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Action Plan to optimise delivery of infrastructure through minimal invasive maintenance work

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Abbreviations of partners

Abbreviation	Partner name
LVB	Leipzig Public Transport Company, Germany
PKA	Public Transport Bus Operator in Gdynia, Poland
UG	University of Gdańsk, Poland
SZKT	Szeged Transport Company, Hungary
Kruch	Kruch Railways Innovations, Austria
MOM	Municipality of Maribor, Slovenia
UM	University of Maribor, Slovenia
ATB	ATB Mobility Bergamo, Italy
Redmint	Redmint social enterprise, Italy
Mobilissmus	Mobilissimus Ltd., Hungary
TM	trolley:motion association, Austria

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1. Introduction

This Action Plan is prepared as part of CE4CE - Circular Economy for Central Europe and sets out how Leipziger Verkehrsbetriebe (LVB) will strengthen circular, resource-efficient and data-driven infrastructure maintenance. The plan focuses on the transition from predominantly reactive and interval-based maintenance towards predictive maintenance, supported by continuous monitoring, digital asset information and structured decision models. In this context, circular economy is understood not only as recycling or waste reduction, but also as the intelligent extension of asset lifetimes, the avoidance of unnecessary interventions and the better use of existing infrastructure capacity.

The Action Plan builds on the CE4CE pilot implemented in Leipzig, where monitoring technologies, sensor-based condition recording and AI-supported analyses were tested under real operating conditions. The pilot provides the technical and organisational evidence base for the measures described in this document. It shows how data from vehicles, track infrastructure, overhead line systems and energy measurements can be converted into operationally relevant information and, in a further step, into strategic asset management knowledge.

For LVB, the topic is directly linked to wider corporate and urban mobility objectives. Leipzig is growing, public transport services are expanding and expectations regarding reliability, climate protection and customer quality are increasing. The official LVB figures and facts page states that the tram network comprises 214.7 km, the bus network 730.7 km, and that LVB operates 13 tram lines, 48 bus lines and 10 night lines. These figures underline the scale of the maintenance challenge and the importance of prioritising infrastructure interventions on the basis of evidence rather than assumptions.

The overall purpose of this Action Plan is therefore to define a practical route towards minimally invasive maintenance work. This means identifying damage earlier, intervening at the right moment, reducing unnecessary asset replacement and ensuring that each maintenance euro and each material input produces maximum value for the system. In the long term, the approach is intended to support an ISO 55001-aligned asset management logic in which infrastructure decisions are transparent, risk-based, lifecycle-oriented and continuously improved.

1.1. Public references used for contextual alignment

The following public sources were reviewed and are used as contextual references for the Action Plan:

CE4CE project website: https://www.interreg-central.eu/projects/ce4ce/ - Official Interreg Central Europe project page describing CE4CE as a project that helps public transport actors transition towards circular economy principles through strategies, pilots and transferable tools.

CE4CE Leipzig pilot news: https://www.interreg-central.eu/news/predictive-maintenance-for-infrastructure-digital-optimization-in-leipzig/ - Official CE4CE news item describing the Leipzig predictive maintenance pilot, its shift from reactive and manual maintenance towards automated, predictive and minimally invasive infrastructure maintenance, and its intended transferability.

LVB company profile: https://www.l.de/verkehrsbetriebe/ueber-uns/ - Official LVB page explaining the company role in shaping future mobility, supporting the transport transition and strengthening sustainability in Leipzig.

LVB facts and figures: https://www.l.de/verkehrsbetriebe/zahlen-und-fakten/ - Official operational baseline for LVB, including network length, lines, fleet information, passenger figures and sustainability indicators.

LVB sustainability: https://www.l.de/verkehrsbetriebe/umweltschutz-und-nachhaltigkeit/ - Official LVB sustainability page describing climate protection, modal split ambitions, climate neutrality objectives and the role of low-emission public transport.

LVB projects and innovations: https://www.l.de/verkehrsbetriebe/ueber-uns/projekte-innovationen/ - Official overview of LVB investments and innovation projects that frame predictive maintenance as part of a broader modernisation agenda.

LVB future network: https://www.l.de/verkehrsbetriebe/ueber-uns/liniennetz-der-zukunft/ - Official information on the future network, including more direct connections, more services, longer operating times and expanded flexible services.

2. Initial situation and challenges

LVB operates a large, intensively used multimodal public transport system in a city with rising expectations for service quality, climate performance and network availability. According to LVB public information, the organisation provided mobility for around 167 million passengers in 2024 and is aiming to attract more users to public transport in the future. The future network initiative also points to more direct connections, denser frequencies and longer operating hours. These service ambitions increase the strategic importance of reliable infrastructure, because even small infrastructure defects can have disproportionate effects on timetable stability, customer experience and operational costs.

The maintenance organisation is confronted with a combination of technical, demographic and organisational pressures. Skilled personnel are increasingly scarce, and the retirement of experienced staff creates a risk that tacit knowledge about damage patterns, network hotspots and intervention priorities is lost. At the same time, many conventional inspection routines remain highly dependent on visual assessments and individual experience. These methods are valuable, but they are not sufficient on their own to detect early-stage deterioration, to quantify trends consistently or to prioritise interventions across a complex network.

Reactive maintenance remains necessary when faults occur, but it should not be the dominant steering logic for infrastructure assets with high operational relevance. Reactive interventions often take place under time pressure, require short-notice access to tracks or overhead line infrastructure, and can result in higher costs than targeted early interventions. Fixed renewal cycles also have limitations. They can lead to the premature replacement of assets that still have usable life, while failing to identify localised defects that develop faster than average lifecycle assumptions would suggest.

Maintenance windows are also becoming more constrained. Dense daytime timetables, night services and public expectations for continuous availability reduce the time available for inspections and works. Under these conditions, minimally invasive maintenance becomes strategically important. It allows LVB to intervene earlier and with smaller measures, reducing the need for larger disruptions later. Achieving this requires better data on actual condition, more systematic damage classification and decision-support tools that link technical condition to operational risk, cost and sustainability impacts.

The current situation therefore calls for a structured transformation. Digital monitoring, automated fault detection and AI-supported analyses can help convert routine operation into a continuous source of condition information. However, technology alone is not sufficient. The information must be integrated into existing maintenance processes, asset management systems, investment planning routines and staff workflows. The challenge addressed by this Action Plan is to make predictive maintenance usable as a daily operational support tool and as a strategic steering instrument.

3. Vision, targets and objectives of the Action Plan

The vision of the Action Plan is to establish a maintenance approach that protects infrastructure value, increases network reliability and reduces unnecessary resource consumption. The approach is aligned with CE4CE objectives because it promotes the circular economy principles of using assets longer, reducing material consumption and avoiding waste through better planning. It is also aligned with LVB sustainability ambitions, including the wider objective of supporting climate protection and the transport transition in Leipzig.

3.1. Integration of predictive maintenance into asset management

Predictive maintenance will be embedded as a functional layer of LVB asset management rather than treated as a separate digital experiment. Sensor data, image-based analysis, vibration measurements, energy data and expert observations will be brought together to create a more reliable picture of asset condition. The aim is to identify defects and negative trends before they result in failures, service disruptions or safety-critical situations.

The asset management value of predictive maintenance lies in the conversion of technical signals into decisions. A vibration anomaly, a detected overhead line deviation or an increasing energy consumption pattern must be translated into a maintenance recommendation, a risk priority and, where relevant, an investment planning implication. This Action Plan therefore places equal emphasis on data collection, assessment logic, workflows and governance.

3.2. Resource efficiency and sustainability

Resource efficiency is pursued through earlier, smaller and better targeted interventions. When damage is detected at an early stage, LVB can often apply corrective measures that extend the remaining useful life of the asset and avoid more material-intensive replacement. This is directly relevant for circular economy objectives because the most sustainable asset is often the one that remains safely and efficiently in use for longer.

Sustainability also depends on reducing the operational impacts of maintenance. Better planning can limit unplanned closures, reduce repeated site visits and optimise the use of specialist vehicles, materials and staff time. Over the lifecycle of infrastructure assets, these improvements can contribute to lower direct costs, fewer indirect service disruptions and reduced environmental impacts associated with maintenance and replacement activities.

3.3. Strategic steering through data-based models

A central objective is to develop a parameter model that connects observed asset condition with future scenarios. The model should support questions such as which assets require intervention first, what happens if a measure is postponed, which renewal strategy produces the best balance between cost and availability, and where a limited investment budget creates the greatest value. It should complement existing Life Cycle Costing approaches by adding a more dynamic and condition-based perspective.

The Action Plan does not replace LVB lifecycle cost models. Instead, it strengthens them by adding current measurements, trend information and monitoring data. This makes it possible to move from generic service-life assumptions towards evidence-based decisions that reflect the actual behaviour of specific assets in specific operating environments.

3.4. Improved availability and network quality

Improved availability is a key operational objective. Predictive maintenance should reduce unplanned failures, support earlier scheduling of corrective works and provide better visibility on emerging hotspots. This is particularly relevant in a system where service expansion, longer operating hours and customer expectations require high reliability. The same information can also support quality objectives, for example by identifying track sections affecting ride comfort or overhead line issues that may affect vehicle performance.

3.5. Transferability and scalability

The approach is designed to be scalable within Leipzig and transferable to other public transport operators. Transferability requires that the solution is not dependent on one isolated technology or vendor. It must be based on clear damage definitions, documented interfaces, reusable data structures, standardised parameters and practical guidance for organisational integration. The CE4CE pilot explicitly supports this logic by developing specifications and learning that can be shared with other operators in the Interreg Central Europe area and beyond.

3.6. Relationship with life cycle costing

Life Cycle Costing remains the financial framework for evaluating infrastructure over its expected service life. It answers questions about total cost, replacement cycles and long-term budget implications. The predictive maintenance approach adds a complementary operational and tactical layer. It asks how an asset is currently behaving, whether its condition is changing faster or slower than expected, and which intervention should be prioritised now.

This distinction is important for implementation. LCC uses longer-term assumptions and average values, while predictive maintenance uses current measurement data, trend analyses and monitoring outputs. LCC supports strategic decisions at the lifecycle level, while predictive maintenance enables targeted interventions and condition-based prioritisation. Together, the two approaches create a stronger basis for investment control: LCC provides the economic envelope and predictive maintenance provides the evidence needed to adjust actions within that envelope.

4. Overview of measures

The Action Plan is structured around six mutually reinforcing measures. Each measure contributes to the transition from fragmented inspection information towards a structured predictive maintenance and asset management system. The measures should not be understood as isolated work packages. Their value arises from their integration: the damage catalogue defines what is observed, the parameter model explains how observations are interpreted, system integration ensures that information reaches users, change management creates organisational adoption, pilot insights provide evidence, and phased implementation reduces risk.

4.1. Development of a digital damage catalogue

The digital damage catalogue is the foundation for consistent, objective and automated assessment of infrastructure defects. It will describe the typical damage patterns relevant for LVB assets, including track defects such as rail corrugation, cracks and breaks, as well as overhead line issues such as contact defects or lateral deviations. Each damage type should be linked to causes, observable indicators, safety relevance, operational impact, expected deterioration behaviour and suitable maintenance responses.

The catalogue should combine operational expertise with digital monitoring results. Visual inspections, sensor measurements, image data, laser scans and AI classifications will be brought into one structured framework. This ensures that damage is not only recorded, but also interpreted consistently. For example, a defect should be described not merely as an anomaly, but as a classified damage pattern with a severity level, a location, a likely consequence and a recommended response pathway.

The CE4CE pilot provides a practical starting point for this measure. It has already generated examples of detected track and overhead line defects, validated selected findings through on-site inspection and shown how dashboards can support localisation and follow-up. These findings will be used to refine the catalogue, define minimum data requirements and ensure that categories are understandable for both maintenance experts and asset managers.

A mature digital damage catalogue will also help to preserve organisational knowledge. As experienced staff retire, standardised damage descriptions, examples, images and decision rules can help transfer expertise to new employees. In this way, the catalogue is not only a technical data product; it is also a knowledge-management instrument that strengthens long-term organisational resilience.

4.2. Development of a parameter model for scenarios and investment control

The parameter model will act as a decision-support tool for operational, tactical and strategic planning. It will link asset condition, deterioration trends, remaining wear reserve, maintenance costs, operational impacts, risk levels and lifecycle assumptions. The model should enable LVB to compare different maintenance strategies and understand the consequences of acting immediately, postponing interventions, bundling works or replacing assets.

The model will be built on a multi-pillar methodology. The first pillar consists of precise individual measurements, such as component wear or geometry values collected at defined points in time. The second pillar consists of structured visual inspections and expert assessments, which remain important because they capture contextual knowledge and site-specific interpretations. The third pillar consists of continuous monitoring data, such as vibrations, overhead line images, laser measurements and energy consumption data. When these pillars are combined, the resulting model becomes more robust than any single data source could be on its own.

Scenario functionality is essential. The model should support questions such as how condition is expected to develop if an intervention is delayed by one year, how a certain budget allocation affects failure risk, or which network sections offer the highest benefit from early intervention. This functionality will support investment planning by making the trade-offs between cost, risk, availability and asset lifetime more transparent.

The model is designed to be transferable because every infrastructure domain uses some form of measurement, inspection and condition assessment. The specific parameters will differ between tracks, overhead lines, energy infrastructure or other assets, but the basic logic remains the same: capture condition, classify risk, forecast development and compare intervention options.

4.3. Integration of monitoring data into existing systems

Monitoring data will only create value if it is available within the systems and workflows used by LVB staff. The objective is therefore to connect new monitoring outputs with existing specialist applications and data environments, including asset management, GIS and maintenance planning systems. Interfaces should allow sensor data, images, classified defects, location references and work recommendations to be accessed without creating parallel information silos.

A central data platform and a standardised data model are key enablers. Where appropriate, data model concepts such as IDX4rail can be reviewed for compatibility with LVB requirements. The aim is to connect condition data to asset objects, kilometrage, component IDs and maintenance histories. This supports a holistic view of each asset and enables dashboard visualisations, map-based views, trend tracking and structured reporting.

The CE4CE pilot dashboards already demonstrate the practical value of integrated visualisation. They consolidate measurement data, location information, images and fault classifications in a form that maintenance teams can use for daily work. In future, this should be developed into a technology-neutral and extensible architecture. Open and documented interfaces are required so that LVB can integrate different monitoring tools and avoid long-term dependency on a single supplier.

This measure will also improve traceability. Decisions about inspections, repairs and renewals can be linked to data and documented evidence. Over time, this creates an auditable chain from detection to prioritisation, intervention and evaluation. Such traceability is an important prerequisite for ISO 55001-aligned asset management.

4.4. Training, change management and organisational development

Predictive maintenance requires a change in working culture as well as new technology. Employees must understand how the new data is generated, what the outputs mean, how reliable the recommendations are and how the information should influence their daily decisions. Change management must therefore be organised as a multi-year process rather than as a single training activity at the end of technical implementation.

User acceptance will be created through early involvement and co-development. Maintenance staff, asset managers, digitalisation experts, operations teams and external technology partners should jointly define requirements, test dashboards and review outputs. This approach ensures that the tools respond to operational realities. It also prevents the perception that digital systems are replacing human expertise; instead, they should be presented as a way to make expert knowledge more visible, transferable and effective.

Competence development will focus on data literacy, system use, interpretation of monitoring results and new decision pathways. Staff need training not only in how to operate dashboards, but also in how to assess uncertainty, validate alerts, document responses and provide feedback to improve algorithms. New role profiles may emerge at the interface between infrastructure engineering, data analysis and asset management.

Organisational development will address responsibilities and governance. Data-based maintenance requires clear rules on who validates alerts, who decides on interventions, who updates the damage catalogue, who maintains interfaces and who evaluates the effectiveness of measures. These responsibilities should be embedded in regular processes so that the predictive approach becomes part of the organisation rather than a project add-on.

4.5. Use of insights from the CE4CE pilot in Leipzig

The CE4CE pilot provides direct input to the Action Plan because it tested technologies and working methods under real operating conditions. The pilot validated the use of vibration sensors for track defects, camera and laser systems for overhead line analysis, energy flow measurements for driving behaviour and edge-computing platforms for local processing. It also tested AI-supported analytics platforms for classification and trend analysis.

The pilot generated evidence on damage patterns, data quality, dashboard usability and organisational feedback loops. It showed that technical detection must be complemented by on-site validation, expert interpretation and iterative improvement of algorithms. It also demonstrated that weekly coordination meetings, training formats and direct feedback from maintenance teams are necessary to transform sensor outputs into usable maintenance knowledge.

These insights will be systematically reused. The identified damage categories feed into the digital damage catalogue, the collected monitoring data supports the parameter model, and the lessons learned on interfaces, dashboards and user needs guide scaling. The pilot is therefore not a completed experiment, but the first implementation stage of a broader transition.

4.6. Phased implementation and piloting

Implementation will follow a phased approach to reduce technical, financial and organisational risk. The first step is to select suitable assets and network sections where the expected benefit is high and where monitoring can realistically be integrated into operations. Selection criteria should include asset criticality, failure history, traffic relevance, maintenance access constraints and potential for learning.

The second step is model development. Suitable sensor technologies are selected, data flows are tested and initial prediction models are created. During this phase, measurement results from the pilot are connected with inspection results and expert knowledge. The goal is not to create a perfect model immediately, but to establish a transparent and improvable baseline.

The third step is integration into processes. Validated outputs are introduced into maintenance planning, asset management reviews and investment discussions. Training, governance clarification and feedback formats are implemented in parallel. The fourth step is scaling, where additional lines, vehicles and asset classes are added once the approach has proven its value. This staged logic ensures that learning from each phase is incorporated before wider rollout.

5. Integration of the CE4CE pilot into the Action Plan

The Leipzig CE4CE pilot is the principal reference case for this Action Plan. It demonstrates how circular economy principles can be operationalised in infrastructure maintenance by extending asset lifetimes, reducing unnecessary inspections and enabling smaller, earlier and more targeted interventions. The pilot also provides the basis for transfer to other operators because it combines technical testing with organisational learning and interface development.

5.1. Pilot objectives

The pilot aimed to develop and test a modular monitoring system for track infrastructure, overhead line infrastructure and energy consumption. Its operational objective was to detect damage patterns earlier and to support targeted prioritisation of maintenance measures. Its strategic objective was to create the data foundation for a parameter model that can guide future investment and lifecycle decisions.

The pilot also had a capacity-building objective. By involving LVB, IFTEC, technology partners and CE4CE partners, it created a shared understanding of how predictive maintenance can work in practice. This is important because future scaling depends on both technical performance and organisational confidence in the results.

5.2. Technical implementation

Three tram vehicles were equipped with monitoring components to collect data during regular operation. Vibration sensors were used to detect track defects, while cameras and laser scanners supported visual and geometric analysis of the overhead line. Energy flow measurement was used to assess driving behaviour and energy efficiency. Edge-computing platforms enabled local data processing, while AI-supported analytics platforms, including CEMIT and PantoHealth, supported fault classification and trend analysis.

The technical implementation was carried out in close coordination with IFTEC, Kruch, CI4RAIL and additional project partners. The systems were selected and integrated with attention to rail-sector requirements, including certifications in accordance with EN 50155 and EN 45545. This is relevant for transfer because solutions used in public transport infrastructure must be robust, safe and suitable for daily operation under demanding conditions.

5.3. Results and insights

The pilot produced several operationally relevant insights. For track infrastructure, critical sections could be identified and selected findings were validated through on-site inspection. For overhead line infrastructure, contact defects and deviations in lateral position were detected and could be addressed through targeted measures. The dashboard environment made damage patterns visible, supported localisation and enabled trend tracking and report generation.

The energy analysis provided initial indications of how driving behaviour and infrastructure condition can be connected to energy use. Although this component requires further development, it creates an additional link between maintenance, operations and sustainability. In the longer term, the combination of infrastructure condition and energy data can support a more integrated understanding of system efficiency.

5.4. Organisational integration

The pilot confirmed that predictive maintenance requires structured coordination. Weekly jour fixe meetings involving asset management and service partners created a routine for interpreting results, discussing anomalies and agreeing follow-up actions. Training sessions and workshops helped users understand the systems and provide feedback on usability. These formats will continue to be important during the transition from pilot to regular operation.

Feedback loops were particularly valuable. They allowed algorithms and dashboards to be refined in response to operational experience. They also helped identify where additional explanations, filters or visualisations were needed. This iterative approach should become a permanent feature of the predictive maintenance system, because asset behaviour, data quality and user needs will continue to evolve.

5.5. Pilot relevance for the Action Plan

The pilot contributes to each core measure of the Action Plan. Its damage classifications and validated examples support the digital damage catalogue. Its data streams and trend observations support the parameter model. Its dashboard experience supports system integration. Its workshops, training and feedback formats provide a basis for change management. Finally, its technical and organisational lessons define the conditions for scaling.

The pilot demonstrates that predictive maintenance is technically feasible, organisationally integrable and strategically relevant for LVB. It should therefore be treated as the starting point for institutionalisation, not as a stand-alone demonstration.

6. Stakeholder and governance

Successful implementation depends on coordinated action across several organisational units and external partners. Predictive maintenance changes how condition information is collected, interpreted and acted upon. Clear stakeholder roles and governance structures are therefore necessary to avoid fragmented responsibilities and to ensure that data-based insights lead to real maintenance and investment decisions.

6.1. Internal stakeholders

Asset Management will hold lead responsibility for integrating predictive maintenance into strategic asset management. This includes defining decision criteria, linking outputs to investment planning and ensuring that the approach supports ISO 55001-aligned asset management principles. Maintenance and IFTEC will provide technical implementation expertise, validate system outputs, calibrate damage categories and define practical intervention measures.

The Digitalisation Team will develop and operate data platforms, interfaces and dashboards. Its role is to ensure technical reliability, interoperability and cybersecurity. Operations and driving staff will provide feedback on ride quality, operational disturbances and user-visible impacts. Controlling and Investment Planning will use the parameter model to assess budget needs, compare scenarios and prioritise investments.

- **Asset Management:** This unit defines asset management objectives, prioritisation rules and the strategic use of predictive outputs.
- **Maintenance and IFTEC:** These actors validate defects, calibrate maintenance responses, implement corrective measures and contribute practical expertise from day-to-day infrastructure work.
- **Digitalisation Team:** This team provides data platforms, interfaces, dashboards and technical support for system integration.
- **Operations and Driving Staff:** Operational staff provide feedback on ride comfort, disturbances, access constraints and practical operating impacts.
- **Controlling and Investment Planning:** These functions use scenario outputs and lifecycle information for budgeting, prioritisation and investment decisions.

6.2. External partners

External technology partners provide rail-certified hardware, monitoring systems, edge-computing platforms, algorithms and analytical services. Their contribution is essential during development and scaling, but LVB should retain sufficient internal knowledge to maintain data sovereignty and avoid dependency on individual suppliers. Other public transport operators contribute peer learning and help validate whether the approach is transferable beyond Leipzig. Universities and research institutions can support model development, evaluation methods and scientific review. Municipal actors can help align the approach with Smart City initiatives, urban data platforms and transport transition objectives. The governance model should therefore allow both operational coordination and strategic exchange with external stakeholders.

6.3. Governance structure

Governance will follow four linked levels. At the strategic level, infrastructure management and asset management define objectives, priorities and resources. At the operational level, project teams consisting of maintenance, digitalisation and external partners implement technical and process measures. At the quality assurance level, regular coordination meetings and review formats validate results and initiate improvements. At the institutionalisation level, validated outputs are embedded in regular maintenance planning, investment control and asset management reviews.

This governance structure must be transparent. Each data output should have an owner, each decision should have a responsible unit, and each feedback item should have a documented follow-up. This is particularly important when predictive outputs influence safety-relevant inspections or investment priorities.

6.4. Stakeholder participation

Participation will be organised through requirements workshops, user testing, regular jour fixe meetings, training sessions and stakeholder reviews. Requirements workshops will define user needs and data outputs. User testing will verify whether dashboards and reports support daily work. Jour fixe meetings will monitor implementation progress and discuss new findings. Training will build competence, while stakeholder reviews will assess whether the approach is ready for scaling.

The participation formats should remain active beyond the pilot phase. Predictive maintenance systems improve through repeated use, feedback and recalibration. Continuous participation therefore becomes a core mechanism for quality assurance and organisational learning.

7. Timeline and implementation steps

Implementation will follow a multi-stage, iterative process that combines technical deployment with organisational integration. The timeline is designed to minimise risk by starting with selected assets, validating outputs under real conditions and expanding only once the approach has demonstrated practical value.

7.1. Phased implementation model

The phased model below translates the Action Plan into implementation steps. The phases are sequential in logic but partly overlapping in practice, because training, data quality improvement and feedback loops must begin early and continue throughout rollout.

1. **Phase 1 - Preparation and requirements definition:** LVB defines the objectives, selects priority lines and assets, confirms stakeholders, maps existing data sources, agrees KPIs and clarifies governance responsibilities.
2. **Phase 2 - Piloting and system integration:** Monitoring systems are installed or extended, data is connected to platforms and specialist applications, initial assessment models are developed, dashboards are prepared and the involved teams are trained.
3. **Phase 3 - Validation and feedback loops:** Forecasts are compared with inspections, damage classifications are validated, algorithms are optimised, processes are adapted and user acceptance is reviewed through workshops.
4. **Phase 4 - Scaling and institutionalisation:** The approach is extended to additional lines, vehicles and asset classes, the parameter model is integrated into investment planning and the resulting processes are embedded in regular operations.

7.2. Iterative development

Implementation will follow a Build - Measure - Learn logic. In the build step, initial prototypes such as dashboards, interfaces and damage catalogue structures are developed and deployed. In the measure step, technical performance, user feedback, data completeness and maintenance impacts are monitored. In the learn step, the results are translated into improvements of algorithms, processes, training materials and governance rules.

This iterative logic is important because predictive maintenance cannot be fully specified at the beginning. Asset behaviour, data quality and user needs become clearer during implementation. The Action Plan therefore treats uncertainty as a normal feature of innovation and addresses it through controlled experimentation and continuous improvement.

7.3. Dependencies and preconditions

Several dependencies must be managed. Suitable vehicles and infrastructure sections must be available for monitoring. Technical compatibility with MR.pro, ZEDAS, GIS and other relevant applications must be clarified. Internal resources are required not only for procurement and installation, but also for data analysis, training, validation, operation and maintenance of the digital systems.

A further precondition is cross-organisational cooperation. Predictive maintenance sits at the intersection of infrastructure engineering, digitalisation, operations, maintenance and controlling. Its success depends on the willingness of these units to share information, align decisions and jointly evaluate outcomes. Senior management support is needed to secure resources and resolve conflicts between short-term operational pressures and long-term asset management objectives.

8. Monitoring and evaluation

Monitoring and evaluation are central to the Action Plan because they show whether predictive maintenance creates the expected value. Evaluation will cover technical performance, operational usefulness, cost impacts, sustainability benefits and organisational adoption. The KPI framework will also support asset management performance evaluation in line with ISO 55001 principles.

8.1. Objectives of monitoring

Monitoring will verify whether sensor systems and analytical methods produce reliable, timely and actionable information. It will assess whether defects are detected earlier than before, whether maintenance actions are better prioritised and whether unplanned interventions can be reduced. It will also assess the quality and availability of data, because poor data quality would weaken both operational decisions and strategic modelling.

Evaluation will also address learning. Each detected defect, false alert, missed detection or successful intervention provides information for improving the system. This means that monitoring is not only a reporting function; it is part of the continuous improvement mechanism.

8.2. Core indicators (KPIs)

The core indicators below are proposed for evaluating implementation progress and impact. Each indicator should be defined with a baseline, a target value or expected trend, a data source and a responsible owner.

- ✓ **Early fault detection:** This indicator measures the share of defects detected before they become visible in conventional inspections or reach a critical condition.
- ✓ **Reduction of unplanned measures:** This indicator compares reactive interventions with predictive or planned maintenance actions.
- ✓ **Infrastructure availability:** This indicator monitors downtime or service restrictions caused by track and overhead line infrastructure.
- ✓ **Energy efficiency:** This indicator tracks energy consumption per vehicle kilometre and selected links between driving behaviour, infrastructure condition and energy use.
- ✓ **Data quality and system availability:** This indicator measures sensor uptime, data transmission rates, completeness of records and plausibility of measurement values.
- ✓ **Response time:** This indicator measures the time between fault detection, validation, decision and initiation of corrective measures.
- ✓ **Cost savings and avoided costs:** This indicator captures avoided repair costs, reduced inspection effort, extended asset service life and improved investment timing.

8.3. Evaluation methodology

Evaluation will combine automated data collection with expert review. Sensor systems and data platforms will provide quantitative information on alerts, trends, locations and system availability. Expert feedback and on-site inspections will validate whether detected patterns are technically meaningful. Existing data sources such as MR.pro, maintenance records, surveys and established assessment methods will be used for comparison.

Workshops and review formats will interpret the results and translate them into actions. This is particularly important where quantitative indicators require contextual interpretation. For example, a temporary increase in detected defects may indicate worsening asset condition, but it may also indicate improved detection capability. Evaluation must therefore distinguish between system learning, data quality effects and real infrastructure trends.

8.4. Feedback loops

Feedback loops will connect asset management, maintenance, digitalisation and external partners. Regular coordination meetings will review new alerts, discuss validation results and decide whether algorithms or categories require adjustment. Dashboards will visualise trends, hotspots and maintenance trajectories. Lessons learned from piloting and rollout will be documented and used to refine processes, training and the parameter model.

8.5. Integration into regular operations

Monitoring and evaluation will be integrated into existing steering instruments, including investment controlling, maintenance planning and asset management reviews. The objective is to create a continuous data-driven steering cycle: condition is monitored, risks are assessed, measures are prioritised, interventions are implemented, and results are evaluated. Over time, this cycle should become part of regular LVB operations.

9. Financing and responsibilities for implementation

The implementation and long-term establishment of predictive maintenance require a stable financial and institutional basis. The Action Plan therefore addresses both the funding of initial measures and the embedding of the approach into LVB governance, data ownership and asset management routines.

9.1. Financing sources

The CE4CE project provides funding for pilot activities and preparatory work. LVB own funds are required for co-financing hardware, system integration, staff resources and long-term operation. Additional national funding opportunities, including programmes supporting digitalisation of municipal transport systems or the mFUND programme of the German Federal Ministry for Digital and Transport, may be reviewed where they match eligible activities.

Long-term operational models should also be considered. Service contracts with technology partners may support operation, maintenance and further development of systems. However, such contracts should be structured so that LVB retains strategic control over data, interfaces, evaluation logic and future supplier choices.

9.2. Data sovereignty and sustainability

LVB should retain full ownership and control over collected and derived data. This includes raw sensor data, processed condition data, damage classifications, model parameters and evaluation results. Data sovereignty is necessary to protect operational independence, enable future scaling and support transferability to other systems or partners.

System sustainability requires modular, standardised and documented solutions. Interfaces, data models and algorithms should be described in a way that allows future maintenance, replacement or extension. Training materials and knowledge-transfer activities will reduce dependency on individual experts or suppliers. This is particularly important for a formal deliverable that aims to create impact beyond the CE4CE project duration.

9.3. Institutional sustainability through ISO 55001-aligned asset management

To ensure long-term safeguarding and systematic further development, LVB aims to gradually align the predictive maintenance approach with the principles of ISO 55001. The standard provides an internationally recognised framework for value-oriented management of physical assets over their lifecycle. Within this Action Plan, ISO 55001 is used as an orientation framework rather than as an immediate certification objective.

The alignment creates added value in several areas. It embeds predictive maintenance as part of an integrated asset management system, links condition data to lifecycle and value considerations, clarifies governance and responsibilities, strengthens risk-based prioritisation and supports transferability to other operators. It also helps to connect monitoring data, the digital damage catalogue, the parameter model and existing LCC approaches into one coherent decision system.

The measures in this Action Plan contribute directly to key ISO 55001 principles. The digital damage catalogue and dashboards strengthen asset information and knowledge. The parameter model supports lifecycle management and scenario planning. Early fault detection and prioritised interventions support risk management. KPIs and evaluation formats support performance evaluation. Piloting, feedback loops and lessons learned support continuous improvement.

9.4. Stepwise implementation of the ISO-aligned approach

The ISO-aligned approach will be developed step by step. The first step is a baseline assessment that maps existing processes, systems and responsibilities against ISO 55001 principles. The second step is process alignment, where decision-making, risk assessment and steering routines are adapted using the improved data base. The third step is integration into governance and investment planning, so that predictive outputs influence strategic decisions. The fourth step is competence development through training and cross-departmental collaboration. The fifth step is institutionalisation through regular reviews, continuous improvement and the possible option of formal certification at a later stage.

10. Transfer potential and scaling

The measures described in this Action Plan are designed for scaling within Leipzig and for transfer to other public transport operators. Transfer is important for CE4CE because the project aims to create solutions that improve circular economy practice beyond individual pilots. Predictive maintenance has strong transfer potential because many operators face comparable challenges: ageing infrastructure, limited maintenance windows, skills shortages, rising costs and increasing expectations for reliability and sustainability.

10.1. Transfer within Leipzig

Within Leipzig, the first scaling step is to extend monitoring and analytics to additional tram lines and asset classes. The selection should be based on criticality, failure history, operational relevance and potential learning value. Once the approach is stable for track and overhead line infrastructure, selected elements can be assessed for bus-related infrastructure, charging infrastructure, energy systems or other operational assets.

The central data platform can also support additional applications, such as passenger-related data, environmental monitoring or broader mobility management. However, scaling should remain focused and value-driven. New use cases should be added only when they have clear users, defined data governance and measurable benefits.

10.2. Transferability to other cities and operators

Other cities and public transport operators can adopt the core logic independently of the exact technical configuration used in Leipzig. The most transferable elements are the damage catalogue methodology, the multi-pillar parameter model, the integration of monitoring data into asset management, the KPI framework and the change-management approach. These elements can be adapted to local assets, data availability and organisational structures.

Technical transferability is strengthened by the use of rail-sector standards and by the development of documented interfaces, data formats and parameters. Organisational transferability is strengthened by the use of ISO 55001 as a common reference framework. This allows other operators to position predictive maintenance within their own asset management systems and to compare maturity levels, governance structures and performance indicators.

10.3. Recommendations for transfer

Operators wishing to replicate the approach should start with a clearly defined asset class and a manageable pilot scope. Maintenance, operations, IT, asset management and finance functions should be involved from the beginning. The technical pilot should be accompanied by governance clarification, user training and a feedback mechanism. Data ownership, interface requirements and supplier responsibilities should be agreed before large-scale implementation.

Transfer partners should also avoid treating predictive maintenance as a purely technological procurement. The most important success factor is the connection between data and decisions. A sensor system creates value only when its outputs are trusted, validated, integrated into workflows and used to trigger better maintenance and investment actions.

11. Conclusions

This improved Action Plan defines a coherent pathway for transforming LVB infrastructure maintenance towards a predictive, resource-efficient and strategically integrated approach. It builds directly on the CE4CE pilot, strengthens the narrative link to circular economy objectives and aligns the measures with LVB priorities for reliability, sustainability and future mobility.

The core contribution of the Action Plan is the integration of technical monitoring, organisational learning and asset management governance. The digital damage catalogue standardises what is detected. The parameter model supports scenario-based decision-making. System integration ensures that data reaches users. Change management enables adoption. Monitoring and evaluation demonstrate value. ISO 55001 alignment creates a durable institutional frame. Together, these elements support minimally invasive maintenance that extends asset life, reduces waste and improves service reliability.

The next step is to move from pilot-based learning to structured implementation. This requires clear responsibilities, stable funding, data governance, iterative development and sustained management commitment. If these conditions are met, the Leipzig approach can become a scalable model for predictive and circular infrastructure maintenance in public transport.