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Report on pilot joint requirements, preparation, implementation and evaluation

Pilot: Digital infrastructure and vehicle optimization through predictive maintenance in Leipzig, Germany

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1. Executive Summary

The CE4CE project empowers circular economy system thinking for actors in public transport from Central European countries to reduce waste and create value along new life cycles of infrastructure and rolling stock. To do so, CE4CE jointly develops solutions that increase knowledge and capacities for the sector, help reduce barriers and costs and initiate the development of new services and skilled jobs, as well as strategies and action plans that improve policy development, learning and exchange on the regional and transnational level. CE4CE aims at bringing circular economy principles into the public transport sector and, thus, reduce waste, increase efficiency in the sector and improve the ecological footprint of public transport.

Furthermore, stakeholders from the public transport community will cooperate in CE4CE to jointly develop and adapt processes and solutions as key enablers for the integration of circular economy principles, like data sharing concepts, new (innovation) procurement guidance, product and business model designs, extended life-cycle assessment, and cost-benefit analysis methodologies.

CE4CE will jointly develop outputs based on co-creation and peer reviews for take up by the public transport sector, e.g. pilot actions and solutions such as the CE4CE Circularity Compass for public transport, the CE4CE Circularity Knowledge platform, a web-based second-hand marketplace, strategies and pilot actions to increase resource-efficiency and pilots demonstrating use more, reuse and recycle approaches for the public transport sector.

CE4CE's partnership reflects the whole value chain and transport sector system perspective including 11 project partners from 6 Central European countries, ranging from public transport authorities/operators, industry and research to interest groups. To enlarge this cooperation, associated partners like the international active networks ICLEI, UITP and EIT Urban Mobility/Raw Materials are strategically involved to maximise communication outreach and knowledge transfer of project results.

This document is a report on pilot action LVB that aims to give an overview of the pilot project implemented under the CE4CE initiative, explaining how they are conducted.

This document is organized as follows*:*

Chapter 2 addresses relevant regions concerned by the pilot action.

Chapter 3 presents the aim and purpose of the pilot concept and the integration of circular economy principles in the project.

Chapter 4 is about key development phases of the pilot action, starting from the design phase to the reporting and documentation phase.

Chapter 5 focuses on preparation and technical requirements for each phase.

Chapter 6 contains the 4 phases of the pilot action implementation.

Chapter 7 explains the operational launch as part of the evaluation.

Chapter 8 presents the monitoring and evaluation phase as a continuous process following the operational launch.

Chapter 9 offers an overview of best practices among Europe that integrate circular economy principles.

Chapter 10 focuses on risks identification that helps define mitigation measures.

Chapter 11 is about the key impacts of the pilot project.

Chapter 12 addresses the possibility of the pilot project to be implemented in other cities and regions.

Chapter 13 contains the references of the document.

2. NUTS region(s) concerned by the pilot action (relevant NUTS level)

The region that is covered by the pilot action refers to the city of Leipzig. Leipzig is one of the fastest growing cities in Germany with currently approx. 610.000 inhabitants. It is located in the center of Germany in the Metropolitan region Central Germany (Metropolregion Mitteldeutschland)

Country (NUTS 0)	DE
Macroregion (NUTS 1)	Region Saxony
Region (NUTS 2)	DED5, Leipzig
Sub-region (NUTS 3)	DED51 Leipzig, Kreisfreie Stadt

3. Basic pilot concept

3.1. Aim and Purpose

The pilot project aims to improve the service life and condition of public transport infrastructure through predictive maintenance and to reduce CO2 emissions and the impact of major infrastructure measures to a minimum. By equipping vehicles with sensors to monitor the condition of infrastructure systems, the project seeks to develop analysis methods for early defect detection. This proactive approach aims to shift from reactive to predictive maintenance, thereby improving the efficiency and sustainability of infrastructure and its management.

3.2. Integration with Circular Economy Principles

The project integrates the principles of circular economy by focusing on the early detection of defects and trends, which enables minimally invasive maintenance measures. This approach is intended to lay the foundations for preventing major damage in order to extend the service life of the infrastructure and conserve resources. In the future, the results of the project should lead to the optimization of maintenance practices, the reduction of waste and the sustainable use of materials.

3.2.1. Basic Concept of the Pilot Project

As part of the pilot project, public transport vehicles will be equipped with advanced sensors that continuously monitor the condition of the overhead line and track components. The data collected is analyzed using sophisticated algorithms to detect early signs of wear and defects. This data-driven approach is intended to lay the foundations for timely, needs-orientated maintenance measures before small faults turn into major damage, reducing the need for extensive repairs and replacements.

3.2.2. Main Activities During the Pilot

Preparation Phase:

- Requirement analysis and planning
- Sensor selection and procurement
- Vehicle integration
- Data management system setup
- Team training

Implementation Phase:

- Data collection and real-time monitoring
- Data analysis and algorithm development
- Initial testing and calibration
- Feedback loop

Evaluation Phase:

- Performance assessment
- Evaluation of the possibilities for predictive maintenance
- Documentation and reporting
- Stakeholder review and feedback
- Scalability and future planning

3.2.3. Alignment with Policies and Strategies

3.2.3.1. Local Policies and Strategies

The pilot project aligns with Leipzig's **Mobility Strategy 2030**[1,2], which emphasizes sustainable, clean, and inclusive mobility for all population groups. The strategy aims to increase passenger numbers and utilization in local public transport while maintaining speed and meeting environmental standards for nitrogen oxide and CO2 emissions. The project supports these goals by enhancing the efficiency and reliability of public transport through predictive maintenance, thereby contributing to a cleaner and more sustainable urban environment.

Challenges:

- Leipzig's historical significance and its role as a major trade hub attract many people, increasing demands on urban and mobility planning.
- Sustainable solutions are mandatory to meet the high requirements for city and mobility design.

3.2.3.2. Regional Policies and Strategies

At the regional level, the project supports the broader objectives of sustainable urban mobility by promoting efficient and data-driven maintenance practices. By leveraging advanced sensor technology and data analysis, the project contributes to the regional goal of optimizing transport infrastructure and reducing environmental impact. This aligns with regional efforts to improve air quality, reduce noise pollution, and enhance the overall quality of life for residents.

Challenges:

- Increasing public transport usage and infrastructure load.
- Urbanization and energy policy trends necessitate optimizing infrastructure lifespan.
- Leipzig's size makes manual processing impractical, necessitating innovative approaches like the CE4CE project.

3.2.3.3. National Policies and Strategies

Nationally, the project aligns with Germany's commitment to sustainable urban development and digitalization. The integration of predictive maintenance practices supports the national agenda for smart cities and digital transformation. By improving the efficiency and sustainability of public transport infrastructure, the project contributes to the national goals of reducing greenhouse gas emissions, promoting energy efficiency, and fostering innovation in urban mobility.

[1] https://www.leipzig.de/umwelt-und-verkehr/verkehrsplanung/mobilitaetsstrategie-2030

[2] https://www.leipzig.de/umwelt-und-verkehr/verkehrsplanung/mobilitaetsstrategie-2030/nachhaltigkeits-szenario

3.2.3.4. European Policies and Strategies

The project also aligns with European Union policies on sustainable urban mobility and climate-neutral smart cities. By implementing data-driven maintenance practices, the project supports the EU's objectives of reducing carbon emissions, promoting resource efficiency, and enhancing the resilience of urban transport systems. The use of advanced technologies and data analysis contributes to the EU's vision of smart, sustainable, and inclusive cities.

3.2.3.5. Digitalisation in the Mobility Strategy

Digitalisation plays a crucial role in Leipzig's Mobility Strategy 2030. It is seen as a key enabler for creating a more efficient, intelligent, and user-friendly transport system. The strategy emphasizes the importance of digital tools and platforms to optimize planning processes, enhance real-time data collection, and improve decision-making. Key aspects include:

- **Digital Information Systems:** User-friendly digital mobility platforms like "Leipzig MOVE" provide comprehensive information on various transport options (public transport, rental bikes, car sharing, etc.), making it easier for citizens to plan their journeys.
- **Intelligent Traffic Management:** Digital systems are used to manage traffic flows, reduce congestion, and prioritize public transport at traffic signals. Projects like "Chamäleon" integrate real-time data to optimize traffic light switching and improve punctuality.
- **Sensor Data Integration:** The use of sensors to collect data on traffic conditions, environmental factors, and infrastructure status helps in making informed decisions and implementing timely interventions.

Urban Data Platform (UDP)[3]

The Urban Data Platform (UDP) in Leipzig is a central hub for collecting, processing, and harmonizing data from various sources. It supports integrated urban development by providing data-based services and insights. The UDP aims to:

- **Break Down Data Silos:** By consolidating data from different municipal systems, the UDP ensures that information is accessible and usable across departments.
- **Enhance Data Sovereignty:** The platform provides a standardized approach to data management, ensuring data security and compliance with regulations.
- **Support Smart City Initiatives:** The UDP enables the development of innovative applications, such as digital twins, which can simulate and optimize urban processes.

Connected Urban Twins (CUT) Project[4]

The CUT project is a collaborative initiative involving Leipzig, Hamburg, and Munich. It focuses on developing and connecting urban data platforms and digital twins to support integrated urban development. Key objectives include:

[3] https://www.leipzig.de/wirtschaft-und-wissenschaft/digitale-stadt/aktuelle-projekte/urbane-datenplattform-und-sensorik

[4] https://www.leipzig.de/wirtschaft-und-wissenschaft/digitale-stadt/aktuelle-projekte/connected-urban-twins

- **Creating Digital Twins:** These are dynamic, virtual models of the city that incorporate real-time data from various sources. They help in visualizing and analyzing urban processes, making it easier to plan and manage city infrastructure.
- **Promoting Cross-City Collaboration:** By sharing knowledge and solutions, the project aims to accelerate the adoption of digital technologies in urban planning and management.
- **Enhancing Urban Resilience:** The project supports the development of resilient and sustainable urban environments by leveraging data and digital tools to address complex urban challenges.

4. Key pilot development phases

This section gives a short overview over the key phases and timeline of the pilot.

Main milestones of the pilot project	Description	Calendar term	Responsible partner
Pilot Design	*Defining the overall concept and design of the pilot project, including objectives, scope, and key deliverables.*	April-23 - Jan-24	LVB (PP1) KRUCH (PP6)
Stakeholders Engagement and joint development	*Engaging key stakeholders trough workshops, hackathons, and other meeting forms to gather feedback, validate assumptions, and align expectations.*	Jan-24 - Mar-24	LVB (PP1) KRUCH (PP6)
Feasibility Study and Preparation	*Conducting feasibility studies to assess technical, financial, and operational feasibility. This also includes securing necessary funding and permits.*	Mar-24 - Apr- 24	LVB (PP1) KRUCH (PP6)

Main milestones of the pilot project	Description	Calendar term	Responsible partner
Procurement Process(es)	*Initiating the procurement process for the goods, services, or equipment required for the pilot project. Includes issuing tenders and selecting vendors.*	Apr-24 - Jun-24	LVB (PP1)
Pilot Implementation	*Overseeing the work of the contractors and ensuring that the implementation follows the project plan.*	Jul-24 - Mar-25	LVB (PP1) KRUCH (PP6)
Operational Launch	*Ensuring that all systems are fully functional, providing initial training for users and operators, and solving any initial operational challenges.*	Jul-24 - Mar-25	LVB (PP1) KRUCH (PP6)
Monitoring and Evaluation	*Collecting data and performance metrics to assess the pilot's effectiveness. This stage focuses on the monitoring of the system in real-time and evaluating its performance against objectives.*	Jul-24 - Mar-25	LVB (PP1) KRUCH (PP6)
Reporting and Documentation	*Compiling findings, data, and analyses into comprehensive reports. This includes both interim and final reports to document progress, results, challenges, and lessons learned.*	Oct-24 - Mar-25	LVB (PP1) KRUCH (PP6)

5. Preparation and technical requirements

5.1. Pilot Design

At the beginning of the project, several internal coordination meetings were held within Leipziger Verkehrsbetriebe (LVB) to discuss and refine the core ideas, requirements, and objectives for the planned pilot. These meetings aimed to clearly define the scope of the pilot and ensure that all relevant operational, technical, and strategic aspects were considered.

As a result of these discussions, it was decided to develop an integrated system for monitoring and identifying faults in the infrastructure. The focus is on the three key components of the urban rail network: track, track bed, and overhead line. The goal is to enable predictive maintenance through continuous data collection and analysis, thereby significantly improving operational safety, availability, and infrastructure lifespan.

Another central goal of the pilot is to monitor the energy consumption of the vehicles. By analyzing driving profiles and energy flows, the aim is to identify and leverage potential for reducing overall energy consumption in the long term.

The pilot was implemented in close coordination with relevant stakeholders, such as IFTEC GmbH & Co. KG. Their involvement was crucial for technical feasibility, integration into existing operational processes, and later evaluation of system performance in real-world use.

5.2. Stakeholder Engagement and Joint Development

Following the internal LVB discussions, a preparatory workshop was held on January 22, 2024, with potential technology providers to define the requirements and use cases for the planned CE4CE pilot project. The goal was to develop a shared understanding of the technical challenges and operational conditions, and to gather initial ideas for possible solutions.

The workshop focused on the requirements for a system to monitor infrastructure components (track, track bed, overhead line) and to analyze the energy consumption of tram vehicles. Topics discussed included suitable sensors, possible installation points in the vehicles, and the use of rail-certified edge computing platforms capable of processing sensor data locally and performing real-time analysis.

Participating Organizations:

- Leipziger Verkehrsbetriebe GmbH (LVB) – CE4CE / Infrastructure and Vehicle Technology
- Kruch Railway Innovations GmbH & Co. KG
- PanthoHealth GmbH
- Ci4Rail GmbH
- CEMIT group AS
- Telschow Bahn Strom GmbH

Workshop Outcomes:

- Presentation of the CE4CE project and overarching goals
- Introduction of initial technical ideas and concepts
- Discussion of potential technical solutions to achieve the goals
- Exchange on operational conditions (e.g., catenary heights, installation locations)
- Initial outline of a possible milestone plan for implementation

The workshop served as an important catalyst for the later development of the tender documents and helped to formulate the requirements in a practical and targeted manner—without pre-committing to specific providers or technologies.

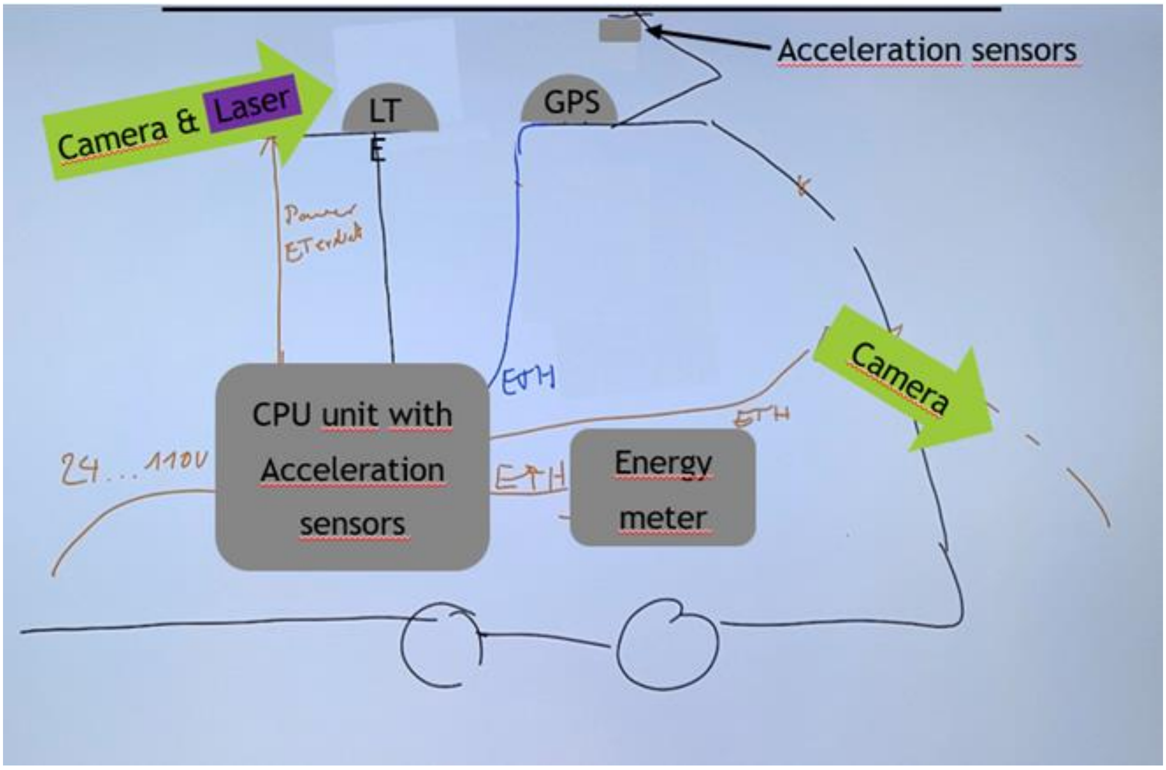


Figure 1: First draft of a possible solution

5.3. Feasibility Study and Preparation

As part of the preparatory coordination, Leipziger Verkehrsbetriebe (LVB), together with project partner Kruch and internal experts from Asset Management, assessed the technical feasibility of the planned pilot project. The goal was to evaluate the ideas and requirements developed during the stakeholder workshop in terms of their practical implementability.

The main focus was on whether the proposed sensors and technologies for monitoring and identifying infrastructure faults (track, track bed, overhead line) and for predicting maintenance needs were technically viable. The analysis examined which components already met the current state of the art and where further development would be needed within the scope of the pilot.

Experts evaluated:

- The technical specifications of the sensors
- Their integration capability into existing systems
- The performance of the planned data analysis algorithms

Also involved in the evaluation was IFTEC GmbH & Co. KG, the service provider responsible for the maintenance and servicing of infrastructure and vehicles.

5.3.1. Financial Feasibility

In parallel with the technical analysis, the financial feasibility of the project was examined. Leipziger Verkehrsbetriebe (LVB) and Kruch jointly calculated the anticipated costs for the procurement and installation of the sensor systems, the development of data management systems, and the implementation of the algorithms. The objective was to ensure that the planned measures could be realized within the available budget of the INTERREG CE4CE project.

5.3.2. Operational Feasibility

The operational framework conditions were also thoroughly examined. In internal coordination meetings, LVB and Kruch analyzed the operational requirements and potential challenges associated with the introduction of a digital monitoring system. This included, among other things:

- the integration of sensors into the existing vehicle fleet,
- the training and involvement of operational staff,
- and potential adjustments to maintenance and operational procedures.

Particular attention was paid to ensuring that ongoing operations would not be disrupted by the implementation and that the necessary personnel and technical resources would be available.

5.3.3. Securing the Necessary Approvals

Another key aspect of the feasibility assessment was the legal and regulatory safeguarding of the project. The infrastructure division of LVB, together with the vehicle division and Kruch, reviewed the approval and certification requirements for the installation of the sensor systems.

Special emphasis was placed on compliance with railway-specific standards. The edge computing platform under consideration must meet the high demands of the railway industry and should be certified according to EN 50155 (electronic equipment on rolling stock) and EN 45545 (fire protection). All installed components, as well as any modifications made to the vehicles, must be fully documented and included in the vehicles' approval documentation.

6. Implementation phase

6.1. Procurement Processes

As part of the CE4CE pilot project, specific decisions were made regarding the tendering strategy and procurement procedures to ensure the successful and compliant implementation of the planned measures. The pilot project was divided into several phases, each covering different aspects of data collection and processing. It was also decided that the measurement technology would be installed on three of LVB's newest generation vehicles.

6.1.1. Implementation Phases:

- Phase 0 (starting mid-June 2024):
  Installation of vibration sensors on vehicles 1 and 2 to monitor the condition of the track and track bed.
- Phase 1 (by July 2024):
  Expansion to include sensors for monitoring the overhead line and analyzing energy consumption, also on vehicles 1 and 2.
- Phase 2 (by October 2024):
  Integration of roof and front cameras for visual monitoring of the overhead line and track area on vehicles 1, 2, and 3.
- Phase 3 (by February 2025):
  Addition of laser scanners for precise analysis of the overhead line systems on all three vehicles.

6.1.2. Tendering Strategy and Separation of Services

As part of the CE4CE pilot project, specific decisions were made regarding the tendering strategy and procurement approach to ensure the successful and legally compliant implementation of the planned measures. The pilot project was divided into several phases, each addressing different aspects of data collection and processing. It was also determined that the measurement tenchnology would be installed on three of LVB's newest-generation vehicles.

A key element of the procurement strategy was the separation of services into distinct areas to allow specialized providers to be engaged for specific tasks. In particular, a distinction was made between:

- Data collection (e.g., sensors, cameras, data transmission)
- Data analysis

This separation ensured that the various aspects of the project could be handled with technical expertise, economic efficiency, and legal clarity.

6.1.3. Outcome of the Procurement Process

CI4RAIL and PantoHealth submitted a joint bid as part of the tendering process.

- CI4RAIL assumed the role of general contractor, taking primary responsibility for executing the contract.
- PantoHealth acted as a subcontractor, supporting CI4RAIL in delivering the agreed services.

Kruch Railwayinnovations GmbH & Co. KG is a project partner and received direct funding for its tasks within the CE4CE project. CEMIT is responsible for data analysis in the area of track and track bed. However, it was not funded through INTERREG, but was instead financed separately by LVB and contracted through an independent tendering process.

Roles of the Pilot Project Partners

- CEMIT: Development of a monitoring solution for track infrastructure condition
- CI4RAIL: Provision of rail-certified hardware for data collection and transmission
- PantoHealth: Development of a monitoring system for overhead line infrastructure

- Kruch: Analysis and monitoring of vehicle energy consumption

Thanks to this structured and transparent procurement process, all necessary components and services were acquired on time and in alignment with the project's objectives.

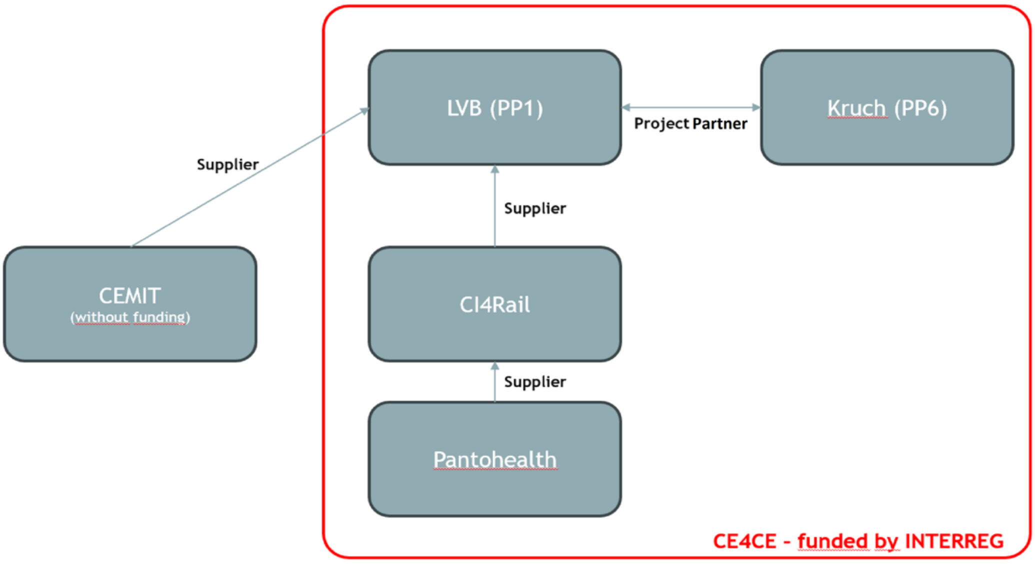


Figure 2: Contract and financing structure

6.2. Pilot Implementation

The implementation phase of the CE4CE pilot project in Leipzig involved the coordination and supervision of all technical and organizational measures required to realize the planned system solutions. A central element was the close collaboration with partners and contracted service providers to ensure that all activities were carried out in accordance with the project plan. The implementation was structured into several coordinated phases:

6.2.1. Sensor and Hardware Integration

In the initial step, vibration sensors, edge computing units, and communication interfaces were integrated into selected tram vehicles. These components were certified according to railway engineering standards and incorporated into the vehicle approval documentation.

6.2.2. Camera Technology and Laser Systems

In a later phase, high-resolution roof and front cameras, as well as laser scanners for precise monitoring of the overhead line condition, were selected, procured, and installed in the vehicles. The selection of these systems was based on defined technical requirements developed in close coordination with the project partners. Integration required both mechanical modifications and software integration into the existing data infrastructure.

6.2.3. Software Development and System Testing

In parallel with the hardware integration, the data platforms were further developed. The cameras and laser systems were connected on the software side, enabling automated processing and visualization of image and measurement data. Initial tests were conducted to calibrate and validate the systems under real operating conditions.

The implementation was accompanied by weekly TEAMS meetings of the pilot working group, during which progress, open issues, and technical challenges were documented and prioritized (e.g. via Action-Item-List). In addition, several on-site workshops were held to support the integration of the systems into the vehicles and their commissioning under real operating conditions. The installed hardware did not become the property of Leipziger Verkehrsbetriebe (LVB), but was instead provided as a service by the project partners. As such, the use of the systems is limited to the duration of the project and is subject to the contractually agreed service and operational conditions.

Implementation was carried out in compliance with relevant standards and norms, including ISO 9001 (quality management), ISO 14001 (environmental management), and ISO 45001 (occupational health and safety). Furthermore, all installed components and the associated modifications to the vehicles had to be fully documented and incorporated into the vehicles' approval documentation. This ensured that the operation of the vehicles continued to meet regulatory requirements and that all technical changes remained traceable. Through close coordination with all project stakeholders, it was ensured that the implementation proceeded smoothly both technically and organizationally, laying the foundation for a successful operational launch.

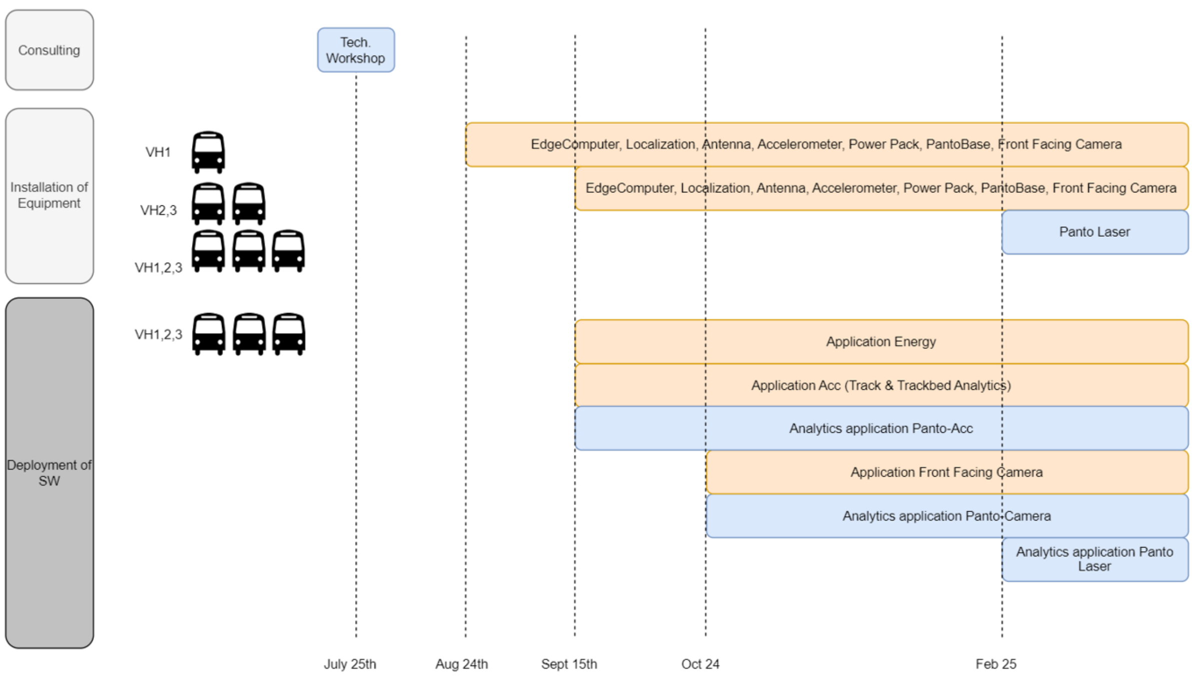


Figure 3: Milestone plan for installation and analytics of the monitoring system

7. Process evaluation

7.1. Operational pilot launch

The operational launch of the CE4CE pilot project in Leipzig was carried out in phases, in line with the implementation stages. The goal was to ensure that all technical components were fully functional under real operating conditions, that operational procedures were clearly defined, and that the involved personnel were properly trained.

To prepare for the start of operations, training sessions were conducted for LVB's technical staff. These covered both the safe handling of the hardware and the use of the developed data platforms, including CEMIT's new "On-Track" platform for track monitoring and PantoHealth's dashboard for analyzing the overhead line infrastructure.

In addition, the service providers CEMIT and PantoHealth held targeted workshops with LVB experts and users to demonstrate the systems in practice, discuss use cases, and incorporate feedback directly into further development. Weekly "Jour Fixe" meetings were also established between the service providers and LVB's asset management experts. These regular meetings facilitated structured knowledge exchange, validation of initial results, and joint prioritization of optimization opportunities.

During the first weeks of operation, system performance was closely monitored. The project team supported the commissioning process, documented technical challenges, and made necessary adjustments—such as calibrating sensors, optimizing data transmission, or refining user interfaces. Regular coordination within the project team ensured that all issues were addressed promptly.

The successful operational launch laid the foundation for the subsequent monitoring and evaluation phase. At the same time, it demonstrated the feasibility of integrating circular economy principles into public transport operations through predictive maintenance and digital innovation.

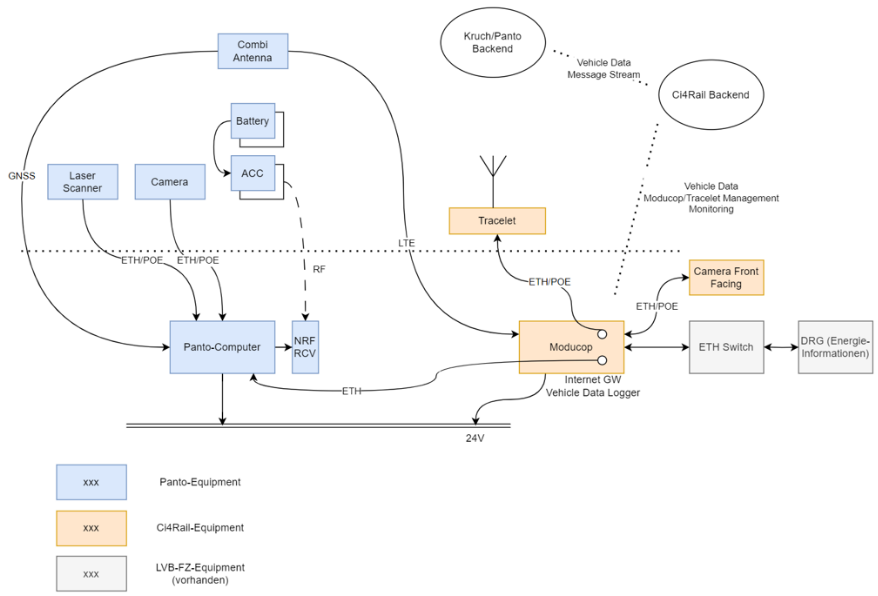


Figure 4: Principle sketch of the system structure

One major part of the project is the monitoring and analysis of the vehicle's energy consumption. During the operational launch and evaluation of the datasets, it was found that the data extracted from the existing (old) “energy meters” on the vehicle was inaccurate and could not be used for research purposes. Kruch attempted to verify the datasets by comparing them with data from other vehicles in different cities and extensive simulation results. Unfortunately, there was no support from the vehicle manufacturer, which created additional obstacles.

As a result, it was concluded that a different data source was needed. Therefore, it was decided to add a “data connector” to the CAN-BUS of the vehicle. This connection will allow energy data to be read directly from the drive chain of the tram, which should resolve the issue.

We are currently addressing this part of the project and anticipate completing it without significantly impacting the overall project timeline. The data research on energy consumption will be carried out in the remaining project periods during the “solution phase”.

8. Testing and evaluation phase

8.1. Monitoring and Evaluation

Following the successful operational launch, the phase of continuous monitoring and evaluation of the deployed systems began. The objective of this phase was to assess the effectiveness of the implemented sensors and data platforms under real operating conditions and to systematically analyze the insights gained.

A central element was the real-time monitoring of infrastructure components—particularly the track, track bed, and overhead line. The data collected by the sensors was automatically transmitted to the respective platforms of the project partners: CEMIT’s “On-Track” platform enabled continuous analysis of ride comfort and the identification of track faults, while PantoHealth’s dashboard highlighted critical points in the interaction between pantograph and overhead line.

The PantoHealth Systems collected data for nearly three months and identified critical points that could lead to increased wear. Eight critical points were selected for inspection, including section insulators, curves, and stiff hangers. Two section insulators were adjusted to improve interaction. One curve with excessive acceleration signals was identified, showing a thin contact wire. Vibration monitoring systems can detect hard points in the network and enable early maintenance interventions.

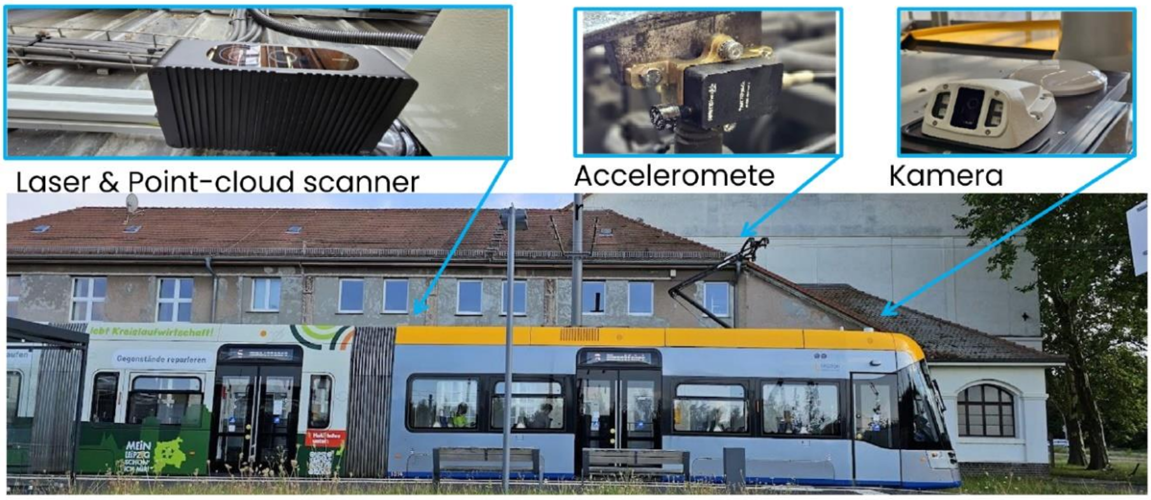


Figure 5: Part of the installed vibration monitoring system on the trams (Pantohealth)

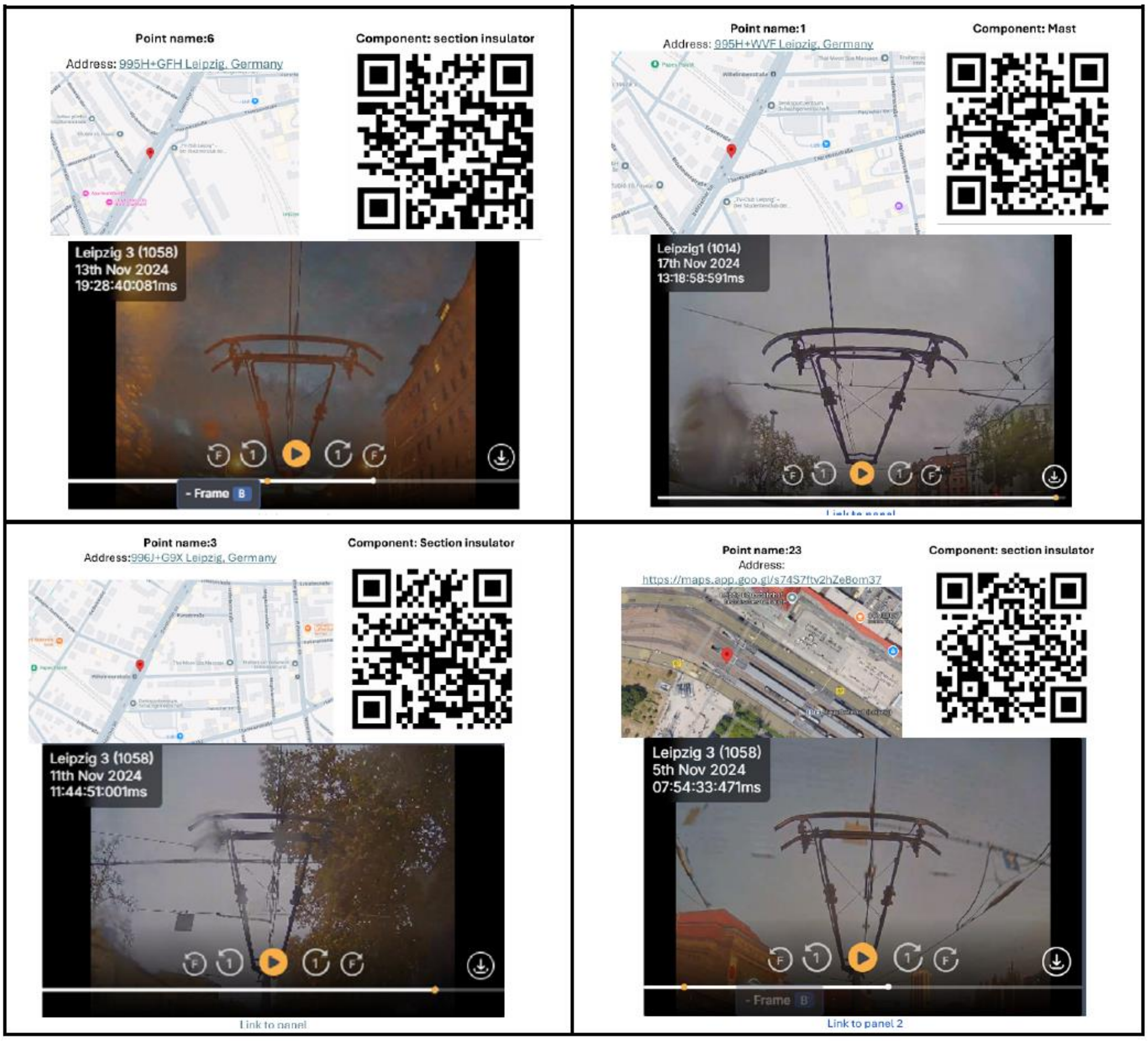


Figure 6: Identified problem areas (hard points) on the overhead line

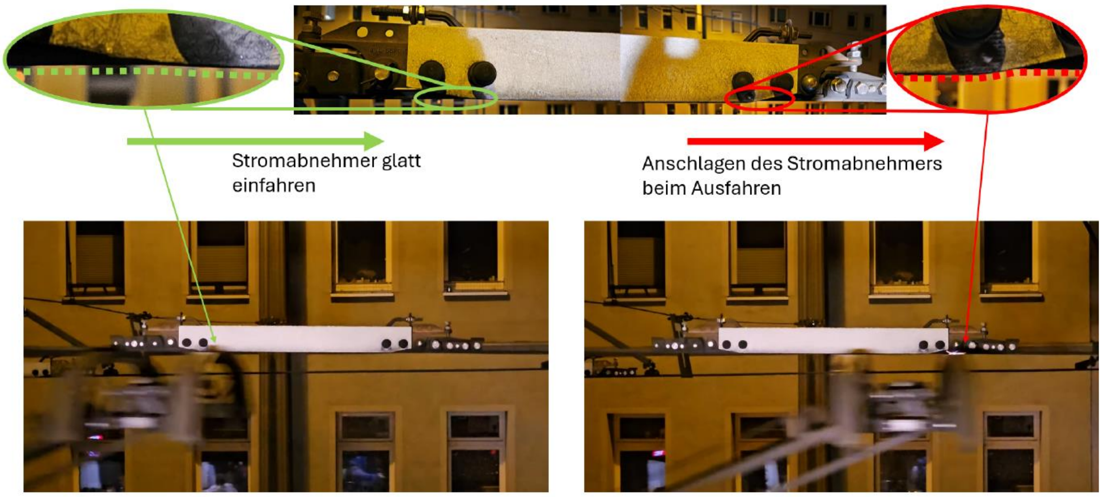


Figure 7: Current collector retracts smoothly and hits the section insulator when extending, no arcing when retracting, but arcing when extending

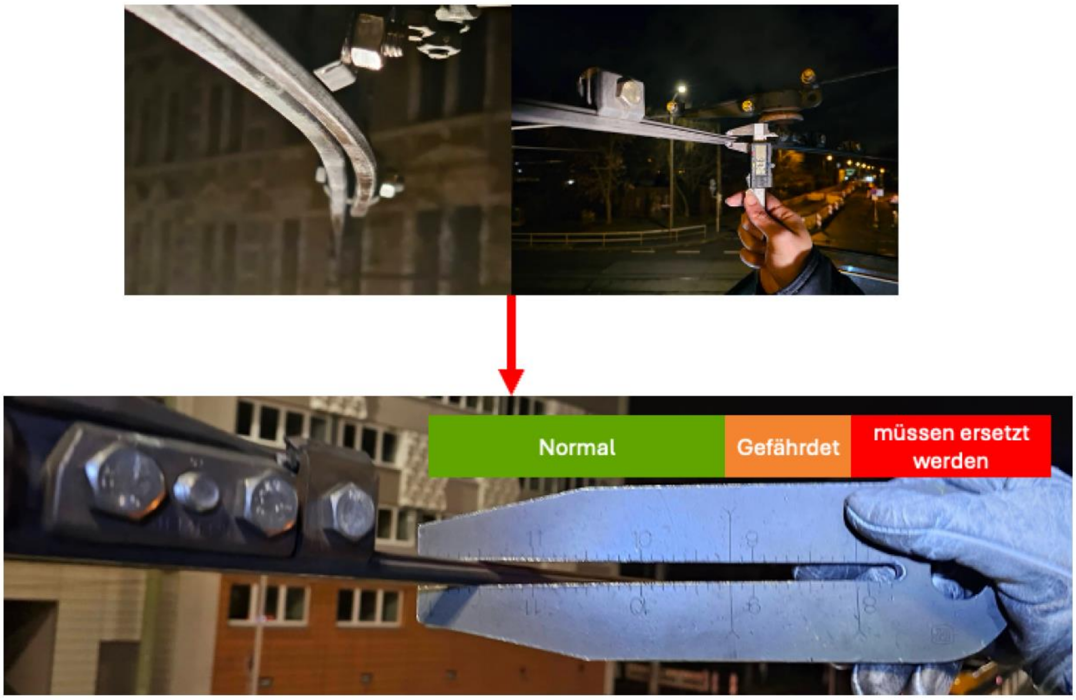


Figure 8: Thickness measurement for the identified hard point in the curve

CEMIT monitored and detected track faults and infrastructure condition on three levels: insulation faults, surface faults, and faulty track structure. Eight track fault areas on Line 1 (14 km) were identified and confirmed, including three new broken rails. Faster deterioration than expected led to a revision of the maintenance plan. Ten track fault areas were inspected, and immediate repairs were carried out.

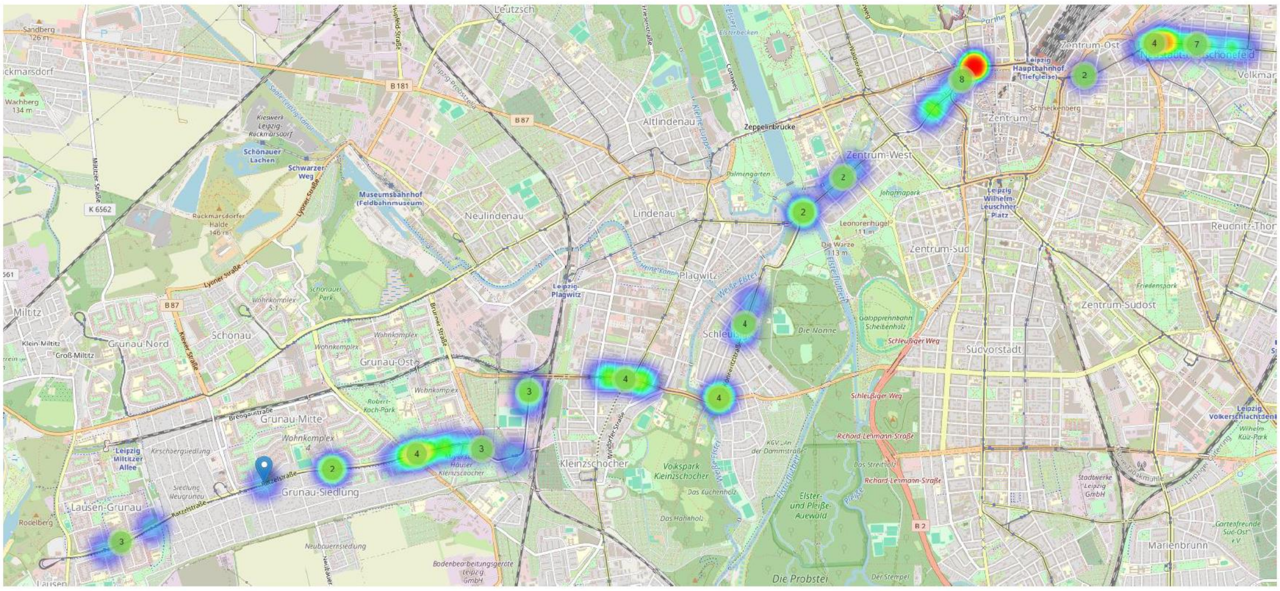


Figure 9: Heatmap with track fault areas

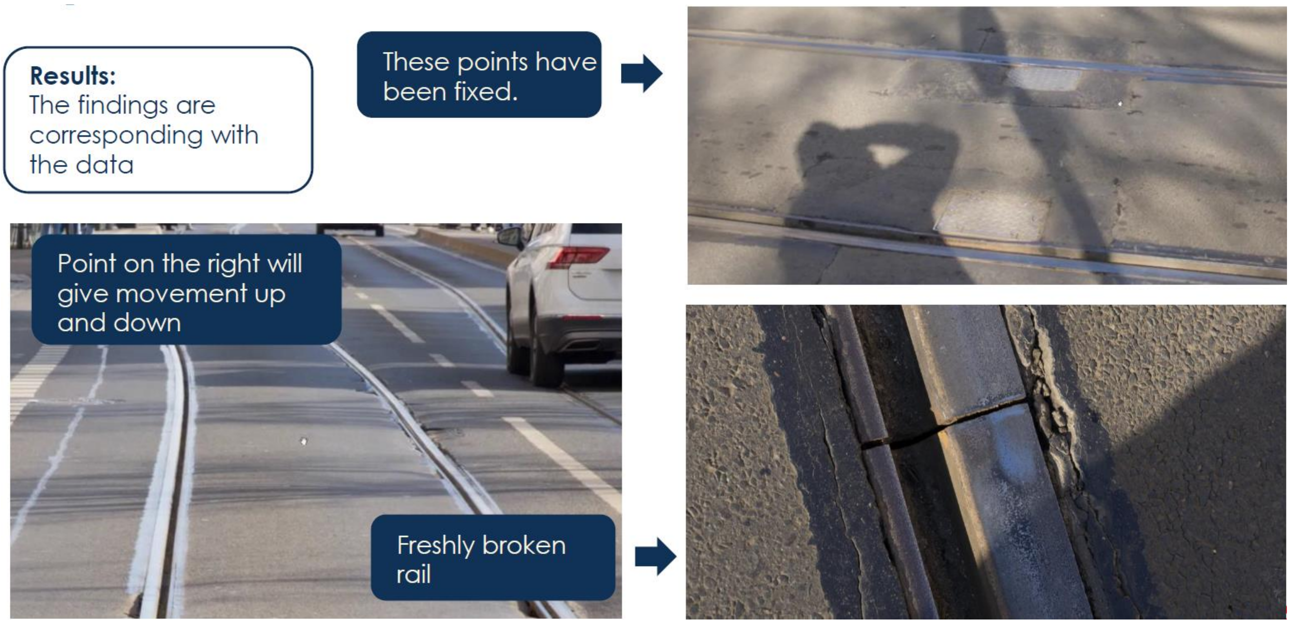


Figure 10: Results of the physical inspection of track defect areas determined using the CEMIT algorithm

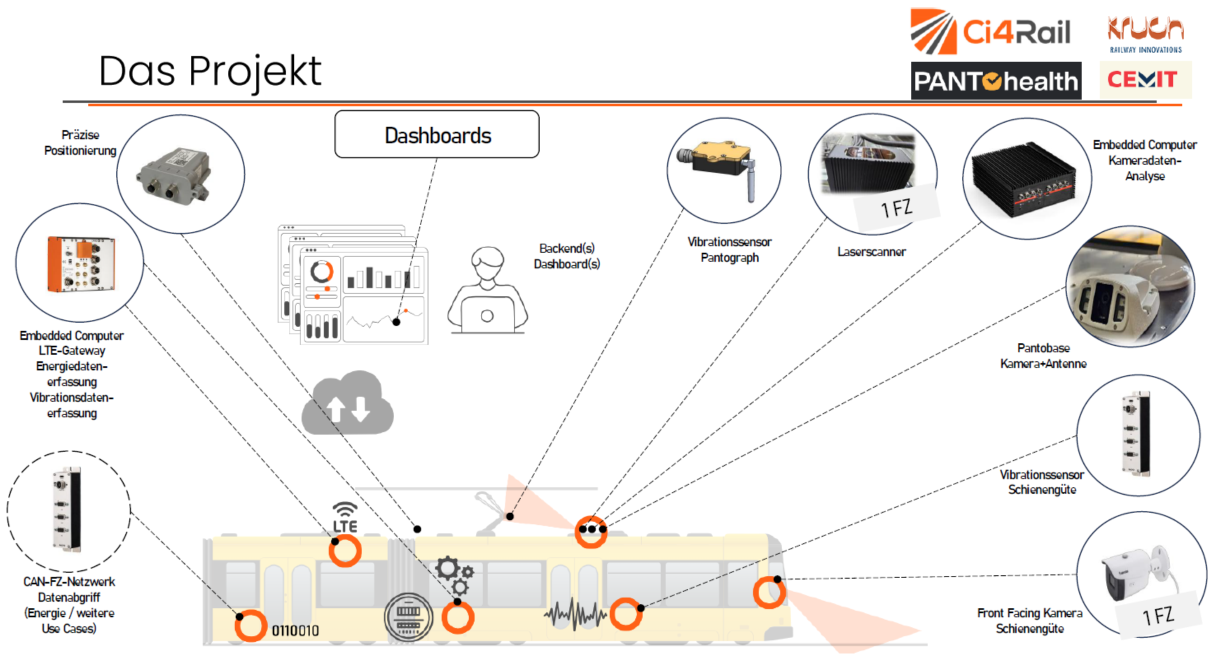
For more detailed information, please refer to the service providers' reports included in the annex.

Special emphasis was placed on feedback loops with LVB's asset management. In weekly coordination meetings, the collected data was jointly analyzed, interpreted, and contextualized with the service providers. This enabled targeted prioritization of maintenance measures and an initial assessment of the systems' predictive capabilities.

Data quality and system stability were closely monitored during the initial weeks. Both technical parameters (e.g., signal strength, data transmission rate, downtimes) and content-related aspects (e.g., plausibility of measurements, recognizability of fault patterns) were evaluated. Early anomalies—such as unexpected vibrations or arcing—were detected by the systems and validated with LVB experts.

To structure the evaluation of results and jointly advance the pilot, a full-day workshop was held on March 26, 2025, with all project participants and relevant stakeholders. The aim was to present the results achieved so far, discuss LVB’s feedback, identify additional use cases, and align on the next steps through to the project’s conclusion in 2026. The event also served to sharpen the shared understanding of the added value achieved, the technical challenges encountered, and the future potential of the deployed systems.

The monitoring and evaluation phase thus forms the foundation for further scaling and transferability of the developed solutions—both within Leipzig and to other cities and transport networks.



8.2. Reporting and Documentation

The systematic documentation of project outcomes and progress was a central component of the CE4CE pilot project in Leipzig. The goal of the reporting process was to present both the technical developments and the organizational and operational insights in a transparent manner and to make them accessible to both internal and external stakeholders.

Various reporting formats were established as part of the project:

- Regular status reports from the project partners documented the progress of individual work packages, identified challenges, and recorded proposed solutions.
- Technical documentation accompanied the integration of sensor systems, software development, as well as the commissioning and calibration of the systems. These documents were particularly important for meeting the railway-specific approval requirements for the vehicles.
- Result reports and presentations were used for internal coordination and communication with external partners.

A key milestone was the pilot workshop held on March 26, 2025, which brought together all project participants—including representatives from LVB, project partners (CEMIT, PantoHealth, CI4Rail, Telschow), and external stakeholders. During the event, the results achieved so far were presented, open questions were discussed, and the next steps were coordinated. The findings presented and developed during the workshop, along with the insights gained throughout the pilot, now form the foundation for the further development of the CE4CE Solutions. These will directly inform the technical and conceptual design of the final system solutions, which are to be further developed, tested, and prepared for broader application by the end of the project in 2026.

9. Best practices

As part of the CE4CE pilot project in Leipzig, not only were innovative technical solutions developed, but insights from comparable projects at the European level were also reviewed. Particularly noteworthy are the best practices identified in the Interreg project CircPro regarding circular public procurement. These include the integration of environmental criteria in tenders, the promotion of durable products, and the use of digital tools to increase efficiency[5].

Examples of good practices from Europe

- **Elektrifizierung und Lebenszyklusoptimierung (Bulgarien):**
  The first public tender for electric buses and charging infrastructure in Bulgaria was conducted with consideration of lifecycle costs and maintenance friendliness. This enabled sustainable procurement and reduced operating costs [5].
- **Green Public Procurement (Italy, Lithuania):**
  In several regions, standardized environmental criteria were integrated into electronic procurement platforms. This facilitated the implementation of circular principles in procurement—such as prioritizing recycled materials or energy-efficient technologies[5].
- **Pre-Commercial Procurement for Durable Road Infrastructure (Lithuania):**
  Development of a novel long-life bitumen to reduce material consumption and maintenance efforts[5].

CE4CE Pilot in Leipzig - distinctive features

The Leipzig pilot project stands out through the systematic integration of digital technologies into the operation and maintenance of public transport. Unlike many other projects that focus on procurement or material cycles, this pilot addresses the usage level of infrastructure and vehicles—where the greatest potential for resource efficiency lies.

Technical features:

- Rail-certified sensors (EN 50155, EN 45545)
- Edge computing for local data processing
- AI-powered analytics platforms for track, overhead line, and energy consumption

5 https://projects2014-2020.interregeurope.eu/circpro/news/news-article/12101/circpro-and-its-17-good-practices/

Monitoring and evaluation:

- Detection of vibrations, pantograph contact, and energy flows
- Assessment of wear, ride comfort, and energy efficiency
- Validation through physical inspections and expert feedback

Impact on energy efficiency and sustainability:

- Extended lifespan of infrastructure components
- Reduced downtime and maintenance costs
- Lower energy consumption through data-driven optimization

Transferability and strategic recommendations

The solutions developed in the project are easily transferable to other cities, operators, and vehicle types due to their modular design and compliance with standards. Particularly effective is the combination of:

- Early stakeholder involvement
- Phased implementation with clear milestones
- Separation of data collection and analysis to maintain data sovereignty and flexibility

The CE4CE pilot demonstrates that circular economy in public transport can be realized not only through material recycling but also through intelligent usage and maintenance—an approach that has rarely been implemented in this form to date.

10. Risks and contingency approach

As part of the CE4CE pilot project, a structured approach was taken to identify, assess, and manage potential project risks. The aim was to detect possible technical, organizational, and operational challenges at an early stage and to define appropriate mitigation measures.

Technical risks

A key risk involved the integration of new sensors and hardware components into existing vehicle and IT systems. To avoid incompatibilities, failures, or data loss, all components were extensively tested in advance and commissioned step by step. The use of rail-certified hardware (e.g., in accordance with EN 50155 and EN 45545) and close coordination with vehicle manufacturers and certification authorities helped minimize these risks.

Operational risks

Installing and operating the systems during ongoing tram service posed specific planning and coordination challenges. To avoid disruptions to service, installation and maintenance work was aligned as much as possible with routine maintenance schedules. In addition, drivers were informed and maintenance staff were trained early on to ensure safe handling of the new technology.

Organizational risks

Collaboration with multiple partners and service providers required clear role definitions and regular communication. Weekly project meetings, centralized project management, and transparent documentation (e.g., action item lists, milestone plans) helped prevent misunderstandings and delays.

Financial risks

To safeguard against budget overruns, all measures were planned in close coordination with project partner Kruch, including service costs, internal efforts, and potential additional expenses. Non-eligible services—such as the analysis of track data—were financed separately by LVB and awarded through an independent tender to ensure financial control.

Contingency measures

For each identified risk, contingency plans were developed by the respective service providers, Kruch, and LVB. These included alternative hardware solutions, additional testing cycles, or adjustments to the project timeline. This flexibility enabled the project team to respond quickly and effectively to unforeseen developments. Risk tracking and monitoring were carried out during the weekly project meetings.

11. Pilot impact and sustainability

The preliminary results of the CE4CE pilot project in Leipzig clearly demonstrate that the use of digital monitoring technologies can make a significant contribution to improving efficiency and sustainability in public transport. Although full data analysis is still ongoing, several key impacts of the pilot can already be identified.

Impact on infrastructure and operations

- **Extended lifespan of overhead line systems:**
  Early detection of wear points and critical contact areas significantly increases the service life of both the overhead line and pantograph components (e.g., carbon strips).
- **Extended lifespan of track and track bed:**
  Continuous monitoring of vibrations and ride comfort enables early identification of structural weaknesses, settlements, or emerging damage in the track area. This allows for targeted maintenance and helps delay costly full-scale renovations.
- **Reduction of infrastructure failures:**
  Continuous condition monitoring supports predictive maintenance, reducing the need for unplanned repairs and service disruptions.

- **Increased vehicle availability:**
  By preventing secondary damage to pantographs, contact wires, or track components, vehicle downtime is reduced, improving fleet productivity.
- **Reduced energy consumption:**
  Energy consumption analysis provides early insights into optimization potential in driving behavior—such as smoother acceleration or more efficient driving profiles.

Contribution to the attractiveness and sustainability of public transport

These effects contribute to making public transport:

- more reliable and attractive for passengers,
- more economically efficient to operate,
- and more environmentally sustainable by reducing the ecological footprint of urban mobility.

In particular, the combination of technical innovation, data-driven maintenance, and targeted energy optimization strengthens the role of public transport as the backbone of sustainable urban mobility.

At the time of reporting, measurements and analyses are still ongoing. A detailed evaluation of the quantitative effects will be carried out at a later stage of the project as part of the development of the final "CE4CE Solutions."

12. Transferability of the pilot action

The digital solutions developed as part of the CE4CE pilot project in Leipzig for monitoring and analyzing infrastructure and energy consumption demonstrate a high degree of transferability to other transport operators and urban mobility systems. The challenges faced by LVB—such as increasing maintenance needs, rising energy costs, and the demand for reliable operations—are common across the public transport sector. Many operators still have untapped optimization potential that can be unlocked through data-driven systems.

A key advantage of the pilot lies in its consistent focus on rail-certified hardware (sensors, edge computers, communication units) and modular software solutions (data management, algorithms, dashboards). These components were developed in compliance with applicable standards (e.g., EN 50155, EN 45545) and can therefore be transferred to other networks and vehicle fleets both technically and regulatorily without difficulty.

Concrete transfer potential:

- **Within Leipzig:**
  The developed systems can be expanded to additional lines and vehicles within LVB's network.
- **To other cities and operators:**
  The solutions are transferable to other tram networks—both in Germany and internationally.
- **To other vehicle types:**
  The underlying technology is fundamentally adaptable to other modes of transport such as subways, regional trains, buses, or even autonomous vehicles.

- **Expansion of use cases:**
  The data platform developed in the project provides a foundation for additional applications—such as passenger counting, driving behavior analysis, or the integration of weather and environmental data.

The more transport operators adopt the developed systems, the greater the overall economic and environmental benefit—through reduced downtime, more efficient maintenance, lower energy consumption, and increased attractiveness of public transport.

The CE4CE pilot project thus contributes not only to digitization and sustainability in Leipzig but also offers a scalable model for other cities and regions aiming to future-proof their transport systems.

13. Annexes

Annex 1: Report Pantoheath

Report Leipzig.pdf

Annex 2: Report CEMIT

260325 Workshop CEMIT Leipzig.pdf

Results and findings from physical inspecti