CE4CE

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

Modules for predictive maintenance of infrastructure and rolling stock at ATB Mobility, Bergamo, Italy

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Contents

1. Main objectives

The solutions tested in Bergamo have a twofold purpose:

(1) to enhance the durability and operational reliability of public transport infrastructure and the rolling stock through the implementation of real-time monitoring and predictive maintenance strategies, and

(2) to optimize energy consumption through running a set of simulations on a digital copy of the electric network, and by this studying possible scenarios and parameter setting and their impact on the most circular use of energy.

In both cases, operational and circularity challenges are tackled by the solutions:

(1) by “continuous monitoring” the early detection of defects and infrastructure wear is enabled. System errors, complete destruction of components and unnecessary repairs and downtimes are reduced. Using artificial intelligence (AI) to develop a predictive monitoring system allows for minimally invasive and well-targeted maintenance interventions, getting the maximum out of time and material. The time of useful life of the infrastructure components (e.g. overhead contact line) as well as the rolling stock (e.g. pantograph) can be increased, namely materials (crucial resources like copper and carbon) are lasting longer, and less waste is produced. Furthermore, the solutions relies on the use of a standard vehicle in operations for data collection, so that no extra vehicles and no extra journeys are needed, extra expenses and energy consumption for monitoring are avoided.

(2) by building a digital copy of the electric power system of the network and using digital simulation technology (Energy Flow Simulations) to study different settings and operation modes, ways to “reuse braking energy in a more efficient way, minimizing the losses” can be identified, “energy consumption” of tram operations is reduced and the circularity of transport networks is improved. These results can be achieved quickly, helping to apply improvements early, maximizing the effect of the intervention. The solution supports a reliable data driven decision-making process: producing clear and trustworthy data to support strategic decisions, helping improve the quality and effectiveness of planning for tram operations and future infrastructure investments, avoiding failure or non-optimal decisions.

1.1. Scope and success factors

Scope

This Annex documents the Bergamo pilot solution for AI-supported overhead equipment (OHE/OCL) and pantograph monitoring, combined with Energy Flow Simulation (EFS) of the T1 Bergamo-Albino electric tram corridor. The pilot covers the 12.5 km T1 line with 16 stations, operated with low-floor trams, using the MC1-CE4CEBergamo vehicle in regular passenger operation. Data sources include GNSS positioning, acceleration and vibration signals, camera/video information, vehicle speed, line voltage and current, traction-control-unit states, and consumed/returned traction energy. The same operational data stream is also used to validate and calibrate the digital twin of the traction power system.

Success factors

At pilot level, success is demonstrated by: (i) continuous collection of vehicle and OHE data during passenger service without dedicated inspection runs; (ii) a dashboard and workflow that rank AI-identified OHE points by risk and support targeted inspection/repair decisions; (iii) field-verifiable identification of 10 measurement points on T1, including 8 “Unhealthy” and 2 “At Risk” points; (iv) completion of inspections for priority points, with 5 points marked “Need to Repair”; (v) EFS calibration against measured operations, reducing the energy simulation error from 67.5% before validation to 5.4% after validation; and (vi) quantified optimisation potential, including a measured/simulated energy spread of up to 62.6% between worst and best trips. Longer-term success should be assessed through sustained KPI tracking: data uptime, false-positive rate, detection-to-action time, repair conversion rate, component lifetime extension, and energy use per vehicle-km.

2. Target groups

2.1 Infrastructure monitoring system

2.1.1. Primary users

A. Operational staff (control room, dspatch, fleet supervision)

Operational staff such as control room operators, dispatchers and fleet supervisors will use the system outputs to receive early warnings on wear, misalignment or structural degradation of the overhead contact line and pantograph interface. The predictive insights generated by the AI-supported monitoring system will enable them to prevent service disruptions and make informed operational decisions. For practical take-up, the solution is supposed to integrate seamlessly into existing control and fleet management systems and provide clear, actionable dashboards rather than raw data streams. Reliable alert prioritisation and a low false-positive rate are essential to ensure trust in the system. Adoption potential is particularly high for tram and light rail operators with electrified networks seeking to increase reliability and reduce infrastructure-related incidents.

B. Maintenance teams (Infrastructure and rolling stock)

Infrastructure and rolling stock maintenance teams will use the AI-generated condition data to plan targeted interventions. By enabling condition-based rather than reactive maintenance, the system is expected to reduce emergency repairs and optimise replacement cycles for critical components such as copper contact wires, section insulators, clamps & fittings and carbon pantograph strips. For successful adoption, compatibility with existing maintenance management systems (CMMS), mobile accessibility for field teams and dedicated training in interpreting predictive diagnostics are required. Furthermore, the solution reduces the need for on-site verification, generating time and cost savings.

C. Asset management and lifecycle management departments

Asset and lifecycle management departments will use the long-term degradation data to improve lifecycle modelling and optimise both CAPEX and OPEX planning. By providing real performance data from daily passenger operation, the solution enables better forecasting of component lifespan and more efficient use of crucial materials such as copper and carbon. For practical implementation, structured reporting formats and KPI dashboards must be available and compatible with existing asset management frameworks. Demonstrated extension of infrastructure and rolling stock lifetime will be a decisive factor for adoption, especially in the context of sustainability and circular economy objectives.

D. Engineering and planning departments

Engineering and planning departments will benefit from access to validated field data that can be used to refine infrastructure specifications and validate design assumptions. The comparison of monitored data with EFS simulations conducted during the preparation phase strengthens reliability and supports continuous improvement. For practical take-up, the system must provide structured, exportable datasets that are interoperable with modelling and simulation tools. Proven consistency and robustness of AI-generated outputs will be essential to build confidence among engineering professionals.

2.1.2. Secondary users

(I) Public Transport Authorities (PTAs)

Public transport authorities can use the solution (or benefit from its outputs) to oversee infrastructure performance, enhance system reliability and align maintenance strategies with long-term policy goals such as decarbonisation and sustainable resource management. The system can support performance-based contracts by providing transparent, data-driven indicators of infrastructure condition. Adoption will depend on a demonstrated cost-benefit ratio, compliance with EU data protection and cybersecurity standards, and clear contributions to climate and sustainability targets. By reducing public service disruptions and extending infrastructure lifetime, the solution offers strong strategic value for authorities.

(II) System suppliers and technology providers

Rolling stock manufacturers, overhead contact line suppliers, AI developers and sensor manufacturers can integrate the solution into future vehicle generations or infrastructure packages. The modular sensor architecture and edge computing approach offer opportunities for commercialisation and scaling across different networks. Adoption by industry partners will require open interfaces, standardised system architecture and a clear business case demonstrating replicability and return on investment. Integration into new tram procurement specifications represents a strong scale-up pathway.

More generally, urban tram and light rail operators across Europe represent the primary replication target group, as the solution can be readily adopted where basic digital infrastructure exists and there is willingness to shift from reactive to predictive maintenance, particularly during fleet renewal cycles when sensor units and edge computers can be efficiently integrated. Because monitoring is performed using standard rolling stock during regular passenger service, no additional vehicles, journeys, or energy consumption are required, significantly lowering operational barriers and facilitating uptake. Metro systems that rely on overhead electrification rather than third rail systems may also benefit, provided technical compatibility, adapted sensor configurations, and compliance with metro-specific operational and cybersecurity standards are ensured. Beyond operators, cities pursuing ambitious sustainability and resource efficiency targets stand to gain from reduced material consumption, extended infrastructure lifespan, and lower waste generation, especially where there is strong political commitment to sustainable asset management and access to digitalisation and green transition funding mechanisms.

Technically, the solution is technically scalable due to its modular sensor packages, edge computing architecture and compatibility with cloud-based AI analytics. Hardware installation on standard tram fleets enables replication without requiring dedicated inspection vehicles, significantly reducing deployment costs compared to traditional monitoring approaches.

Furthermore, organisational scalability can be achieved through the development of standardised training programmes, integration guidelines and KPI frameworks that allow new operators to implement the system efficiently. Clear governance models and defined responsibilities will support smooth integration into existing operational structures.

Finally, financial scalability is strengthened when operators face high emergency repair costs, ageing infrastructure or increasing material prices. The demonstrated extension of component lifetime, reduction of downtime and optimisation of maintenance resources provide a strong return on investment. Access to EU or national funding programmes for digitalisation and sustainable mobility can further accelerate uptake.

2.2 Energy flow simulations

2.2.1 Primary users

A. Energy management and Power supply departments

Energy management teams and power supply engineers are the primary users of the digital twin of the electric network. By building a digital copy of the traction power system and applying Energy Flow Simulations (EFS), they can analyse operational settings and network configurations to identify opportunities to reuse braking energy more efficiently and minimise transmission losses. The simulation environment allows to test improvements virtually before implementation, enabling faster and lower-risk optimisation of energy flows.

B. Operational planning and traffic management

Operational planning teams can use simulation results to adjust timetables, vehicle dispatch strategies and traction power settings in order to maximise recuperated energy usage. By understanding how different operational modes influence energy exchange between vehicles and substations, planners can optimise service patterns while maintaining reliability.

Practical implementation requires close coordination between simulation specialists and operational planners, as well as the ability to test multiple scenarios quickly. The possibility to achieve measurable energy savings in a short timeframe significantly strengthens adoption potential.

C. Infrastructure and substation engineers

Infrastructure engineers responsible for substations and grid interfaces can use the digital twin to assess voltage stability, load peaks and the impact of different traffic densities on the power network. The simulation-based approach allows identification of weak points, bottlenecks or inefficiencies in energy distribution without physical interventions.

For practical take-up, the model must be calibrated with high-quality network data and updated in case of infrastructural changes of the transport network. Demonstrated improvements in energy efficiency and reduction of peak loads will be key drivers for adoption.

D. Asset management and sustainability departments

Asset managers and sustainability officers can use the simulation outputs to quantify energy savings, reduction in losses and improvements in circular energy use. By increasing the reuse of braking energy within the network, the system supports circularity principles and contributes directly to climate and energy efficiency targets.

2.2.2 Secondary Users

(I) Public Transport Authorities (PTAs)

Public transport authorities can use the digital twin results to support strategic energy planning, infrastructure investment decisions and climate reporting obligations. The ability to test hundreds of operational scenarios digitally enables evidence-based decision-making and reduces the risks associated with infrastructure upgrades.

Adoption conditions include demonstrated energy savings, alignment with regional or national climate strategies, and compliance with energy efficiency regulations. Authorities are particularly likely to support uptake when quick, measurable improvements can be achieved without large capital investments.

(II) System suppliers and Technology providers

Suppliers of substations, traction power equipment, simulation software and digital infrastructure can integrate the modelling approach into their service portfolios. The digital twin concept offers commercial opportunities in network optimisation, consultancy services and performance monitoring.

Adoption by industry partners requires interoperability with existing systems, scalability across different network sizes and a clear business model demonstrating value creation through reduced energy consumption and improved grid stability.

In general, urban tram and light rail operators with electrified traction systems represent the primary replication target group. Any operator with overhead contact line infrastructure and regenerative braking vehicles can adopt the digital twin and Energy Flow Simulation approach. Adoption is particularly feasible when operators possess basic digital network documentation and monitoring systems. Because improvements are identified through simulation rather than physical trial-and-error, implementation can be rapid and cost-efficient. Operators facing rising electricity prices or sustainability obligations have strong incentives to adopt such solutions.

Metro systems and regional electrified rail networks can also apply the methodology, provided that sufficient network data is available to construct a reliable digital twin. The simulation approach is transferable to any DC or AC traction power system where regenerative braking energy can be reused.

Beyond operators, cities pursuing energy transition and climate neutrality targets can benefit from the reduced energy consumption and improved circular use of recuperated braking energy. By minimising losses and optimising network performance, the solution directly contributes to urban decarbonisation strategies.

From the technical point of view, the digital twin and simulation approach is highly scalable because it is software-based and does not require extensive physical infrastructure modifications. Once the electric network model is established, additional scenarios can be tested at marginal cost. The methodology can be replicated in networks of different sizes and configurations, provided sufficient data is available.

Organisational scalability can be achieved through standardised modelling procedures, documentation templates and training modules for energy and infrastructure departments. Once internal expertise is developed, operators can continuously refine and expand the simulation model.

Financially, scalability is particularly strong because the solution primarily requires modelling and simulation software rather than large capital investments. Energy savings can often be realised quickly after implementation of identified optimisation measures. Rising electricity prices and increasing regulatory pressure for energy efficiency further strengthen the business case.

2.2. Roles and RACI Snapshot

- Asset Management / Engineering. Owns objectives, KPIs, prioritisation (R/A).
- Maintenance (Infrastructure/Rolling Stock). On-site verification, work orders, feedback loops (R).
- IT / Data Platform. Interfaces, object IDs, georeferencing, data quality & uptime (R).
- Technology/Analytics Partners. Hardware/edge services, algorithms, dashboards, training (C).
- Operations / Control Room. Incident reporting, comfort feedback, service impact (C/I).

(R=Responsible, A=Accountable, C=Consulted, I=Informed)

3. The solution concept

3.1 Infrastructure monitoring system

Circular economy principles were applied through the testing of a predictive, data-driven monitoring system for tram infrastructure and rolling stock components. The pilot focused on equipping standard tram vehicles operating in daily passenger service with advanced sensor units, data connectors, edge computers and data modems. These devices enabled continuous monitoring of critical components such as the overhead contact line, the pantograph interface and related structural elements.

The objective of the pilot was to test whether real-time operational data, analysed using advanced methods and artificial intelligence (AI), could enable early detection of wear, misalignment and structural degradation. The collected data was also compared with Energy Flow Simulation (EFS) results prepared during the project's preparatory phase to ensure consistency and reliability. The pilot aimed to demonstrate that predictive, condition-based maintenance could replace reactive maintenance practices, thereby reducing unnecessary repairs, preventing severe component failures and increasing overall system sustainability.

3.1.1 Short definition of the solution

The final solution is an AI-supported predictive monitoring system that transforms standard tram vehicles into mobile diagnostic units operating during regular passenger service. By continuously collecting and analysing infrastructure and rolling stock data, the system detects early indicators of wear and degradation and enables targeted, minimally invasive maintenance interventions.

The solution is primarily used by maintenance teams, asset managers, operational staff and infrastructure engineers. It supports condition-based maintenance planning, lifecycle optimisation and operational reliability management.

The system increases the useful lifetime of key infrastructure components such as overhead contact lines and pantographs, reduces material waste (notably copper and carbon), avoids unnecessary large-scale repairs and eliminates the need for dedicated monitoring vehicles. As a result, it improves resource efficiency, reduces costs and contributes to a more sustainable and low-emission public transport system.

3.1.2 Circularity gaps identified and circularity principles applied

Several circularity gaps were identified in overhead contact line maintenance practices. Maintenance is largely reactive or time-based, leading to components being replaced either too late, after significant damage, or too early, before reaching their actual technical end of life. At the same time, there was limited continuous visibility of wear in the pantograph-overhead line interaction, resulting in undetected degradation and inefficient intervention cycles. Critical materials such as copper and carbon are frequently replaced based on precautionary schedules rather than real performance data, contributing to unnecessary resource consumption. Minor defects can escalate into major failures, causing extensive repairs, service disruptions, and high material use. In addition, traditional inspection methods require dedicated monitoring vehicles or additional runs, increasing energy consumption and operational costs. The solution addresses these gaps through continuous sensor-based monitoring and AI-driven predictive maintenance, enabling early fault detection, reducing cascading damage, extending component lifetime, and eliminating the need for extra monitoring journeys by using trams in regular passenger service as data collection platforms.

The pilot directly supports key circular economy principles by enabling early defect detection that extends the useful life of infrastructure components and rolling stock parts through timely, condition-based interventions. Predictive maintenance reduces waste by preventing complete component failure and avoiding premature replacement of high-value materials such as copper contact wires and carbon pantograph strips. By maximising the utilisation of existing assets and aligning interventions with actual wear conditions, the system lowers overall demand for raw materials and reduces resource extraction pressures. In addition, monitoring is performed using standard trams in daily passenger service, eliminating the need for dedicated inspection vehicles, extra journeys, or additional energy consumption. This integrated approach enhances system efficiency while avoiding resource-intensive monitoring practices and supporting more sustainable asset management.

3.2 Energy flow simulations

Circular economy principles were applied by developing and testing a digital twin of the tram network's electric power system. The pilot focused on modelling a digital copy of the traction power infrastructure and applying Energy Flow Simulation (EFS) technology to analyse hundreds of possible operational settings and scenarios.

The objective of the pilot was to understand how energy flows through the tram network and to identify ways to reuse regenerative braking energy more efficiently while minimising energy losses. Through simulation, the pilot explored different operational configurations and traffic patterns in order to optimise tram operations, reduce overall energy consumption and improve the circular use of energy within the system. By testing these scenarios digitally, the project aimed to generate reliable data that could support strategic decision-making for operations and infrastructure planning while avoiding costly trial-and-error interventions in the real network.

3.3 The solution definition

3.3.1 Bergamo pilot use cases as baseline for solution definition

1. **OHE/OCL condition monitoring. Identify and geolocate critical pantograph-OHE interaction points on the T1 route, assign health/risk status, and prioritise field inspections before faults escalate.**
2. **Pantograph interaction diagnostics. Use acceleration signatures, camera/video checks and GNSS/stationing to detect hard points, contact irregularities and component-specific problems affecting masts, clamps, section insulators, overlaps and crossings.**
3. **Energy and digital twin validation. Compare measured speed and energy profiles from regular passenger operation with EFS results, calibrate the simulation model and identify operating patterns that improve recuperation and reduce losses.**

The final solution is a digital twin and simulation-based optimisation tool for tram network power systems. By creating a digital model of the electric network and running Energy Flow Simulations, the system allows operators to analyse hundreds of operational scenarios and identify the most efficient configurations for energy use and braking energy recovery.

The solution is primarily used by energy management teams, infrastructure engineers, operational planners and asset managers. It supports data-driven decision-making for tram operations, energy management and infrastructure investment planning.

The solution enables transport operators to optimise energy flows, reduce energy waste and increase the reuse of recuperated braking energy. This improves the overall efficiency and sustainability of tram operations while supporting better planning decisions and reducing the environmental footprint of electric transport systems.

3.3.2 Circularity gaps identified and circularity principles applied

Several circularity gaps in tram network energy management were identified. Operators often had a limited understanding of how traction energy and regenerative braking energy flowed through the network, making it difficult to identify optimisation opportunities. The digital twin addresses this by providing a dynamic representation of the power system and enabling detailed analysis of energy flows. Another challenge was the inefficient reuse of regenerative braking energy, which is often lost due to operational constraints or network limitations. Through energy flow simulations, the system identifies operational configurations that maximise the use of recuperated energy and reduce losses. In addition, the absence of reliable modelling tools increased the risk of non-optimal operational or infrastructure decisions. The simulation environment therefore provides clear and reliable data to support evidence-based planning. Finally, testing operational improvements directly in the network could be disruptive and risky. The digital twin allows operators to test multiple scenarios virtually before implementing changes in real operations, improving efficiency and decision-making.

The pilot supports key circular economy principles by improving energy and resource efficiency in tram networks. By optimising energy flows, the solution increases the reuse of regenerative braking energy instead of allowing it to be dissipated as waste. The simulation approach helps identify operational configurations that reduce transmission losses and improve energy distribution. Through the digital twin, operators can optimise the performance of existing power infrastructure without requiring major new investments. This enables more efficient use of current assets and reduces unnecessary resource consumption. In addition, reliable simulation data supports more sustainable planning and informed infrastructure and operational decisions.

3.4. Implementation guidance

- Do: Keep data acquisition, edge processing and analytics modular, document interfaces, and ensure operator ownership of operational and asset data.
- Do: Validate AI-ranked hot spots through targeted field inspections and feed the inspection outcome back into the algorithm and dashboard thresholds.
- Do not: Rely on raw sensor streams alone. Replication requires object IDs, georeferencing/stationing, time stamps, data-quality flags, and a clear link between detected events and maintainable assets.
- Do not: Treat schedule delay alone as a sufficient energy indicator. The Bergamo analysis found no correlation between delay and energy consumption, while direction and schedule adherence were relevant factors.

- Do not: Deploy the EFS model without calibration against measured speed and energy profiles; the Bergamo validation showed that model accuracy improved materially only after adjustment to real service data.

4. The solution development

4.1 Technical and functional requirements

4.1.1. Infrastructure monitoring system

System architecture and hardware/ software requirements

The infrastructure monitoring system uses a modular onboard architecture installed on the tram roof/pantograph area. The reference configuration consists of GNSS/RTK positioning, acceleration and vibration sensors, camera/video acquisition, a rail-certified edge computing unit, a CAN data logger or equivalent vehicle-bus interface, a modem/communication unit, power supply and mounting hardware. The installed equipment referenced in the annexed presentation material includes GNSS RTK TRACElet, an embedded MEC computer, CAN data logger, camera, vibration sensor and OHE sensor package.

Data-related requirements

Required data sources are high-frequency acceleration and vibration signals from the roof/pantograph area, vehicle speed, GPS position, direction and traction-control-unit status, line voltage and current, consumed and returned energy per traction-control-unit, camera/video evidence and timestamped object/location references. In the Bergamo data collection phase, the Grafana dashboard recorded 7+ variables and refreshed operational data at high temporal resolution; the detailed sample day showed stop-and-go speed profiles, continuous route logging, traction states, line current peaks around 200 A and a typical operating voltage of around 800 V.

Analytics and functional requirements

The analytics layer must perform onboard preprocessing, filtering, event localisation, peak detection, pattern extraction and classification. The pilot methodology uses characteristic acceleration signatures to distinguish critical OHE elements and defects: section insulators typically generate sharp, high-amplitude vertical impulses lasting roughly 0.5-1 s; jumpers generate broader, lower-amplitude shocks; masts, overlaps and crossings tend to be more visible through video/geometric profiling. The user interface must provide geo-localised hot spots, health/risk categories, trend views, synchronised video/vibration evidence, inspection status and exportable records for maintenance and asset management.

Regulatory, safety and organisational requirements

All components mounted on operational vehicles must be mechanically secure, fire-safe, vibration-resistant and compatible with railway/tramway environmental requirements, including EN 50155 and EN 45545 where applicable. The system must not interfere with safety-critical vehicle functions. Cybersecurity, data ownership, anonymisation of operational/driver-related data, access rights and responsibilities for data validation must be agreed before roll-out. Operationally, the system requires a maintenance workflow that converts AI detections into inspection tickets, repair decisions and feedback to the analytics provider.

4.1.2. Energy flow simulations

System architecture and modelling requirements

The EFS solution is a calibrated digital twin of the tram traction power network. The model must represent substations, overhead contact systems, vehicle characteristics, timetables/service patterns, route gradients and operational speed profiles. The annexed journal text specifies a MATLAB/Simulink environment with SimPowerSystems modules as the modelling basis for representing substations, OCS, vehicles and timetables under different operational conditions.

Required input and validation data

The model requires measured speed profiles, vehicle energy consumption and recuperation, line voltage and current, position/stationing, direction, traction status, timetable data, power supply diagrams and OHE/substation parameters. In Bergamo, hundreds of measured rides and detailed vehicle time-series data were used to adjust the speed profile and calibrate the simulation. This reduced the error from 67.5% before validation (EFS 62.20 kWh versus measured 37.14 kWh) to 5.4% after validation (EFS 39.13 kWh versus measured 37.14 kWh).

Functional requirements for energy optimisation

The simulation tool must allow fast comparison of operational scenarios, calculation of optimal speed profiles, assessment of recuperated braking energy, identification of direction-dependent energy differences and evaluation of schedule adherence effects. The Bergamo analysis showed significant energy differences between Bergamo-Albino and Albino-Bergamo, no significant morning/afternoon difference, no correlation between schedule delay and energy consumption, and a significant impact of schedule adherence on energy use. The tool must therefore support planning teams in testing parameter settings virtually before changing real operations.

Outputs and integration requirements

Key outputs include energy per trip and per vehicle-km, best/worst trip comparison, recuperation potential, losses, voltage/current behaviour, sensitivity to timetable and driving profiles, and decision-ready recommendations for power supply or operational adjustments. Outputs should be exportable to energy management, asset management and planning workflows so that the simulation supports both short-term operational optimisation and long-term circular investment decisions.

Minimum reference configuration

- Rail/sector-grade hardware and edge computing installed on defined roof/pantograph mounting points; GNSS/RTK, acceleration/vibration, camera/video, CAN/vehicle-bus, modem and power-supply modules; resilient mobile communication; documented operator ownership of operational and asset data.
- Data model foundations. Every event requires timestamp, position/stationing, vehicle direction, speed, sensor channel, quality flag, asset/object reference, health score, inspection status and repair decision. These data fields make the dashboard actionable and allow future integration with GIS, asset management, SCADA and maintenance management systems.
- Functional UX. The user interface must show real-time and historical dashboards, geolocated detections along T1, health/risk categories, inspection queues, evidence views combining vibration and video, EFS comparison outputs and export functions for maintenance reports and management KPIs.

4.2 Solution implementation

A structured design-build-test methodology has been applied in the Bergamo pilot, organised into preparation, implementation, and evaluation phases.

4.2.1 Design and preparation phase (concept and system architecture)

The process began with an in-depth requirement analysis conducted jointly by ATB and KRUCH between April 2023 and early 2024. Several coordination meetings and on-site visits in Bergamo were organised to define operational constraints, infrastructure characteristics, and technical objectives. The core goal was to develop a modular, sensor-based monitoring system focused on the interaction between the pantograph and overhead contact line (OCL), a critical interface subject to mechanical stress, thermal load, and material wear.

A co-design workshop held at KRUCH's Vienna facility focused on mechanical integration at the pantograph, vibration resistance, cable routing, power supply concepts, GNSS positioning accuracy, cybersecurity requirements, and onboard edge-processing capabilities. The outcome included confirmation of the pilot scope, finalisation of sensor configurations, agreement on communication interfaces, and alignment on certification and compliance requirements under tramway regulations and relevant EN standards.

Parallel to the hardware design, KRUCH and ATB jointly defined the data architecture. This included the configuration of onboard edge-computers for real-time preprocessing (filtering, event detection, compression), secure data transmission protocols, and backend storage and analytics structures. In addition, KRUCH—together with its supplier KRUCH SIDOS—developed a digital twin of Bergamo's T1 line using MATLAB, SIMULINK, and SIMPOWERSYSTEMS, based on detailed route data, substation diagrams, OCL layouts, and vehicle parameters. This simulation environment enabled comparison between measured operational data and pre-modelled Energy Flow Simulation (EFS) scenarios.

A comprehensive feasibility study was conducted, covering technical durability (vibration, electromagnetic compatibility), mechanical integration within limited roof space, operational non-disruption, financial compliance with the CE4CE framework, and modular replication potential. Regulatory approvals and documentation were prepared to ensure compliance with safety, fire resistance, and occupational standards (ISO 9001, 14001, 45001, 50001).

4.2.2 Build phase (procurement, assembly, and pre-testing)

During Q3-Q4 2024, KRUCH led the procurement and assembly of all technical components. These included GNSS modules, acceleration and vibration sensors, camera systems, power supply units, onboard edge-computers, CAN-bus interfaces, and communication modules. Instead of performing installation preparation directly in Bergamo, all units were preassembled and fully functionally tested at KRUCH's Vienna workshop. This approach ensured quality control, minimised on-site intervention time, and reduced operational downtime at ATB.

The modular test units underwent laboratory validation, including sensor calibration, data synchronisation tests, signal stability checks, and initial algorithm verification. The digital twin model was finalised in parallel to prepare for validation against real-world measurements.

4.2.3 Implementation phase (installation, calibration, and live testing)

In Q4 2024 and early 2025, the preassembled sensor units were transported to Bergamo and installed on tram vehicle #004. Mechanical mounting was designed to avoid permanent structural modifications. The installation primarily targeted the pantograph area and associated roof components.

Following installation, the system entered the testing and commissioning stage. Calibration procedures included static and dynamic validation of acceleration sensors, time synchronisation across modules, verification of GNSS positioning in dense urban environments, optimisation of camera alignment, and stabilisation of power supply connections. The onboard edge-computer was configured to preprocess data streams before secure transmission to backend systems.

Real-time data collection began during regular passenger operation, eliminating the need for additional monitoring vehicles or test runs. Continuous data streams were analysed using custom-developed algorithms to detect anomalies, wear patterns, and infrastructure irregularities. Measurement data were systematically compared to prior EFS simulations to validate consistency between modelled and actual system behaviour.

Implementation was supported by regular coordination meetings, structured on-site visits, and real-time troubleshooting sessions. KRUCH supervised software deployment and analytics tuning, while ATB provided operational integration, vehicle access, and infrastructure expertise. Subcontractors—including KRUCH SIDOS, PANTOhealth, and CI4RAIL—contributed to simulation modelling, analytics refinement, and system validation.

4.2.4 Evaluation and operational launch

The operational launch followed a gradual, supervised rollout. ATB maintenance and infrastructure staff received targeted training on system handling, data interpretation, and workflow integration to ensure that the new monitoring system complemented existing maintenance practices. During the first operational weeks, sensor performance, data transmission stability, and environmental robustness were closely monitored.

The evaluation phase focused on assessing predictive maintenance potential, early fault detection capability, data reliability, and alignment with circular economy objectives. Analytical results were documented and reviewed jointly by both partners. Particular attention was given to detecting early-stage infrastructure degradation and assessing how condition-based insights could support longer component lifetimes and reduced material consumption.

Finally, scalability and replication potential were assessed. The modular design, preassembly strategy, digital twin integration, and structured stakeholder involvement demonstrated that the system can be transferred to other tram and metro networks with overhead electrification. The pilot thus established a technically validated, operationally integrated foundation for predictive, circular asset management in public transport infrastructure.

4.2.5 Step-by-Step roll-in

1. Design & requirements. Confirm the pilot corridor, maintainable assets, data access points, safety constraints, KPI set and acceptance criteria with operations, maintenance, IT/data and energy-management teams.

2. Procurement strategy. Keep sensor/edge hardware, communications and analytics services modular; define CAN/vehicle-bus, GIS/asset-management and dashboard interfaces; clarify data ownership and cybersecurity requirements.
3. Phased installation. Start with GNSS, vibration/acceleration and edge computing; add camera/video and vehicle-bus energy data once mechanical mounting, power supply and communication stability are proven.
4. Calibration & validation. Commission the system during passenger service, compare AI detections with field inspections, and calibrate the EFS model against measured speed and energy profiles before using it for operational decisions.
5. Co-design & routines. Maintain regular ATB/KRUCH review meetings, action lists and a structured backlog for dashboard, threshold and algorithm refinements; ensure that inspection feedback is systematically returned to the analytics workflow.

4.3 Operational use, performance and maintenance

Following its operational launch in early 2025, the system has been running in continuous monitoring mode under real passenger service conditions, using tram #004 as a mobile sensing platform. The installed sensor suite—GNSS modules, acceleration and vibration sensors, high-resolution cameras, CAN-bus interfaces, onboard edge-computers, and communication units—operates autonomously during daily service without interfering with vehicle control systems. Data sets are transmitted every 1–3 seconds, enabling near real-time monitoring of pantograph-overhead contact line (OCL) interaction, vehicle dynamics, driver inputs, speed, and energy consumption. Edge devices perform initial filtering, signal validation, and event detection before secure transmission to backend systems, where AI-supported algorithms analyse vibration signatures, contact irregularities, and mechanical anomalies. The system remains stable under varying environmental conditions (temperature, humidity, urban GNSS shadowing), with only minor signal interruptions observed and resolved through calibration and configuration refinement.

Performance evaluation focuses on several key performance indicators (KPIs): signal availability and stability rate, GNSS positional accuracy, anomaly detection sensitivity, correlation between vibration peaks and visual confirmation, false-positive rate of automated alerts, and consistency between measured data and Energy Flow Simulation (EFS) outputs from the digital twin. Identified “points of interest” along the line are ranked in an online dashboard according to health status, allowing infrastructure teams to review exact positions, time-stamped vibration curves, and synchronised video feeds. Preliminary results show a high detection sensitivity for contact irregularities and mechanical disturbances, while false positives—mainly triggered by temporary track geometry effects or external vibrations—are systematically reviewed with ATB’s technical staff to continuously improve algorithm thresholds. The comparison between real-world measurements and simulated load scenarios further validates model assumptions and enhances predictive accuracy.

Maintenance activities are increasingly aligned with the system’s outputs. Instead of relying solely on fixed inspection intervals, ATB integrates system-generated alerts and ranked risk locations into its routine inspection planning. When the dashboard indicates elevated vibration levels or irregular pantograph movement at specific coordinates, targeted field inspections are scheduled, allowing early-stage defects to be verified and addressed before escalation. Traditional visual inspections and preventive maintenance schedules remain in place but are gradually complemented by condition-based triggers derived from sensor analytics. This hybrid approach strengthens reliability while maintaining regulatory compliance. Over time, accumulated data supports refinement of maintenance intervals, optimisation of component replacement timing, and prioritisation of critical OCL segments.

From an operational perspective, the system has proven compatible with daily service. Drivers are not required to modify behaviour, and maintenance staff access processed insights through a user-friendly web interface rather than raw data streams. ATB personnel report that the ranked health-status list and visualisation tools significantly improve transparency and decision-making confidence. Regular coordination meetings between KRUCH and ATB created a structured feedback loop in which anomalies are jointly assessed, detection logic is refined, and practical maintenance implications are discussed. This collaborative evaluation process not only stabilises technical performance but also builds institutional capacity for predictive, data-driven asset management.

Beyond mechanical monitoring, the continuous energy data collection enables comparison between operational driving patterns and digital twin simulations. By analysing energy flows, acceleration behaviour, and infrastructure loading scenarios, the system generates additional insights into efficiency improvements and circularity potential. The monitoring and evaluation phase therefore serves both as a technical validation of detection quality and as a strategic learning platform for integrating predictive maintenance into ATB's broader asset management framework, with clear potential for scaling to additional vehicles and lines.

Operational evidence from the 2025 monitoring phase

The annexed data collection report records an analysis period from April to October 2025. Vehicle data were analysed for approximately 100 trips, including rides on 8, 16 and 24 April 2025, with maximum speeds around 65 km/h on T1. A detailed Grafana extraction for MC1-CE4CEBergamo on 4 September 2025 (07:28-16:19) documented speed profiles, acceleration RMS, total energy drives, traction status, line current and line voltage across the vehicle systems.

For OHE monitoring, the dashboard identified 10 measurement points on the Bergamo-Albino route: 8 were classified as "Unhealthy" (risk 31-59%) and 2 as "At Risk" (risk above 60%, requiring immediate inspection). Five inspections had already been completed and five items were marked "Need to Repair". The affected component distribution was dominated by masts/towers (5 points, 50%), followed by clamps (2 points, 20%), and one point each for a section insulator, overlap and crossing. The most affected areas listed in the data collection annex were Ranica, Nembro, Albino and Bergamo.

For energy performance, the EFS validation showed that calibration against real speed profiles and energy data is essential. After validation, the EFS error fell to 5.4%. The energy study also identified a highest-consumption case of 42.93 kWh without recuperation, a measured mean of 37.14 kWh, a lowest case of 25.35 kWh with recuperation, and an energy spread of up to 62.6% between worst and best trips. These results make the pilot actionable for both maintenance prioritisation and operational energy optimisation.

Operating procedures and KPIs

- Workflow. AI/event detection -> geolocated hot spot and health score -> dashboard review by ATB/KRUCH -> targeted field inspection -> repair/no-repair decision -> update maintenance record -> feedback to analytics and EFS calibration.
- KPI core set. Data refresh/availability, GNSS and stationing accuracy, number of AI-identified OHE points by health status, at-risk share, inspection completion rate, repair conversion rate, false-positive rate, detection-to-action time, EFS validation error, energy per trip/vehicle-km, recuperated energy share, best/worst energy spread, avoided emergency repairs and estimated component lifetime gain.

5. Integration and transferability aspects

The modular monitoring solution developed in the CE4CE pilot project in Bergamo is designed to integrate smoothly with existing public transport (PT) infrastructure, digital systems, and operational processes. It was implemented within the ATB Bergamo environment while ensuring compatibility with common systems used across European urban transport networks.

Integration into PT systems

The monitoring solution connects with key PT systems such as depots, SCADA platforms, Geographic Information Systems (GIS), and Asset Management (AM) systems. Sensors installed on tram vehicles collect infrastructure condition data using GNSS positioning, acceleration sensors, and onboard edge computing. These data streams can be transmitted through standard communication modules and integrated into monitoring platforms used to supervise traction power, signalling, and infrastructure performance.

In depot environments, the system supports maintenance planning by providing condition-based data that can feed asset management systems, enabling a shift from reactive to predictive maintenance. Integration with GIS platforms allows infrastructure conditions to be visualised geographically, helping operators identify critical locations. Because the system uses rail-compatible hardware and standard interfaces such as CAN-bus, it can connect to existing vehicle diagnostic systems with minimal modifications.

Interface requirements and compatibility

The solution relies on standard hardware and communication interfaces to ensure interoperability. Sensor units include GNSS receivers, acceleration sensors, and onboard edge computers connected via CAN-bus and other vehicle communication protocols. Data can be transmitted through mobile networks or internal operator data platforms. Compatibility with existing IT environments is supported through modular software architecture and open data formats. This enables integration with operator databases, asset management tools, and digital monitoring platforms without requiring proprietary interfaces. The modular design also allows system components—such as sensors or communication modules—to be adapted to different operator standards.

Preconditions for replication in other contexts

Replication requires several basic conditions. Vehicles must provide access to power supply and communication interfaces for sensor installation. Operators should also have basic digital infrastructure capable of receiving and analysing monitoring data, as well as organisational coordination between operations, maintenance, and IT teams. Compliance with rail safety standards and vehicle certification procedures is also necessary. Since the Bergamo system was designed in line with established norms and operational practices, only limited adaptation is expected for deployment in other European networks.

Technical, regulatory, and organisational transferability

The solution is technically transferable due to its modular hardware architecture, widely used sensor technologies, and compatibility with standard vehicle communication systems. This allows installation on different vehicle types, including trams, regional rail vehicles, trolleybuses, or potentially electric buses.

Regulatory transferability is supported by the use of certified rail-compatible components and compliance with European safety and communication standards. Organisationally, the system aligns with common PT maintenance processes, helping operators address ageing infrastructure, improve service reliability, and optimise maintenance planning.

Readiness Checklists

- Technical. Vehicle data access (CAN/TCMS or equivalent) enabled; stable onboard power supply; certified mechanical mounting; camera/vibration/GNSS alignment checked; communication coverage validated on the corridor.
- Data. Object IDs, stationing and georeferencing available; timestamp synchronisation verified; metadata and quality flags documented; EFS input data, speed profiles and energy measurements validated.
- Organisation. RACI agreed between operations, maintenance, IT/data and suppliers; inspection workflow defined; dashboard training completed; regular review routines and feedback loops established.

6. Challenges and lessons learned

During the Bergamo pilot, several technical, regulatory, organisational, and human-factor challenges were identified, providing valuable lessons for future deployment.

Technical challenges mainly concerned data quality and hardware performance in real operating conditions. Urban environments caused intermittent GNSS signal loss and complex vibration patterns, while early testing revealed issues such as camera alignment, voltage stability, and occasional false positives in vibration-based anomaly detection. These issues were addressed through sensor recalibration, improved signal filtering, and iterative refinement of detection algorithms supported by comparisons with Energy Flow Simulation (EFS) results and the digital twin model.

Regulatory constraints required careful documentation and compliance with tramway safety standards. Although the system did not interfere with safety-critical components, installation near the pantograph required verification of mechanical safety, fire resistance, and alignment with relevant EN standards. Close coordination with ATB’s technical teams ensured that approvals were obtained without affecting vehicle certification.

Organisational and human-factor challenges related mainly to integrating the new monitoring system into existing maintenance workflows. Staff initially required training to interpret sensor-based data and integrate it into inspection routines. This was mitigated through training sessions, regular coordination meetings, and the development of user-friendly dashboards that translate raw data into actionable insights.

Key lessons learned include the importance of pre-testing hardware, iterative algorithm refinement under real conditions, and early involvement of operators and maintenance teams to ensure user acceptance and smooth operational integration.

Specific lessons from the annexed Bergamo data

Model accuracy depends on measured operational data. The first EFS comparison overestimated energy use substantially; only after measured speed profiles from real service were incorporated did the validation error fall to 5.4%. For future deployments, simulation work should begin with a clear data-quality plan and a sufficient sample of trips across directions and operating conditions.

AI detections are most useful when they become maintenance decisions. The OHE monitoring dashboard produced actionable rankings, but the pilot also showed that automated health status must be paired with field inspection, repair/no-repair classification and feedback to the algorithm. This is why the workflow must include a structured “detection -> inspection -> repair decision -> feedback” loop.

Energy optimisation requires attention to operational behaviour rather than simple assumptions. In Bergamo, direction and schedule adherence were relevant for consumption, while time of day and schedule delay alone were not significant explanatory factors. This is important for operators because it shifts optimisation from generic timetable compliance towards evidence-based driving profiles and energy-aware operational planning.

Sensor fusion is needed for robust localisation and diagnosis. Acceleration is strong for high-impact pantograph/OHE events, while video and geometry profiling are important for spatially regular components. GNSS shadowing and timing errors can occur in urban networks, so event localisation should combine time stamps, stationing, vibration signatures and visual evidence.

Change-Management Patterns

- Early, continuous co-design with asset management, infrastructure maintenance, rolling-stock maintenance, operations and IT/data teams increases adoption and shortens learning cycles.
- Secure the vehicle data path early; direct vehicle-bus or traction-control-unit data are needed for reliable speed, energy, current and voltage analysis.
- Contractually separate hardware/data capture from analytics services where possible, while keeping interface, cybersecurity, data ownership and IP clauses clear.

7. Expected change

The solution is expected to generate significant operational improvements and long-term benefits for public transport infrastructure management. By introducing continuous monitoring and predictive analytics, maintenance activities can shift from reactive interventions to condition-based planning, reducing unexpected failures and improving service reliability. This enables operators to prioritise maintenance resources more efficiently, lowering operational costs associated with emergency repairs, service disruptions, and unnecessary inspection runs. Over time, the early detection of wear in the pantograph-overhead contact line interface will extend the useful lifetime of critical infrastructure components and rolling stock parts, reducing the frequency of replacements and optimising the use of high-value materials such as copper and carbon.

Environmental benefits are also expected, as more precise maintenance planning reduces material consumption, avoids premature component replacement, and lowers the demand for resource-intensive infrastructure renewals. The system further contributes to energy efficiency by analysing real operational behaviour and supporting optimisation through comparison with digital twin simulations. In addition, because monitoring is performed using trams in normal passenger service, no additional inspection vehicles, journeys, or energy consumption are required, resulting in lower overall CO_2 emissions.

For operators and maintenance staff, the system introduces new digital tools that improve decision-making through data visualisation, geographic mapping of infrastructure conditions, and integration with asset management systems. This enhances transparency, supports long-term infrastructure planning, and strengthens collaboration between operations, maintenance, and IT teams. Passengers benefit indirectly through more reliable services, fewer disruptions caused by infrastructure failures, and improved overall network performance. In the long term, the modular and interoperable architecture of the solution allows replication across other tram and rail networks, contributing to more sustainable, resilient, and circular public transport systems across Europe.

Quantified expected changes based on pilot evidence

For infrastructure management, the immediate change is a move from dispersed visual inspection evidence to a ranked digital view of OHE health. The Bergamo assessment showed that most of the T1 line has a remaining service life above 30 years, while a smaller set of critical points needs closer attention. This enables ATB/TEB to concentrate inspections and repairs on the locations that matter most, avoiding both premature large-scale renewal and late intervention after damage has propagated.

For energy management, the change is the ability to quantify and simulate the effect of operating patterns. The validated EFS model can calculate optimal speed profiles, evaluate schedule adherence and identify potential savings. The observed 62.6% spread between worst and best trips demonstrates that operational behaviour and recuperation strategy can materially influence energy use.

Before / After

Before: Visual or time-based inspection limited continuous visibility of pantograph-OHE interaction, simulation models with insufficient real-service calibration, and energy decisions based mainly on aggregate consumption data.

After: Continuous vehicle-based monitoring, AI-ranked OHE health points, targeted inspections and repair decisions, calibrated EFS with 5.4% validation error, and operational energy planning based on measured speed/energy profiles and scenario comparison.

8. Sustainability, transferability and replicability

The solution demonstrates strong environmental, economic, and organisational sustainability while offering high potential for replication in other public transport networks.

Environmentally, predictive monitoring enables earlier detection of infrastructure wear, extending the lifetime of components such as copper contact wires and carbon pantograph strips. This reduces material consumption, waste generation, and the need for resource-intensive infrastructure renewals. Because monitoring is performed using trams in regular passenger service, no additional inspection vehicles or energy-consuming test runs are required, further reducing CO_2 emissions.

Economically, the system supports a shift from reactive to condition-based maintenance, lowering costs related to emergency repairs, service disruptions, and unnecessary component replacement. The modular hardware approach keeps investment costs manageable, while automated monitoring and data analysis help reduce operational costs over time.

Organisationally, the system improves coordination between operations, maintenance, and IT teams by integrating monitoring data into asset management, GIS, and other existing transport systems.

Due to its modular design and use of standard sensors and communication interfaces, the solution can be replicated in other tram or electrified transport networks with limited adaptation. The presentation materials stress that the approach is open, scalable and transferable: modular hardware, edge software and backend systems can be combined with CAN-bus or MVB-bus interfaces; use cases can be added over time; installation can be adapted to trains, trams, metro vehicles and trolleybuses; and AI algorithms can be retrained for local infrastructure signatures. Next steps include presenting the quantified pilot results, demonstrating operational benefits to decision-makers, and supporting integration into long-term infrastructure management and energy strategies.

Replication conditions and business model considerations

Replication is most attractive where operators manage overhead electrification, ageing or high-value OHE assets, rising energy costs and limited resources for dedicated inspection runs. The business model can combine a moderate one-off investment in onboard hardware and integration with recurring analytics, dashboard support and model-maintenance services. The economic case should capture avoided emergency repairs, reduced disruption costs, better timing of replacements, reduced energy use and the value of extending the useful life of copper, carbon and other high-impact materials.

Maturity path for replication:

1. **Reactive/time-based maintenance**
2. **Condition-based monitoring on one line/vehicle**
3. **Predictive maintenance with validated AI detections and field feedback**
4. **Optimised/circular operation combining asset-health trends, EFS-based energy optimisation and lifecycle planning.**
5. **Step-up criteria are data quality and uptime, inspection feedback rate, KPI trend improvements, process maturity, role competence and management commitment.**

9. Conclusions

The Bergamo pilot successfully demonstrated a modular, sensor-based monitoring solution that enables continuous, real-time assessment of the interaction between tram pantographs and the overhead contact line during normal passenger operation. By combining onboard sensors, edge computing, and data analytics, the system proved capable of detecting infrastructure irregularities, supporting predictive maintenance, and integrating with existing asset management and monitoring platforms.

The pilot contributes directly to the CE4CE objectives by promoting circular infrastructure management: extending asset lifetimes, reducing material waste, and lowering energy use by eliminating dedicated inspection runs. It also established a practical framework for data-driven maintenance, strengthened collaboration between operators and technology providers, and validated the solution’s technical feasibility and scalability. Overall, the pilot provides a transferable model for more sustainable, efficient, and resilient public transport infrastructure management across European networks.

The annexed evidence strengthens this conclusion with quantified pilot results: approximately 100 analysed trips, high-frequency operational variables, 10 AI-identified OHE measurement points, 5 inspection outcomes requiring repair, a validated EFS model with 5.4% residual error, and a potential energy spread of up to 62.6% between worst and best trips. These results demonstrate that AI monitoring and digital twins are not only conceptual tools but practical enablers of circular public transport management.

Roll-out recommendations

Scale deliberately after validation: start with additional T1 vehicles or selected high-risk OHE segments, connect the dashboard to asset-management/GIS workflows, maintain annual KPI and algorithm reviews, refresh staff training, and use the calibrated EFS model to compare operational and investment scenarios before committing to physical infrastructure changes.