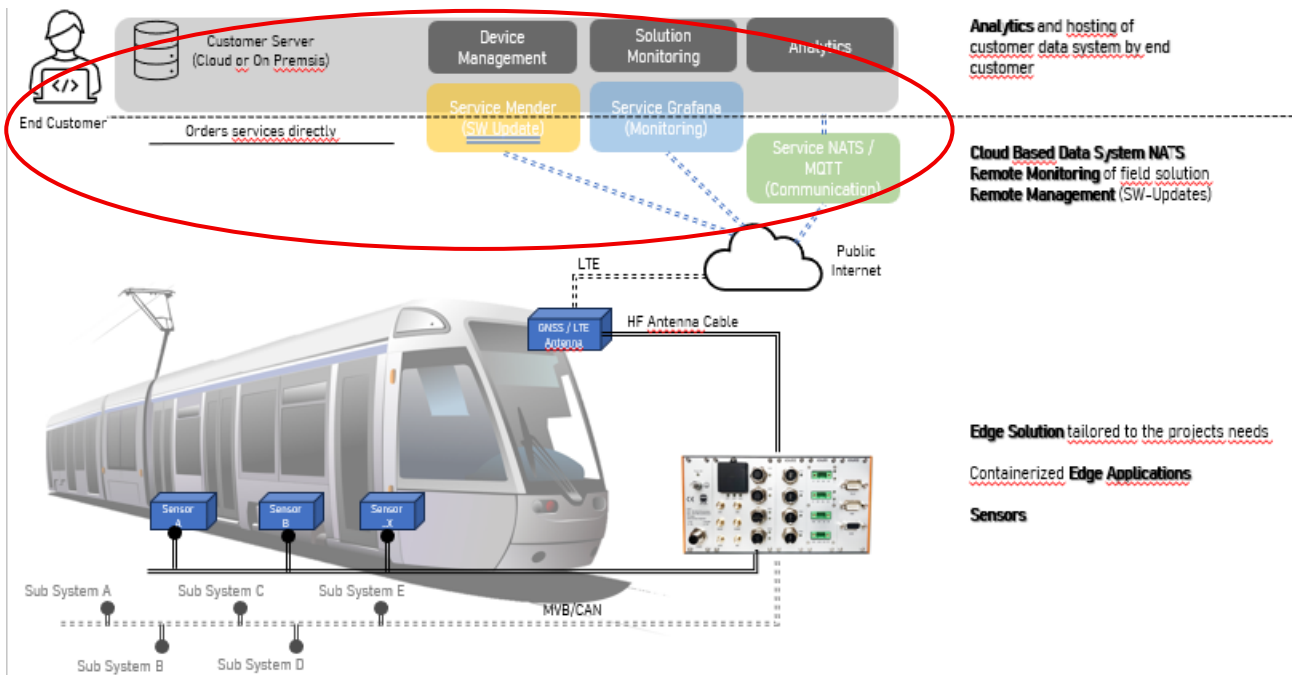


Figure 4 The analytics modules

These analytics modules turn previously subjective, manual inspections performed in regular or sporadic intervals, into measurable, reproducible, continuously carried out digital processes.

Beyond automated anomaly detection, the analytics modules generate network-wide condition insights. Examples include:

- identification and ranking of critical infrastructure points requiring intervention,
- systematic analysis of section insulators and other overhead components,
- mapping of contact wire wear and thickness development,
- creation of network heatmaps indicating areas of increased mechanical stress,
- continuous refinement of detection algorithms to minimise false positives.



### 3.3.4. Georeferencing and integration with asset management systems

All findings are:

- precisely georeferenced,
- linked to object identifiers (masts, spans, track sections),
- and prepared for integration into MR.pro®, GIS systems, and municipal data platforms.

This results in the first continuous, objective, network-wide condition map, enabling direct transfer into inspection, ticketing and planning processes.

### 3.3.5. Dashboards and decision support tools

Users receive:

- interactive map-based interfaces,
- fault categories and severity levels,
- trend curves and timelines,
- exports for maintenance tickets and workflows,
- prioritisation support.

This creates a closed decision chain from detection to operational intervention.

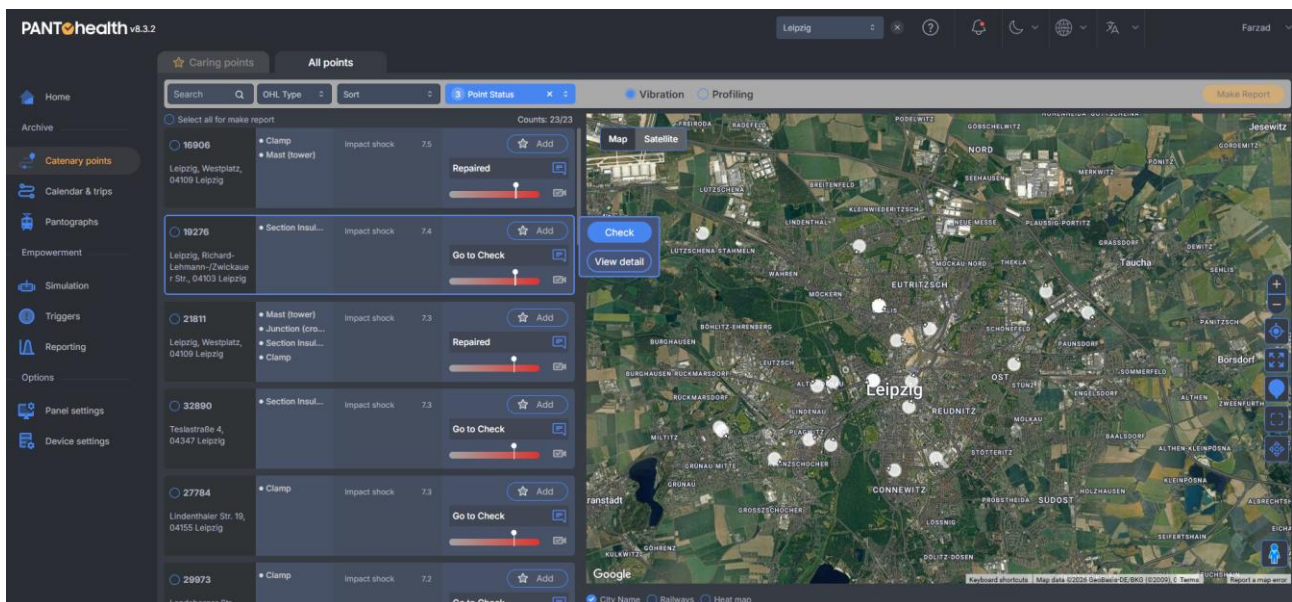


Figure 5 Example of detected abnormalities in the network of the overhead contact line

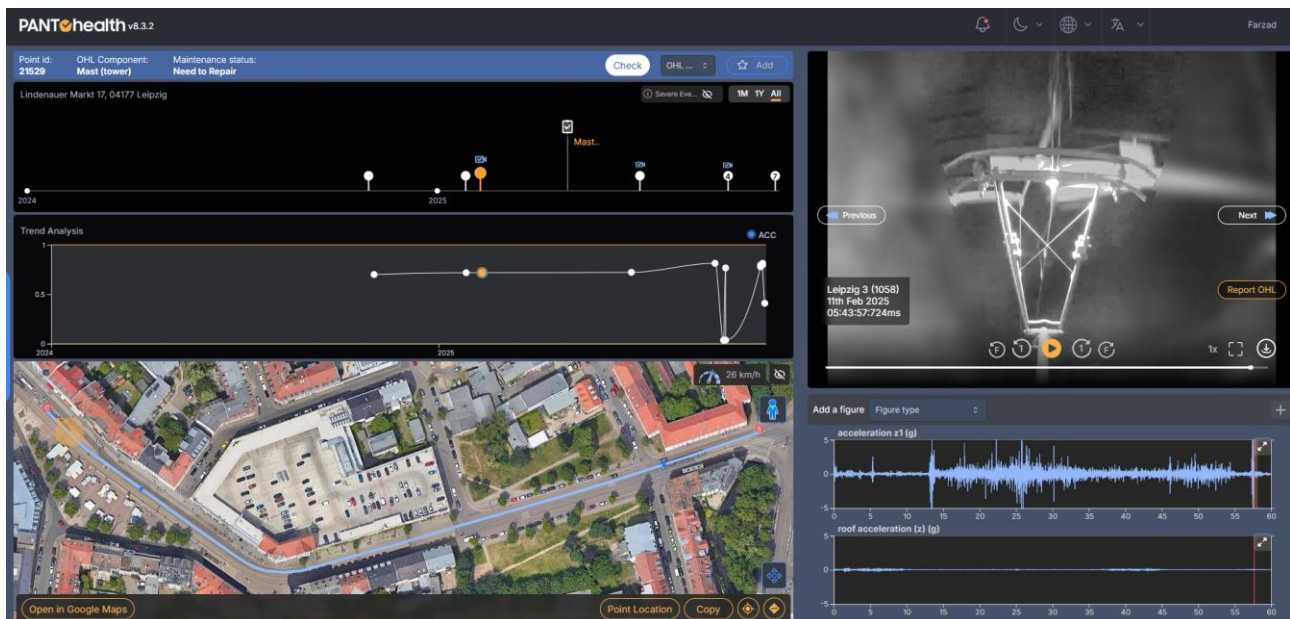


Figure 6 Example of misadjusted section insulator in the network

### 3.4. Circular Economy relevance of the solution

The solution supports multiple core principles of the circular economy:

- **lifetime extension** of infrastructure assets through early interventions,
- **resource savings** by avoiding late, material-intensive repairs,
- **waste reduction** through targeted maintenance rather than full replacements,
- energy savings through better use of energy and recuperated braking energy
- **knowledge preservation** by digitising condition data and reducing dependence on subjective expertise.

It enables operators to implement **sustainable, minimally invasive, and evidence-based maintenance strategies**.

### 3.5. Typical Use Cases

#### 3.5.1. Track and track bed

- detection of surface defects, structural weaknesses, settlements
- hotspot identification and prioritisation using heatmaps

#### 3.5.2. Overhead line and pantograph interaction

- detection of hardpoints, misaligned components e.g. section insulators, faulty components
- triggering of targeted, prioritized, minimally invasive adjustments



### 3.6. DO'S and DON'Ts (best-practice rules)

Derived directly from the pilot experience:

#### DO's

- separate data acquisition and analytics to avoid vendor lock-in
- validate AI findings on site before process integration
- ensure clean object IDs and georeferencing for integration and replicability

#### DON'Ts

- avoid operating without metadata (object IDs, positioning, timestamps) because integration and replication will fail
- do not rely solely on AI interpretations without field validation
- do not roll out the system without early involvement of Asset Management and Maintenance teams.

## 4. The solution development

The development of the Leipzig predictive maintenance solution followed a structured, multi-phase process. It combines technical implementation steps, organisational integration, and a modular procurement strategy to ensure the solution is scalable, data-sovereign, vendor-independent, and replicable.

### 4.1. Technical and functional requirements

The technical and functional requirements were derived both from LVB's operational context and the performance packages defined in the tender. They formed the basis for the solution's design and implementation.

#### Hardware and system requirements

- Use of rail-certified sensors and hardware compliant with EN 50155 and EN 45545  
→ ensuring resistance to shock, vibration, temperature and compliance with fire-safety standards
- Vehicle mounting points for sensors, cameras, laser units and the edge computer at defined mounting positions (roof, bogies, interior).
- A robust onboard power and transmission setup using PoE switches, GNSS/LTE/NRF antennas and appropriate cabling.

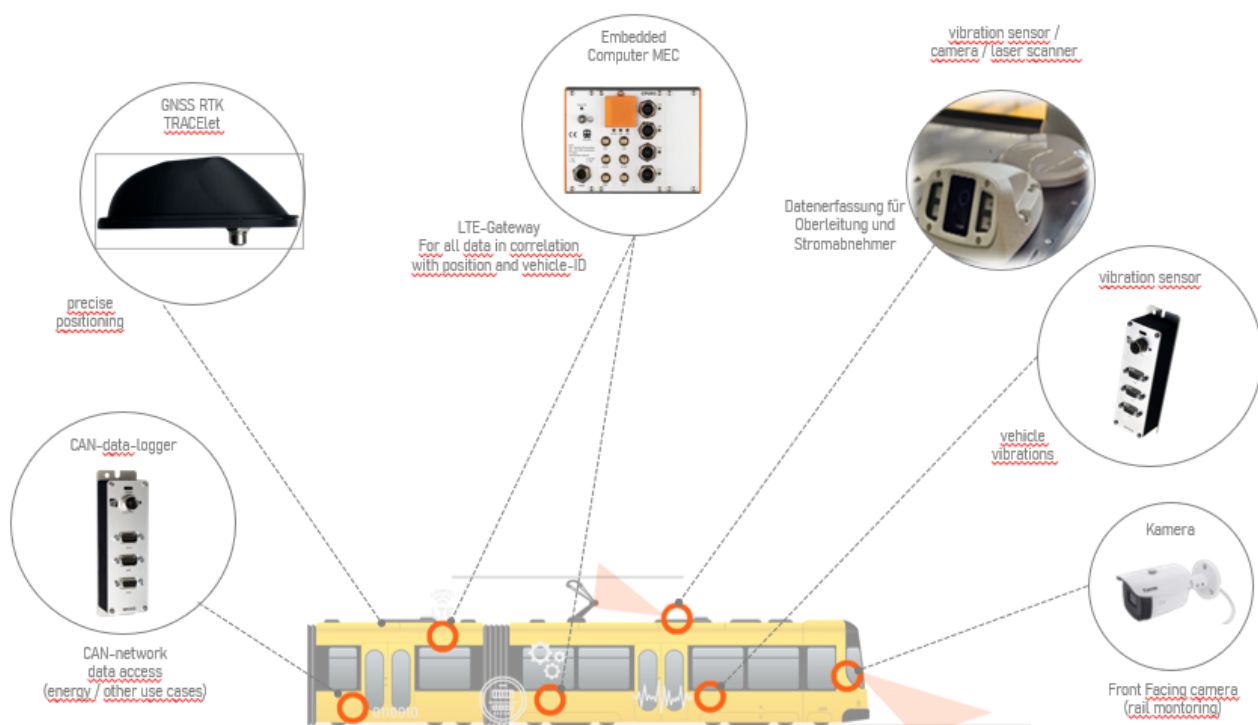


Figure 7 Hardware and system requirements

### Data and interface requirements

- Full georeferencing and unique object IDs for all infrastructure components.
- A structured data model with timestamps, versioning and quality flags.
- Integration with MR.pro®, GIS systems and possible data platforms.
- Contractual guarantee of full LVB data ownership; no usage rights for contractors.

### Functional requirements

- Automated, AI-supported fault classification for track, trackbed and OHL.
- Trend analysis across repeated measurement runs.
- Intuitive dashboards for asset management, maintenance and operations.
- Export, alarming and ticketing functions for operational execution.

These requirements served as the binding basis for design, procurement and implementation of all modules.



## 4.2. Development logic: Design → Build → Test

The solution was realised via a clear development methodology addressing technical and organisational needs.

### (1) Design phase

In interdisciplinary workshops with Asset Management, IFTEC, IT/Data Platform and technology partners, the team defined:

- use cases, KPIs and validation logic;
- sensor and camera setup, mounting positions;
- the end-to-end data flow (Sensor → Edge → Backend → Dashboard);
- AI thresholds and verification mechanisms;
- the architectural principle of functional separation between data acquisition and analytics.

### (2) Build phase

Implementation comprised:

- integration of vibration sensors, positioning units, camera and laser systems;
- installation of the edge computer and a robust vehicle-to-backend data channel;
- construction of the full data path through analytics and dashboards;
- documentation of vehicle modifications to comply with rail engineering standards.

The modular integration approach enabled independent calibration and testing of each subsystem.

### (3) Test phase

Extensive testing included:

- calibration runs for all subsystems;
- training of AI algorithms
- AI results with on-site inspections;
- finalisation of fault classes, thresholds and quality parameters;
- assessment of pipeline stability, uptime and precision.

The test phase confirmed the operational viability of the automated detection logic (e.g., hardpoints, contact faults, track defects).



### 4.3. Pilot implementation in live operations

The implemented solution was extensively tested during regular tram service.

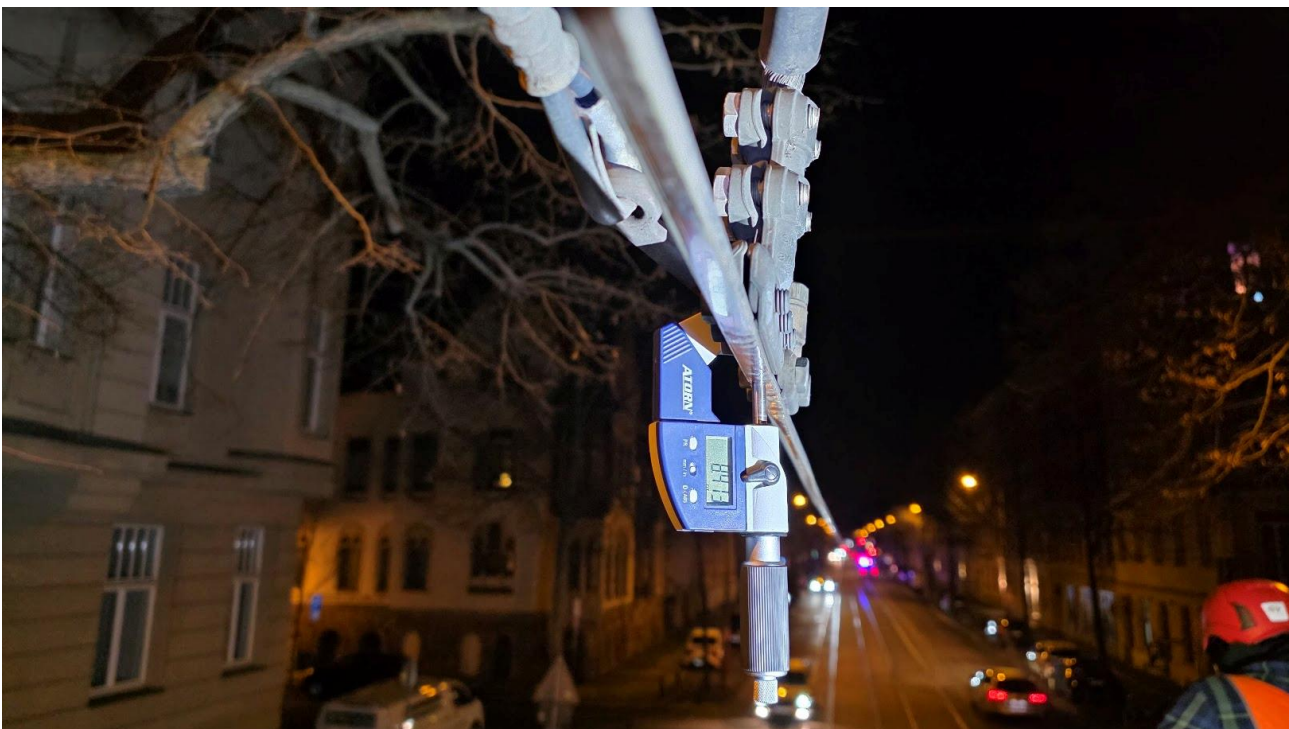
#### (1) Data Capture

Among other things, the system detected and analysed:

- new track defects, including three confirmed rail breaks;
- OHL hardpoints, insulator issues and contact anomalies, including misaligned section insulators;
- condition changes and trends across repeated runs.

#### (2) Validation

All automated findings were verified in the field, validated, prioritised and transferred into maintenance action lists by Asset Management and IFTEC. For example, a point with critical thickness of 15% less than minimum permitted threshold was found and validated in a field inspection.



*Figure 8 Point with critical thickness of 15% less than minimum permitted threshold*

In addition, a misadjusted section insulator which was damaging all passing pantographs was identified and reported to be readjusted.



*Figure 9 A misadjusted section insulator*

Real-world pilot achievements included:

- rapid identification of new defects
- shorter response times
- more precise planning of interventions
- improved operational safety
- extended lifetime of infrastructure components (e.g. contact line)
- extended lifetime of vehicle components (e.g. pantograph)

### **(3) Work routines and communication**

Key workflows introduced:

- weekly joint progress meetings (Jour Fixe) between LVB, IFTEC and technology partners
- continuous refinement via a shared action-item list
- iterative improvements of dashboards, data quality and algorithms



This created the foundation for a stable, reliable monitoring chain beyond the pilot context.

## 4.4. Operational playbook - from diagnosis to action

The aim of this section is to ensure a uniform process in daily operations so that automated analytical findings are reliably, quickly and effectively translated into operational measures - for track/track bed and overhead line (and optionally energy use cases).

### 4.4.1. Common workflow (all modules)

- **Detection (System):** Automated detection (vibration/OHL signals/image features) with georeferencing and object assignment.
- **Triage (Asset Management):** Visual review in the dashboard (confidence, history, trend); classification of severity and urgency.
- **Ticketing (Asset Management /IT):** Creation of a work item (Asset Management System/MR.pro®/GIS link), including coordinates, object ID, and evidentiary graphic/frame.
- **Dispatch (maintenance):** Field inspection and intervention (immediate action vs. scheduled task); allocation of materials and personnel.
- **Closure & Feedback:** Finding confirmed/not confirmed, photo/report, date, effort; write-back to the dashboard (training/threshold tuning).
- **KPI-Logging:** Automatic recording of: detection-to-action time, confirmed findings, follow-up events, outage minutes, costs/materials.

### 4.4.2. Specific: overhead contact line / pantograph (OHL)

- **Typical findings:** hard points, misalignment/height deviations, section insulator issues, contact anomalies/arcing critical thickness in the contact wire
- **Field actions:** adjustment (e.g., insulators), replacement of worn components, preventive re-tensioning
- **Special aspects:** Use trend curves for contact quality per geolocation; if recurring peaks appear, conduct root-cause analysis (e.g., suspension system)

### 4.4.3. Specific: track / track bed

- **Typical findings:** insulation faults, surface defects, structural faults, hotspots identified via heatmaps
- **Field actions:** visual inspection (sleepers, rails, ballast), immediate intervention if necessary, medium-term planning (tamping, replacement, grinding)
- **Special aspect:** link with ride comfort profiles and repeat runs to determine deterioration rates; newly detected fractures should be prioritized.



#### 4.4.4. Energie-use-cases

- **Data source:** CAN-Bus/ direct data of the traction system (instead of outdated energy loggers).
- **workflow:** baseline per line → hypotheses (acceleration ramps, recuperation) → A/B measures → monitoring energy/km + punctuality.
- **Special aspect:** Secure manufacturer-independent data interfaces early; data quality is critical to success.

#### 4.4.5. Escalation and safety

- **Safety critical:** Automatic escalation chain (operations manager/control center) in case of threshold exceedance; documented approval before recommissioning if required.
- **Audit-Trail:** Complete traceability (who performed which step and when).

#### 4.4.6. Roles & responsibilities (compact)

- **Asset Management (A/R):** triage, prioritizing, ticketing, KPI-Review.
- **Maintenance (R):** Field validation, intervention, feedback
- **IT/Data (R):** Data pipeline/uptime, object IDs, interfaces, user management
- **Partner (C):** Algorithm tuning, dashboard adjustments, training
- **operations (C/I):** Feedback on ride comfort and operational impact

### 4.5. Stakeholder involvement and co-design

The solution was developed using a consistent co-design approach involving:

- **Asset Management:** requirement definition, evaluation
- **IFTEC:** feasibility, operational validation
- **Drivers / Operations:** feedback on ride quality and anomalies
- **IT teams:** data architecture and system integration
- **Technology partners:** sensing systems, algorithms, dashboards

This approach ensured high acceptance, strong practical relevance and shortened development cycles.

### 4.6. Procurement and tendering strategy

The procurement strategy was a key success factor. It guaranteed technical modularity, data sovereignty and vendor independence.

#### Functional Separation of Work Packages

The tender defined two distinct functional domains:

- a. Data acquisition (hardware, sensing, edge computing, data channels)



- b. Data analytics (algorithms, AI models, dashboards)

This separation maximises flexibility and prevents single-vendor lock-in.

### Tender Results

- **CI4Rail:** main contractor for sensing, edge computing and data transmission;
- **PantoHealth:** subcontractor for OHL analytics;
- **CEMIT:** separate LVB tender for track and trackbed analytics (outside Interreg);
- **Kruch Railway Innovations:** analytics and energy-data concept (project partner).

### Modular Technical Setup

The tender specified the following modules:

- vibration sensors,
- positioning sensors,
- edge computer incl. PoE switch,
- camera and laser systems,
- pantograph sensor,
- cable systems for CAN, Ethernet and power.

### Engineering Services

- full integration of sensing and on-train systems;
- edge applications for energy, vibration and image data;
- vehicle-to-cloud data channel;
- frontend and backend dashboards;
- integration testing.

### Data Rights and Governance

The tender set out binding rules:

- all project data belong entirely to LVB;
- contractors receive no usage rights;
- provision of an E/R diagram and structured data storage;
- read-only access for internal interfaces.

### Operations and Service Components

During the project term, the following were defined:



- hosting and operation of backend systems;
- operation of OHL analytics software;
- maintenance of edge and sensor components;
- mobile connectivity services;
- system monitoring.

These provisions demonstrate that the solution was developed as a fully operable system, not merely a pilot installation.

## 4.7. Key insights and lessons from the solution development

The pilot phase produced important technical, organisational and procedural insights:

### Technical insights

- AI findings must be consistently validated in the field
- data-pipeline stability is more crucial than sensor precision alone
- georeferencing and object IDs are essential for integration and replication

### Organisational insights

- predictive maintenance requires organisational change, not only technology
- clear RACI structures and feedback routines are essential
- co-design accelerates solution maturity

### Process-related insights

- automated findings add value only if fully operationalisable
- validation loops are vital for maturity progression
- structured action lists enable faster, more efficient interventions

## 4.8. Practical implementation guide (operator playbook)

The guideline builds on the architecture, role model, and governance structure validated during the pilot project and translates them into a clear implementation pathway.

### Step 0 - Define initial situation and scope

- Prioritize objectives: early detection (safety/availability), resource efficiency (Circular Economy), budget stability.
- Define scope: start with one module (e.g., track/track bed or overhead contact line) and 1-2 lines; expand to the full chain after validation.
- Define success criteria: early-detection rate, ratio reactive: predictive, data uptime, “detection → action” time, energy/km.



### Step 1 - Establish governance and roles (RACI)

- Asset Management is responsible for objectives, KPIs, and prioritization (R/A).
- Maintenance (e.g., IFTEC) validates on site, implements measures, and provides feedback (R).
- IT/Data Platform is responsible for interfaces, object IDs, georeferencing, data quality/uptime (R).
- Technology/analytics partners provide sensors/edge systems, algorithms, dashboards, and training (C).
- Operations/control center/driving staff report anomalies and assess impacts (C/I).

### Step 2 - Prepare data model and object IDs

- Define an object catalog (masts, tension lengths, track sections) with unique IDs and chainage.
- Define metadata schema (timestamps, versioning, quality flags); objective: AM/GIS integration (e.g., MR.pro®, GIS) without ad-hoc interfaces.

### Step 3 - Secure minimum technical configuration

- Edge computer & peripherals: EN 50155/EN 45545, stable power supply, PoE switch, antennas (GNSS/LTE).
- Sensors: vibration (track/track bed), pantograph/OHL oscillation, roof/front camera; optional laser scanner.
- Vehicle-to-cloud channel: buffering, resilience during connectivity loss, end-to-end telemetry.
- Data rights: full data ownership by the operator, read-only system access for internal analyses, E/R diagram of data storage.

### Step 4 - Phased installation and calibration

- Phase A: integrate core measurements (e.g., vibration), perform baseline runs, test edge applications.
- Phase B: add OHL sensors + roof camera; test initial thresholds/heuristics.
- Phase C: retrofit camera/laser scanner; refine classifications.
- Calibration: algorithmic findings must always be cross-checked with field inspections (sampling plan).

### Step 5 - Establish co-design and routines

- Weekly jour fixe (AM, maintenance, IT, partners) with action-item list.
- Backlog for dashboard UX, thresholds, data quality; definition-of-done for alerts/findings.
- Training: interpretation of heatmaps, derivation of measures, ticketing process.

### Step 6 - Operational run and KPI review (learn)

- Apply the runbook (see 4.3.1).
- Monthly KPI reviews: early detection, reactive ratio, uptime, “detection→action,” energy/km; document lessons learned.
- Quarterly model maintenance: thresholds/algorithms, object IDs, interfaces, SOPs.

### Step 7 - Scaling and institutionalization

- Scale to additional lines/vehicles after stable KPI trend improvements.
- Integrate with strategic tools: anchor the parametric investment/scenario model in the Action Plan.



- Replication: document architecture, data model, and processes - transfer to additional operators.

## 5. Challenges and lessons learned

The development and piloting of the predictive maintenance solution in Leipzig took place in a complex technical and organisational environment. The pilot revealed a set of practical challenges and actionable insights that are critical for scale-up, process integration, and replication by other operators. The sections below summarise the key lessons learned from technical, organisational, and process perspectives.

### 5.1. Technical challenges and insights

#### Data quality and sensor robustness

Field validation confirmed that pipeline stability and data consistency are more critical for reliable analytics than maximum raw sensor resolution. Variability in data transmission, positioning signals, or edge-buffering has a stronger impact on result quality than initially anticipated. This underlines the need to harden the Sensor → Edge → Backend chain before further feature expansion.

#### Georeferencing and object mapping

A recurring hurdle was the precise mapping of measurements to real assets (e.g., masts, spans, track sections). The pilot demonstrated unequivocally that metadata quality (positioning, object IDs, timestamps) is a non-negotiable prerequisite to operationalise AI detections in asset-management and GIS systems, and to enable reproducible trend analyses over time.

#### Algorithmic precision and field validation

All AI-based detections required systematic on-site validation. Lessons learned included:

- Some false positives could only be excluded through physical inspections.
- Continuous algorithms fine-tuning with real-world data is essential for maturing detection quality.

The pilot confirmed practical value by identifying multiple OHL hardpoints and rail defects that were verified in the field.

#### Modularity of the technical architecture

The functional separation between data acquisition and analytics proved to be a cornerstone for solution stability and extensibility. This separation, defined already in the tender, enabled independent evolution of analytics, preserved data sovereignty, and reduced vendor lock-in risk.

### 5.2. Organisational challenges and insights

#### Internal process adaptation

Introducing continuous monitoring required a realignment of roles, responsibilities, and decision pathways. Only through regular joint meetings, structured validation routines, and a shared action-item register did workflows stabilise and institutional learning accelerate.

#### Capability building and acceptance



Predictive maintenance changes job profiles across maintenance, asset management, and IT:

- interpreting AI findings and heatmaps,
- using dashboards for trend-based decisions,
- embedding detections into work orders.

Stepwise, capability building and co-design with end-users proved decisive for acceptance and everyday use.

#### **Working with multiple technology partners**

The modular procurement structure meant several partners had to be aligned (CI4Rail, PantoHealth, CEMIT, Kruch Railway Innovations). This made clean interfaces, clear role definitions, and persistent communication indispensable to keep pace and quality through the pilot.

### **5.3. Process-related challenges and insights**

#### **Operationalisability of automated findings**

A core learning: automated detections only create value when they are:

- unambiguously locatable,
- prioritised against risk/impact,
- transferred into action lists (tickets), and
- confirmed by domain experts.

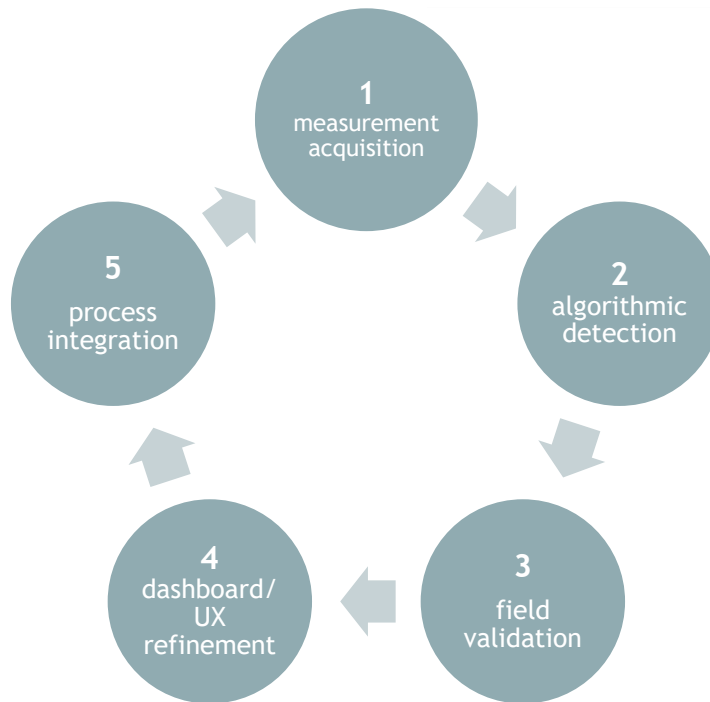
This required clear rating criteria and verification procedures to close the loop from analytics to field execution.

#### **Integration with existing systems**

Integrating monitoring data into MR.pro®, GIS, or data platforms sets high requirements for data formats, object structures, and metadata completeness. A standardised data model (object IDs, stationing, timestamps, quality flags) is indispensable to avoid ad-hoc interfaces and maintain long-term maintainability.

#### **Maturity progression**

The pilot confirmed that predictive-maintenance systems evolve through iterative cycles:



Iterating through this loop is essential for scaling, institutionalising routines, and moving from proof-of-concept to a stable operational chain.

## 5.4. Procurement and governance challenges and insights

### Complexity of modular procurement

By splitting data acquisition and analytics, the tender demanded a technically clean, legally distinct, and organisationally coordinated procurement approach. While more complex initially, the benefits in modularity, independence, and long-term flexibility clearly outweighed the coordination effort.

### Data rights as a critical success factor

The binding clause that all data belong to LVB was pivotal for scalability and interoperability, replicability by other operators, prevention of vendor lock-in, and the ability to pursue independent analytics innovation in the future. This governance decision underpins the solution's longevity far beyond the pilot runtime.

## 5.5. Overall lessons learned

From development and piloting, four overarching conclusions emerge:

1. **Predictive maintenance is not a technology project alone; it is an organisational change journey** that must be co-designed with end-users and decision-makers.
2. **Data quality, metadata and pipeline stability outweigh raw sensor precision** for reliable and repeatable analytics.
3. **Co-design and field validation are indispensable** to achieving solution maturity and user acceptance.



4. **A modular procurement strategy with full data sovereignty** is the foundation for replication and vendor-independent evolution.

These insights provide a robust basis for **scale-up**, **institutionalisation** under the Action Plan, and **transfer** to other public transport operators.

## 5.6. Readiness checklists for adoption

This section describes compact **checklists** for technical, data-related, organizational, go-live and scaling aspects. They are based on the solution validated in Leipzig and the overarching solution requirements of the project.

### A) Technical readiness (vehicle and system)

- **Edge-Computer** rail-certified (EN 50155/EN 45545), suitable mounting points documented.
- **Sensos** according to scope (vibration, OHL sensor, roof/front camera; optional laser scanner) with wiring (Ethernet/CAN/power).
- **Communication**: stable vehicle → cloud channel, edge buffering during outages, telemetry/alerting active.
- **Approval documentation**: vehicle records updated; modifications fully documented.
- **Operations/Hosting**: backend systems, dashboards, monitoring (uptime, packet loss, latency) established.

### B) Data readiness (model and interfaces)

- **Object-IDs** for all relevant assets (masts, tension lengths, track sections) including chainage/geocoordinates.
- **Metadata-schema** with timestamp, version, quality flags; E/R diagram of the data storage available.
- **Interfaces to AM/GIS** (e.g. MR.pro®, GIS, data platform) specified; mappings documented
- **Data rights**: **100% data ownership** by the operator, internal read-only access; third-party usage rights contractually excluded.

### C) Organization and processes (governance)

- **RACI** formally agreed (AM, maintenance, IT/data, operations, partners).
- **Weekly jour-fixe** established; action-item list maintained; backlog management for UX/algorithms.
- **Runbook** (4.3.1) published and trained; SOPs for escalation/safety defined.
- **KPI-Set** set including baselines and reporting cycles (monthly/quarterly) defined.

### D) Go-Live-criteria (minimum viable operation)

- **Data-Uptime** of the pipeline  $\geq$  defined threshold (e.g., 95%).
- **Validation rate**:  $\geq$  “x” % of false-positive alerts eliminated during the pilot phase.
- **Detection** → **action-time** consistently below the target value.



- **Initial measures** (e.g., OHL adjustment, immediate track interventions) successfully completed and documented.

#### E) Scaling criteria

- **KPI-trend** shows significant improvement (early detection  $\uparrow$ , reactive ratio  $\downarrow$ , uptime  $\uparrow$ ).
- **Dashboards/processes** accepted by end users (training rate, usage frequency).
- **interfaces stable**; **Object-ID-management** institutionally established.
- **Action plan integration**: parametric model/investment scenarios under preparation (or already live).

## 6. Expected changes

The introduction of the Leipzig predictive maintenance solution leads to a series of short-, medium- and long-term changes affecting operations, maintenance, asset management and strategic infrastructure planning. These expected changes are derived from the demonstrated capabilities of the pilot, the validated system behaviour and the governance structures established within CE4CE.

### 6.1. Operational change

#### Earlier detection of infrastructure issues

During the pilot, multiple track defects and OHL anomalies were detected at an early stage – including several hard points and three previously unknown rail breaks that were subsequently confirmed and repaired by IFTEC. This capability enables earlier intervention, improving operational stability and reducing the likelihood of service disruptions.

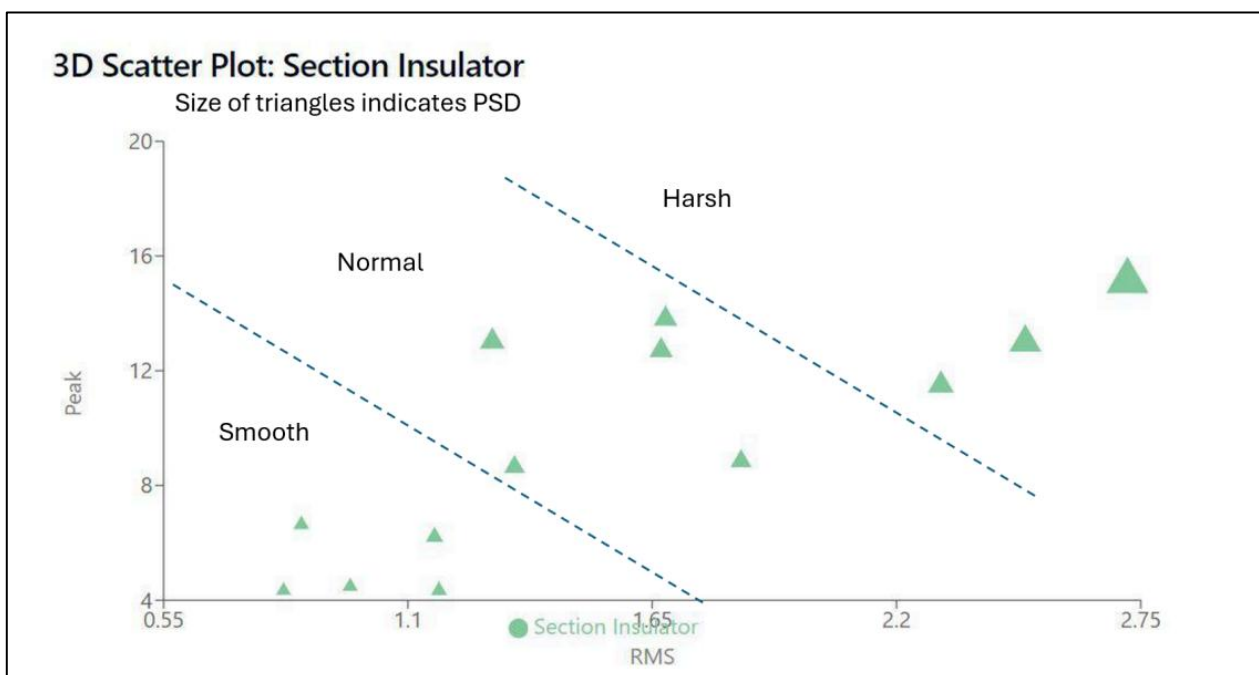


Figure 10 Example of OHL anomalies



This plot shows the classified operational quality of the section insulators. This gives a clear focus and priority on the section insulators, that need maintenance activities. The items which causes harsh interaction between OHL and pantograph could easily be adjusted, as shown in the picture below.



*Figure 11 Example of harsh interaction between OHL and pantograph*

The result is an improved operational quality with less harmful impact and thus extended lifecycle, both of the section insulator as well as of the pantograph.

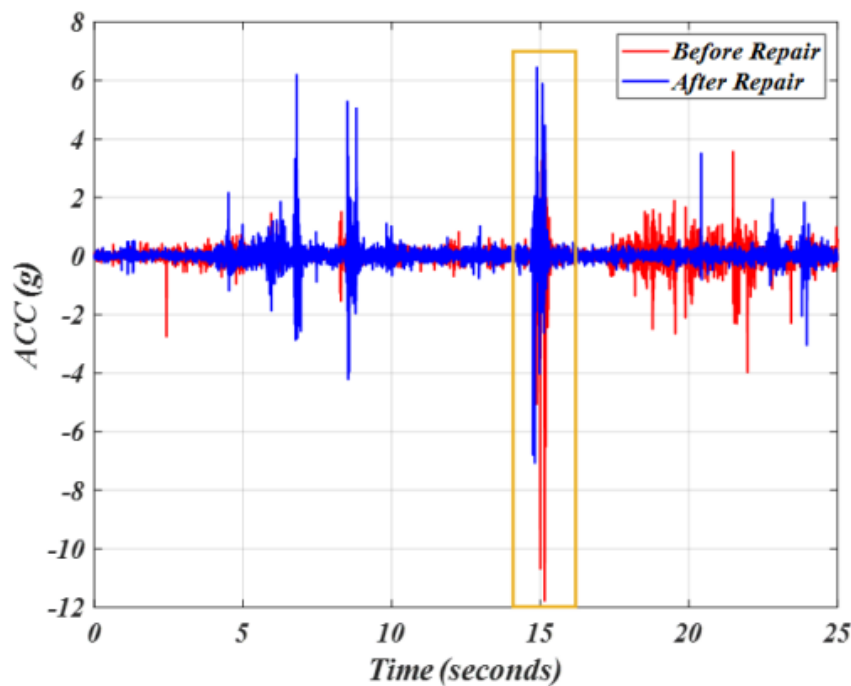


Figure 12 Before and after analysis conducted in Leipzig within the solution development

### Reduction of unplanned maintenance activities

Continuous data collection during revenue service shifts maintenance away from reactive interventions and towards proactive scheduling, reducing emergency works.

### More efficient resource allocation

Precise localisation of anomalies and hotspot identification allow maintenance teams to plan interventions more efficiently, improving labour and material deployment.

### Enhanced operational safety

Early detection of critical areas in both track and overhead infrastructure improves network safety and reduces operational risks.

## 6.2. Changes in processes and workflows

### Establishment of a continuous monitoring process

The solution introduces an ongoing, data-driven monitoring routine that complements and optimises existing manual inspection cycles.

### More structured decision-making

The combination of automated detections, metadata quality and validation routines leads to more objective maintenance decisions, clearer prioritisation frameworks, and improved documentation and auditability.



### **New roles and competencies**

The use of dashboards, AI insights and trend analyses requires new skillsets in asset management, maintenance and IT teams, increasing the importance of data literacy and analytical competence. These competencies were actively supported through targeted training sessions and workshops provided by the contracted technology partners, ensuring that LVB and IFTEC staff could effectively interpret system outputs and integrate them into operational routines.

## **6.3. Circularity and sustainability impacts**

### **Extension of asset lifetime**

Early detection of degradation allows for timely, minimally invasive interventions that extend the lifetime of track and OHL components.

### **Reduction of material-intensive interventions**

By avoiding late-stage damage, the system decreases the need for complete renewals and other resource-intensive maintenance activities.

### **Lower waste generation and emissions**

Fewer emergency interventions and reduced material turnover contribute to lower waste volumes and lifecycle-related environmental impacts.

## **6.4. Strategic change**

### **Foundation for scenario-based planning**

The continuous data stream forms the basis for future development of lifetime prediction models, scenario simulations (e.g. postponing interventions), and condition-based investment steering. These developments will be pursued under the **Action Plan**, building directly on pilot evidence.

### **Improved investment decision-making**

Budget planning can be based on trend data, deterioration patterns and risk modelling instead of fixed intervals and expert judgement alone.

## **6.5. Governance and organisational change**

### **Strengthened data sovereignty**

The binding tender requirement that all data remain the property of LVB ensures long-term independence from technology suppliers and enables flexible future development.

### **Interoperable system architecture**

The modular separation of sensing and analytics supports long-term extensibility, system upgrades and technology substitution without disrupting operations.

### **Enhanced cross-organisational collaboration**



The pilot demonstrated improved cooperation between Asset Management, IFTEC, IT/Data Platform and Operations, supported by weekly routines and structured validation processes. This collaboration will strengthen further as the solution matures.

## 6.6. External change and transfer potential

### Replicability for other operators

Compliance with rail sector standards (EN 50155/EN 45545), modular architecture and clear interface definitions make the solution easily transferable to other public transport operators.

### Applicability to other vehicle and infrastructure types

The sensing and analytics concept can be extended to light rail, metro, regional rail and potentially bus infrastructure.

### Support for municipal coordination

Georeferenced condition data can feed into city-wide digital twins, infrastructure planning processes and multi-stakeholder construction coordination.

## 6.7. Overall expected impact

In summary, the predictive maintenance solution is expected to deliver:

- higher operational stability,
- more efficient maintenance processes,
- extended infrastructure lifecycles,
- reduced resource usage,
- better strategic decision-making,
- strengthened data sovereignty,
- high scalability and transfer potential.

These impacts provide the foundation for institutionalization within the Action Plan and replication by other cities and operators.

## 7. Sustainability, transferability and replicability

The predictive maintenance solution developed in Leipzig has been designed to be environmentally, organisationally, and financially sustainable, while offering a high degree of transferability and replicability for other public transport operators. Its modular architecture, clear governance structures, and compliance with rail standards enable long-term use and evolution beyond the CE4CE project timeline.



## 7.1. Environmental and economic sustainability

### Asset lifetime extension

Continuous monitoring and early detection of degradation support timely, minimally invasive interventions, extending the lifetime of track and OHL components and reducing the frequency of resource-intensive renewals.

### Reduced waste and resource use

By avoiding late-stage, large-scale interventions, the solution lowers material consumption and aligns with circular economy principles through more efficient resource use and the prevention of unnecessary waste.

### Financial sustainability

Moving from reactive to predictive maintenance stabilises cost structures over time, reduces emergency works, and improves budget predictability for medium- and long-term planning.

## 7.2. Organisational and institutional sustainability

### Strengthened data sovereignty

The tender framework secures full LVB ownership of all data, enabling independent use, processing, and integration with other systems without dependence on any single vendor.

### Modular system architecture

The functional separation between data acquisition and analytics enables long-term evolution, module substitution, and the integration of additional providers or technologies as needs change.

### Anchoring in organisational practice

Pilot routines—weekly joint meetings, structured validation cycles, and action lists—lay the groundwork for institutionalised workflows and reinforce cross-functional collaboration between Asset Management, IFTEC, IT/Data Platform, and Operations.

## 7.3. Technical transferability

### Rail standards compliance

Sensors, edge computers, and camera/laser systems comply with EN 50155 and EN 45545, making them deployable across European rail fleets and simplifying technical transfer.

### Standardised data and interfaces

Object IDs, georeferencing, structured metadata, and defined interfaces to asset-management and GIS platforms facilitate integration into other operators' IT landscapes without deep re-engineering.

### Modularity as the transfer lever

Operators can adopt individual modules (e.g., track analytics only, or OHL monitoring only) or implement the full end-to-end chain, depending on their priorities and readiness.

## 7.4. Replicability

### Applicability to diverse networks

Many European operators face similar challenges (skills shortages, rising renewal needs, dense



timetables). The Leipzig solution addresses these systematically, making it readily transferable to tram, light rail, metro, and regional rail contexts.

#### **Replicable operating procedures**

The pilot-proven validation and decision routines are generic and can be adapted with minimal effort to other organisational settings.

#### **Governance building blocks**

The combination of data sovereignty, modular procurement, and clear roles offers a transportable model that other cities can adopt as a template.

## 7.5. Business model considerations

#### **Service and maintenance options.**

Because hardware provision, edge maintenance, and analytics software are decoupled, operators can choose flexible operating models—from full service arrangements to mixed setups with internally managed components.

#### **Cost transparency and planning.**

The modular tender structure yields transparent cost blocks (hardware, edge, analytics, hosting), simplifying medium- and long-term budgeting and total cost of ownership tracking.

#### **Vendor independence.**

Thanks to data ownership and open interfaces, operators retain the freedom to switch providers or add analytical partners without destabilising the overall system.

## 7.6. Preconditions for transfer and scale-up

Successful transfer to other operators—or scale-up within Leipzig—requires:

- a maintained asset inventory with unambiguous object IDs,
- reliable geodata/stationing,
- defined interfaces to AM/GIS systems,
- clear RACI roles and cross-team routines,
- training and capability building for end-users,
- institutionalised governance processes (joint reviews, validation cycles).

## 8. Conclusions

The Leipzig predictive maintenance solution developed under CE4CE demonstrates that data-driven, vehicle-based monitoring can deliver substantial benefits for the efficiency, availability and sustainability of public transport infrastructure. By combining on-train sensing, edge computing, AI-supported analytics and georeferenced visualisation, the pilot reliably identified relevant infrastructure defects at an early stage and enabled targeted, minimally invasive interventions—covering both track/track bed and overhead line systems as well as condition changes observed across repeated runs.



The project equally shows that predictive maintenance is not only a technological upgrade but an organisational evolution. New routines for joint validation, structured action lists, cross-functional coordination and rising data literacy were successfully introduced during the pilot, strengthening collaboration between Asset Management, IFTEC, IT/Data Platform and Operations. These routines provide a robust foundation for institutionalising predictive practices.

A key result of the solution work is the strategic safeguarding of data sovereignty and modularity. The functional separation between data acquisition and analytics—combined with the binding clause that all data remain LVB property—creates long-term independence from single vendors, supports scalable evolution of analytical modules, and ensures future interoperability with city platforms and asset systems. This governance choice significantly improves the solution’s longevity and adaptability.

The pilot further confirms the solution’s high transferability and replicability. Components comply with EN 50155/EN 45545, the data model is interoperable, and the process logic (detection → validation → prioritisation → action) is generic, allowing the Leipzig approach to be adopted by other operators across Europe in tram, light rail, metro and regional rail contexts.

Finally, the solution forms a credible basis for strategic next steps under the Action Plan. Continuous condition data, classifications and trend insights enable scenario-based planning, condition-driven investment steering and lifecycle-oriented decisions that align with circular economy principles. Together, these elements position the solution as a practical lever for long-term sustainability and resource efficiency in public transport infrastructure.

In sum, the Leipzig predictive maintenance solution proves that data-centric maintenance is a decisive lever for transforming public transport infrastructure management—technically robust, organisationally feasible, economically sensible and transferable at European scale—thereby delivering a material contribution to CE4CE objectives and to sustainable, resource-efficient mobility infrastructure.

The Leipzig solution is durable, modular, economically viable, and technically robust. It provides a scalable, Europe-transferable model that helps public transport operators:

- ✓ make maintenance more sustainable,
- ✓ use resources more efficiently,
- ✓ extend asset lifecycles,
- ✓ preserve data sovereignty, and
- ✓ institutionalise predictive maintenance practices.

As such, it is a key building block for the strategic evolution of public transport infrastructure in line with circular economy principles.