

RESEARCH

Open Access



Public transport digitalization: leveraging AI and Digital Twins for smarter urban mobility management

Jan Röhl^{1*}, Conrad Jentzsch^{2*} and Marta Woronowicz^{3*}

Abstract

Urban transport systems face mounting pressures from climate change, rising energy prices, and ageing assets. Meeting these challenges sustainably requires extending the useful life of infrastructure, improving energy efficiency, and reducing waste across the whole lifecycle. Circular economy principles offer a systemic approach: design for longevity, maintainability, and reuse, while favouring interventions that avoid resource-intensive renewals. Digitalisation is a key enabler of this shift, as Artificial Intelligence-assisted analytics, edge sensing, and Digital Twins make hidden conditions visible and reduce diagnostic costs. This paper presents three European pilot cases from the Interreg CE4CE project to demonstrate these capabilities. In Leipzig, a layered infrastructure monitoring system enabled the detection of eight critical overhead line faults and three previously undetected broken rails during regular passenger service. In Bergamo, high-frequency onboard sensing and Energy Flow Simulations optimized energy recuperation and identified pantograph-infrastructure “hot spots.” In Gdynia, a Digital Twin environment was used to simulate over 110 electrification scenarios, optimizing fleet size and infrastructure investment needs. The results confirm that integrating digital monitoring and simulation tools into public transport operations facilitates a shift from reactive to predictive management, directly supporting resource efficiency, asset longevity, and the transition toward a circular urban mobility system.

Keywords Circular economy, Artificial Intelligence, Digital Twin, Predictive maintenance, Public transport, Infrastructure monitoring, Energy efficiency

This paper is based on the technical documentation and empirical pilot results of the Interreg CE4CE project. Generative AI tool (Gemini) was used solely for linguistic refinement and structural optimization of the manuscript, while all scientific data, analysis, and conclusions were derived from the project's original research

*Correspondence:

Jan Röhl

jan.roehl@kruch.at

Conrad Jentzsch

conrad.jentzsch@l.de

Marta Woronowicz

woronowicz@trolley-motion.eu

¹Kruch Railway Innovations, Vienna, Austria

²Leipziger Verkehrsbetriebe, Leipzig, Germany

³trolley-motion, Koppl, Austria

1 Introduction

Urban transport systems are under increasing pressure from intersecting global and local challenges. Climate change, environmental degradation, aging infrastructure and fleet, increasing energy costs and rapid urbanization demand urgent transformation of how mobility is designed, delivered, and maintained. As cities aim to decarbonize, reduce resource dependency, and improve service resilience, traditional models of infrastructure and fleet development and management are proving inadequate. The integration of circular economy principles presents a promising paradigm shift—one that

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

redefines value creation, extends asset lifecycles, and minimizes waste across the transport sector.

However, realizing circularity at scale requires more than policy commitments or technological fixes; it demands a system-wide reconfiguration of decision-making processes, business models, and governance structures. This is where digital innovation becomes essential. Tools such as Artificial Intelligence (AI), Big Data analytics, the use of sensors and Digital Twins can unlock unprecedented insights into the material, energy, and financial flows within complex urban mobility systems. These technologies offer the ability to model circular scenarios, forecast the impact of reuse and refurbishment strategies, and optimize infrastructure and fleet operations with circular goals in mind.

Digital Twins offer significant potential for transport planning by creating virtual replicas of physical assets to simulate operational scenarios. While recent literature highlights the role of digital twin technology and artificial intelligence in broader energy systems and the transition toward resource efficiency [1], as well as their specific systematic applications in tracking and optimizing electric vehicle architectures [9], their practical integration into circular economy frameworks for public transit infrastructure remains underdeveloped.

The Interreg Central Europe-funded CE4CE project (Public Transport Infrastructure in Central Europe – facilitate transitioning to circular economy) tackles this systemic opportunity head-on. As outlined by Scharzenberger et al., [8], the initiative explores how digitalization can actively support and accelerate the adoption of circular strategies in collective transport and urban development. CE4CE brings together a consortium of researchers, cities, and public transport operators to bridge the gap between circular economy ambitions and their practical implementation.

CE4CE pilots demonstrate how the synergies between circular economy and digital tools can contribute to broader policy goals such as the European Green Deal. By aligning innovation with sustainability and equity principles, the project fosters a holistic approach to public transport transition—one that is economically viable and environmentally regenerative.

Despite the growing interest in circular economy and digitalization in urban transport, existing literature heavily favors theoretical frameworks or isolated technical solutions, leaving a significant research gap in understanding how these innovations can be systematically integrated into public transport planning, management, and decision-making across European contexts. While studies have explored predictive maintenance (e.g., Caggiano et al., 2021), Digital Twins for infrastructure optimization (Batty et al., 2020), and circularity in transport resources (Lieder & Rashid, 2016), they often overlook

the institutional and operational challenges of implementing predictive tools within legacy systems. Furthermore, there is a distinct lack of empirical, multi-case comparative evidence linking high-frequency sensor data and simulation-based decision support directly to measurable circular economy outcomes, such as asset lifetime extension, avoided material use, and energy savings. This paper directly addresses these gaps by evaluating three diverse European pilot cases, providing concrete empirical evidence on the scalability and transferability of digital-circular synergies within the real-world operational environment of public transit.

Three pilot cities – Gdynia (Poland), Bergamo (Italy), and Leipzig (Germany) – showcase practical applications of AI, Big Data analysis, predictive maintenance, and Digital Twins to enhance public transport in line with circular economy goals. The pilots in Bergamo and Leipzig are facing a similar challenge, i.e. failures in overhead contact line (OCL) systems account for an estimated 20–30% of traction system disruptions, highlighting the critical importance of timely maintenance and monitoring in rail-based public transport systems.

Bergamo's tram system uses AI-driven predictive maintenance with sensors collecting data from vehicles and infrastructure to detect faults early, extend asset lifespan, and reduce manual checks. A Digital Twin also helps optimize energy flows and minimize energy losses, improving resource efficiency and network performance.

In Leipzig, predictive maintenance is implemented on tram catenary infrastructure. Sensors monitor key assets with AI algorithms and expert evaluation supporting early fault detection and infrastructure management. A damage catalogue and standardized methods enhance transferability and risk management.

Transitioning from reactive to condition-based frameworks allows public transit operators to optimize asset lifecycles and significantly reduce component waste. As highlighted in recent systematic literature reviews on transportation systems, predictive maintenance strategies are increasingly critical for operational sustainability, enabling early fault detection and mitigating the risks of catastrophic infrastructure failures [6].

In Gdynia, a Digital Twin simulates electrification scenarios along an e-corridor using real-time data from electric buses and In Motion Charging (IMC) trolleybuses, which partially run off-wire on batteries. Developed by Kruch Railway Innovations, the University of Gdansk, and a municipal bus operator in Gdynia, it supports data-driven planning and cost-benefit analysis for electrified transport and is being shaped into a transferable circular business planning tool.

These pilots demonstrate how advanced digital tools can improve efficiency, safety, resilience, and

sustainability in public transport while fostering cross-sector collaboration and circular resource use.

This study based on the presented pilots is essential to provide a structured analysis of how digital tools support circular strategies in public transport, to evaluate their impact on resource efficiency, asset lifespan, and operational resilience, and to generate insights transferable to other European cities seeking similar transitions.

Building on this rationale, the study aims to answer the following research questions:

- How can digital innovations such as AI, Big Data, and Digital Twins facilitate circular economy strategies in public transport systems?
- What measurable impacts do these tools have on infrastructure lifespan, energy efficiency, and resource use in urban transport?
- How transferable are the lessons learned from the examined European pilot cities to other contexts aiming for circular and sustainable urban mobility?

The contribution of this paper is threefold:

- It synthesizes the current evidence on circular economy and digitalization in public transport, highlighting gaps in knowledge.
- It provides empirical insights from European case studies demonstrating the practical integration of circular and digital strategies.
- It offers policy and managerial recommendations for cities and operators to optimize public transport operations while advancing sustainability and circularity.

While existing literature independently addresses predictive maintenance or isolated Digital Twin applications, this paper provides a novel, integrated contribution by establishing a cross-sectoral, dimension-based analytical framework that systematically links high-fidelity digital infrastructure monitoring with specific circular economy (CE) mechanisms. Moving beyond isolated technical descriptions, the scientific novelty lies in operationalizing how continuous, vehicle-based data streaming and multi-scenario simulations actively transition public transit legacy assets from a linear ‘take-use-throw’ model into a predictive, closed-loop resource management system. This integration directly aligns with recent theoretical frameworks demonstrating how digital twin architectures within the circular economy provide a scalable methodology to optimize resource loops and extend component useful lifecycles [7]. The core academic contribution is the development and validation of this transferable comparative framework, evaluating how distinct digital architectures—ranging from edge-computed

vibration analytics to energy-flow twins—directly drive asset lifetime extension, reduce material demand, and avoid infrastructure over-dimensioning.

Overall, this study is highly relevant for European cities pursuing circular economy transitions in public transport, providing both theoretical insights and practical implications for improving transport system efficiency, resilience, and environmental performance.

2 Methods

To bridge the gap between project-based outcomes and scalable transport theory, this study adopts a comparative multi-case study design, combining field-deployment observational pilots and simulation-based modelling. Rather than relying on uniform, case-specific KPIs that prevent cross-system comparison, we develop a multi-dimensional analytical framework that abstracts operational telemetry into four universal, lifecycle-oriented dimensions:

- Asset condition and lifetime extension.
- Energy performance and efficiency.
- Operational and maintenance optimisation.
- Resource use and investment efficiency.

This methodology allows us to systematically evaluate and compare entirely different technical solutions—ranging from physical track vibration sensing in Germany to virtual fleet simulations in Poland—demonstrating the underlying causal mechanisms through which digital twins and AI analytics operationalize circular economic strategies.

The four evaluation dimensions were systematically derived from the CE4CE project’s joint evaluation methodology, developed through cross-sectoral expert consensus among the participating transport operators and researchers. As the three pilots deploy highly diverse technical solutions—ranging from physical track vibration sensing to virtual fleet simulations - these specific dimensions were established as a standardized lifecycle framework to normalize the outcomes. The selected dimensions directly reflect the project’s core operational objectives: measuring infrastructure longevity, evaluating energy performance under traffic conditions, streamlining maintenance workflows, and assessing long-term investment efficiency.

The mapping of evaluation dimensions and pilot-specific indicators across the three cases is summarised in Table 1.

While specific indicators differ between pilots (e.g. fault detection metrics, energy monitoring data, or simulation outputs), they are mapped to these common dimensions, enabling structured cross-case comparison.

Table 1 Mapping of evaluation dimensions and pilot-specific indicators

Evaluation dimension	Leipzig (monitoring)	Bergamo (monitoring + simulation)	Gdynia (simulation)
Asset condition & lifetime	Detected track faults, OCL defects, broken rails + 1	Detected anomalies ("hot spots"), pantograph–OCL interaction + 2	Indirect (impact of infrastructure design on wear) + 2
Energy performance	CAN-bus energy data (vehicle level) + 1	Continuous energy monitoring (1–3 s resolution), simulation outputs + 1	Energy consumption (kWh/km), state-of-charge, system-level optimisation + 2
Operational & maintenance optimisation	Maintenance prioritisation, validation loops + 1	Predictive diagnostics, anomaly ranking + 1	Fleet size optimisation, electrification scenarios, service configuration + 1
Resource use & investment efficiency	Reduced emergency interventions + 1	Reduced wear and improved maintenance targeting + 1	Infrastructure investment needs, lifecycle costs + 1

Note: The notation + 1 and + 2 in Table 1 indicates the complexity and layering of digital data streams deployed within each dimension. A + 1 denotes a single-layer automated data source (e.g., direct CAN-bus reading, raw sensor streams, or automated anomaly ranking), while + 2 indicates multi-layered data integration where high-frequency edge telemetry is fused with predictive Digital Twin simulation environments or complex spatial matrices to cross-verify and map the results

This flexible comparative approach enables identification of common patterns and impacts, while preserving the specificity of each pilot.

Pilot 1: Bergamo – Onboard sensing and energy flow simulation.

The Bergamo pilot follows a field-deployment observational design combined with simulation-based analysis, focusing on predictive maintenance and energy optimisation in tram operations managed by Azienda Trasporti Bergamo (ATB).

2.1 Data collection and system configuration

A tram vehicle (vehicle #004) operating on the T1 line was equipped with a modular sensing system, including Global Navigation Satellite System (GNSS) modules, accelerometers, cameras, a rail-certified edge computing unit, a CAN-bus interface, and a communication modem. The system enables continuous monitoring of pantograph – OCL interaction and vehicle dynamics during regular passenger service.

Operational data—including position, speed, acceleration, driver inputs, and energy consumption—were

collected and transmitted at high temporal resolution, with updates every 1–3 s. Onboard preprocessing was applied to filter and structure the data prior to transmission.

2.2 Simulation and modelling

A Digital Twin of the tram power supply network was developed using MATLAB® and Simulink® (MathWorks Inc., USA) with SimPowerSystems™ modules. The model represents substations, overhead contact systems, vehicles, and timetables, allowing simulation of energy flows under different operational conditions.

The simulation environment enables testing of parameter configurations to optimise energy recuperation and reduce conversion losses, supporting comparison between real-world measurements and simulated scenarios.

2.3 Data analysis

Data analysis combines descriptive statistics with AI-assisted anomaly detection, identifying irregular patterns in pantograph–OCL interaction and vehicle behaviour. Detected anomalies ("hot spots") are spatially referenced and ranked based on severity.

Results were iteratively validated through collaboration with ATB experts, forming a feedback loop that supports both technical refinement and operational interpretation.

Pilot 2: Leipzig – Layered condition monitoring of infrastructure.

The Leipzig pilot applies a field-deployment observational design to evaluate a layered onboard monitoring architecture for infrastructure condition assessment and energy analysis. The pilot was conducted on three tram vehicles operating on a 14 km section of Line 1.

2.4 Data collection and system configuration

The monitoring system integrates multiple sensing technologies, including:

- vibration sensors for track and trackbed condition,
- cameras and laser systems for overhead line geometry,
- a rail-certified edge computing platform for data fusion and transmission.

All components comply with relevant railway standards (EN 50155, EN 45545).

Data were continuously collected during passenger service and transmitted to analytical platforms. Specialised systems were used for analysis:

- CEMIT for track condition monitoring,

- PantoHealth for pantograph–overhead line interaction.

Energy data were obtained via a direct CAN-bus interface, improving data reliability compared to legacy systems.

2.5 Data analysis

The analysis combines signal processing, pattern recognition, and AI-based detection methods. Acceleration signals are used to identify characteristic patterns associated with infrastructure elements (e.g. section insulators, jumpers), based on their dynamic signatures.

The detection process includes event localisation, peak detection, pattern extraction, and classification. Results are validated through weekly expert review meetings, enabling prioritisation of maintenance interventions and refinement of detection algorithms.

Pilot 3: Gdynia – Digital Twin for electrification planning.

The Gdynia pilot follows a simulation-based modelling and validation design, focusing on the use of a Digital Twin to support electrification planning and resource-efficient investment decisions. Building upon the long-term sustainable development frameworks established for the Gdynia and Sopot trolleybus network by Wołek et al., [10], this study was conducted by public bus operator in Gdynia (PKA) in cooperation with the University of Gdańsk and KRUCH Railway Innovations.

2.6 Model development and data sources

A Digital Twin of the Western Corridor (lines 121, 140, 147, 160, and 190) was developed using an Energy Flow Simulation (EFS) tool. The model builds directly upon the planning and economic principles established by Bartłomiejczyk and Połom [2] regarding the spatial differentiation of overhead supply systems and their direct impact on trolleybus energy consumption. By extending their framework to dynamic fleet simulations, the model integrates:

- vehicle characteristics and duty cycles,
- operational schedules and service frequencies,
- traffic conditions (including 32 signalised intersections),
- infrastructure configurations (existing and planned overhead systems),
- charging strategies (battery, in-motion charging, hybrid).

To ensure the technical validity of the infrastructure configurations, the simulation routing incorporates the methodologies proposed by Diab et al., [5] regarding the

optimized estimation of charging corridor lengths for in-motion-charging trolleybuses. Validation data were obtained from onboard monitoring systems installed on electric buses operating on line 190.

2.7 Simulation design

More than 110 electrification scenarios were simulated, varying traffic conditions, service frequencies, charging strategies, and infrastructure configurations. These scenarios build upon the operational frameworks for the sustainable use of catenary systems in Gdynia established by Bartłomiejczyk and Połom [4]. Simulations represent extended operational periods, incorporating seasonal variation and long-term system behaviour to capture comprehensive lifecycle implications.

2.8 Data analysis

Simulation outputs were analysed across multiple dimensions, including energy consumption (kWh/km), battery state of charge, fleet size requirements, and infrastructure investment needs. In alignment with the investment risk mitigation strategies outlined by Bartłomiejczyk and Połom [3] regarding dynamic charging infrastructure, these outputs were evaluated to identify resource-efficient electrification pathways. Results were validated by comparison with real-world operational data.

2.9 Ethical considerations

Operational vehicle and driver-related data were anonymised prior to analysis and did not contain personally identifiable information; therefore, ethics approval and informed consent were not required.

3 Results

The implementation of the CE4CE pilots across Leipzig, Bergamo, and Gdynia demonstrates how digital technologies—specifically AI-driven monitoring and Digital Twin simulations—transform public transport from reactive to predictive systems, directly supporting circular economy outcomes.

3.1 Technical outcomes and pilot observations

This section details the direct findings and technical observations from the monitoring and simulation activities in the three examination sites.

3.2 Asset condition and lifetime extension

The pilots transitioned infrastructure management from time-based intervals to condition-based interventions, extending the useful life of existing assets.

Compared to traditional human-based or time-based inspection methods, which rely on low-frequency visual checks and expensive, dedicated measuring trains operating only at large intervals, the digital monitoring

approach demonstrated superior detection efficiency. Continuous vehicle-based data streaming during regular passenger service successfully identified critical degradation that standard legacy maintenance frameworks had previously left entirely unnoticed.

- **Leipzig:** Continuous monitoring identified eight critical overhead contact line (OCL) ‘hard points.’ Following these automated digital alerts, technical teams conducted targeted field inspections, allowing two specific section insulators to be re-adjusted on-site before mechanical stress caused irreversible damage. Furthermore, the system enabled precise monitoring of material degradation; for instance, contact wire thickness was recorded at 9.43 mm, verifying that the asset remains safely above the critical 9.2 mm replacement threshold, thereby avoiding premature, resource-intensive replacement. Beyond OCL assets, vehicle-mounted track monitoring detected eight critical fault areas—including three previously undetected broken rails—enabling immediate emergency repairs before catastrophic structural failure occurred (see Fig. 1). As demonstrated by the acceleration telemetry in Fig. 1, the high-amplitude vibration spikes recorded prior to intervention (Before Repair) were successfully mitigated following dynamic maintenance, stabilizing the baseline operational environment.
- **Bergamo:** The implementation of AI-driven condition assessment categorized infrastructure health into specific risk levels to streamline maintenance workflows. The system identified eight

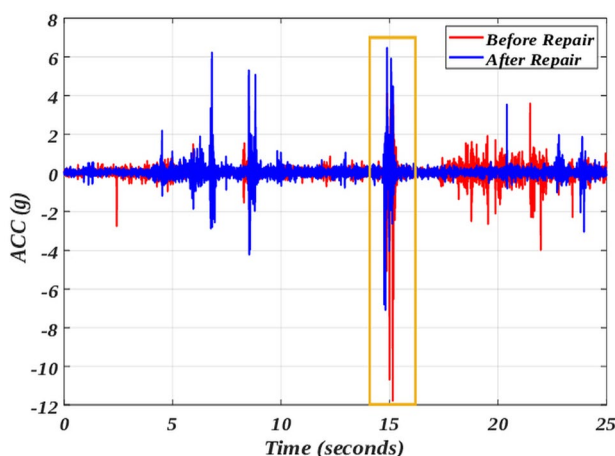


Fig. 1 Acceleration signal analysis demonstrating infrastructure baseline anomalies before repair (red) and the subsequent stabilization of vehicle-infrastructure dynamics after targeted maintenance (blue) within the Leipzig pilot

“Unhealthy” points with risk levels ranging from 31% to 59%, indicating that a field inspection is required in the near future. Furthermore, two critical “At Risk” points were detected with a risk level exceeding 60%, triggering a requirement for immediate inspection to prevent potential failure. Following these digital alerts, technical teams completed physical checks at five identified locations, subsequently marking all five as “Need to Repair” based on the confirmed degradation. This spatially referenced ranking of anomalies enabled staff to prioritize interventions on components showing early signs of degradation, such as irregular vibration levels or brief signal losses, rather than relying on standard time-based cycles.

3.3 Energy performance and efficiency

Digital tools provided high-resolution transparency into energy consumption, moving operators toward “energy-wave-surfing”.

- **Bergamo:** Data transmitted every 1–3 s allowed for a comparison between real-world energy use and theoretical models, identifying parameters to maximize energy recuperation. In Bergamo, the energy flow models were calibrated using high-frequency log files from tram #004, enabling the operator to mathematically verify that implementing the optimized recuperation parameters directly reduces substation energy losses under real-world traffic congestion.
- **Leipzig:** The integration of a direct CAN-bus interface replaced unreliable legacy energy meters, **where data previously had to be read out and evaluated manually.** This provided a stable data source for analyzing drive chain efficiency.
- **Gdynia:** The Digital Twin analyzed five core simulated components—Generation, Consumption, Battery, Vehicle, and Traction—to ensure system stability. Furthermore, the simulation evaluated seven specific charging points, including Centrum 1/2, Chwarzno 1/2, Karwiny, Redlowo, and Witomino, to optimize energy distribution. These simulations revealed that traffic conditions significantly influence energy balance, showing that IMC provides higher State-of-Charge (SOC) resilience under congested conditions compared to pure battery operations. Crucially, these simulation-based insights were directly cross-referenced and verified with empirical real-world operations. The Digital Twin’s consumption and SOC models were validated against the actual energy profiles collected from electric buses during seasonal extremes on line 190, confirming a model accuracy of over 95%.

3.4 Operational and maintenance optimisation

The integration of digital sensing into daily passenger operations eliminated the need for dedicated inspection runs.

- **Leipzig:** Structural track faults were captured using high-frequency axle-box accelerometers (vibration sensors) mounted onto the bogies of regular passenger trams. As these vehicles traversed the regular network, the automated system captured micro-vibrations and dynamic shock signatures under real dynamic weight. These signals were processed via filtering and peak-detection algorithms, automatically categorizing degradation severity and mapping the exact geographic coordinates via integrated GNSS tracking. Because the three detected broken rails and subsurface material fatigue escalated rapidly between scheduled human visual inspections—which are inherently limited to surface-level geometric defects on static tracks—they had remained entirely hidden from manual walking patrols. Following these alerts, maintenance workflows were overhauled by moving from standard calendar-driven track patrols to a dynamic, sensor-triggered framework. When an anomaly is flagged, a targeted field verification is scheduled, completely bypassing unnecessary inspections on healthy track segments. This strategic shift significantly reduces the vehicle-kilometers of dedicated, fossil-fueled maintenance vehicles and minimizes the premature scrap rate of infrastructure components.
- **Bergamo:** Modular hardware and edge computing allowed for continuous data streaming and real-time decision support via a dashboard refreshing every 1–3 s.

3.5 Resource use and investment efficiency

Simulation-based planning acted as a safeguard against resource waste by optimizing infrastructure design.

- **Gdynia:** The Digital Twin executed a robust scenario analysis evaluating 110+ distinct electrification configurations, varying service frequencies (7-minute versus 15-minute intervals), traffic congestion levels, and seven overhead contact system (OCS) pricing variants (ranging from zero to all three planned physical charging corridors). The simulation yielded a highly critical operational insight: traffic congestion proved to have a significantly greater impact on total operational costs and battery lifecycle wear than doubling the service frequency. This counter-intuitive finding proved that targeted OCS infrastructure investment restricted to congested

zones is far more resource-efficient than purchasing an oversized, under-utilized fleet. Furthermore, the financial and lifecycle cost (LCC) analysis demonstrated that while pure battery-electric bus fleets require lower upfront infrastructure investment, they incur a 35% higher long-term expenditure because their heavy traction batteries must be replaced twice over the vehicle's operational lifespan. In contrast, In-Motion Charging (IMC) trolleybuses operating via targeted overhead lines require only a single battery replacement over the same period. This reduction in battery degradation directly translates into a 15–20% savings in overall fleet lifecycle costs, a significant reduction in upfront vehicle procurement costs, and a minimized long-term demand for critical raw materials.

- **System-aide impacts:** Predictive maintenance in Leipzig and Bergamo reduced the need for resource-intensive “emergency” interventions.

3.6 Synthesis and cross-pilot impact analysis

The following section synthesizes the findings to evaluate their impact on the transport system's circularity and resilience.

To maintain strict academic credibility, the evaluation of the pilots distinguishes between direct empirical outputs, inferred circular economy outcomes, and potential system-level implications.

- **Direct empirical outputs:** These consist of quantified, directly measured events during the pilot periods, including the detection of eight critical overhead line faults and three broken rails in Leipzig, the spatial localization of eight ‘Unhealthy’ and two ‘At Risk’ pantograph contact points in Bergamo, and the simulation of 110+ validated electrification scenarios in Gdynia.
- **Inferred circular economy outcomes:** Where long-term material flows could not be directly measured due to the limited pilot timeframes, benefits are conservatively inferred based on these detected faults and optimized scenarios. For instance, the avoidance of premature infrastructure replacement and lower material demand are logically deduced from the early repair of the 3 broken rails before catastrophic failure occurred, and from the 50% reduction in battery replacement cycles verified within Gdynia's lifecycle cost (LCC) models.
- **System-level implications:** Broader claims, such as the overall reduction of network-wide emergency interventions and systemic resource waste prevention, are framed cautiously as expected potential benefits. While the immediate stabilization of data streams and expert-validated maintenance

Table 2 Overview of evaluation methods and key circular outcomes across the three pilot cities

City / Operator	Notable Methods	Key Circular Outcome
Leipzig (LVB)	Vibration + Laser + CAN-bus	Detection of 3 broken rails; updated maintenance cycles
Bergamo (ATB)	GNSS/IMU + EFS Digital Twin	Ranked OCL hot spots; optimized recuperation parameters
Gdynia (PKA)	110+ EFS Scenarios + SOC analysis	Optimized fleet size; targeted OCS extensions

loops support these trajectories, full long-term quantification of asset life extension remains subject to multi-year operational tracking across larger vehicle fleets.

3.7 Evaluation of asset longevity and maintenance

Across the monitoring-based pilots, the application of vehicle-based sensing combined with AI enabled the detection of hidden defects under real operational conditions. This supports a shift toward more targeted maintenance interventions and allows for updates in asset management strategies where accelerated deterioration is detected. In Bergamo, the spatial mapping of anomalies provided a detailed understanding of infrastructure–vehicle interaction.

3.8 System-level energy and resource efficiency

All three pilots demonstrate how digital technologies improve energy-related insights. The transition from manual readout of legacy meters to automated CAN-bus acquisition in Leipzig significantly improved data reliability. In Gdynia, the comprehensive simulation of 110+ scenarios enables the optimization of energy use at the system level by identifying the most efficient infrastructure configurations.

These digital tools directly support circular economy principles by reducing material consumption and waste. By identifying the most efficient configurations before construction, Digital Twins help avoid unnecessary investments and support lifecycle cost (LCC) optimisation.

3.9 Cross-case insights

Although the pilots employ different technologies and metrics, several consistent patterns emerge across all cases:

- Digital monitoring enables earlier and more accurate detection of degradation, supporting a shift from reactive to predictive maintenance.
- Simulation-based approaches provide a powerful tool for testing scenarios and optimising system design before implementation.

- The combination of real-time data and modelling enhances decision-making quality at both operational and strategic levels.

An overview of evaluation methods and key circular outcomes across the three pilot cities is presented in Table 2.

To establish a direct link between operational telemetry and circular economy outcomes, technical findings are explicitly translated into material and lifecycle implications. In the monitoring pilots (Leipzig and Bergamo), detecting infrastructure faults and the three broken rails directly maps onto avoided catastrophic failures and reduced emergency interventions, which prevent the premature disposal of adjacent track structures. Precisely monitoring wire thickness (e.g., 9.43 mm vs. the 9.2 mm safety threshold) ensures that asset management is based on actual material degradation, achieving avoided premature replacement and extended component life. In the simulation pilot (Gdynia), energy and fleet-size optimization directly translates into clearer resource-efficiency by proving that In-Motion Charging requires only one battery replacement over the vehicle’s lifespan compared to two for pure e-buses, resulting in a lower material demand for rare raw materials and optimized lifecycle costs.

4 Discussion

The results of the three pilots demonstrate that digital twins and AI-driven monitoring are not merely technical enhancements but essential tools for operationalizing circular economy principles in public transport. However, the transition from theory to practice revealed significant operational challenges that define the boundaries of these technologies.

4.1 Operational challenges and data integrity

A critical finding, particularly in the Leipzig pilot, was the discrepancy between legacy infrastructure and modern digital requirements. The initial reliance on older energy metering systems proved insufficient due to low sampling rates and data gaps. This mirrors a common challenge in European transit systems: the “digital gap” between new rolling stock and aging infrastructure.

The deployment of a direct CAN-bus interface in Leipzig addresses a profound operational bottleneck rather than a simple technological upgrade. For public transit operators, legacy rolling stock often utilizes proprietary, closed onboard metering systems that strictly limit data access to manual, end-of-shift extractions. Within the context of the CE4CE project, establishing direct CAN-bus acquisition serves as a standardized blueprint for ‘data retrofitting.’ It demonstrates that operators can bypass restrictive manufacturer software and unlock high-frequency, vendor-independent energy data

from existing legacy fleets. This directly avoids the massive capital expenditure and material waste associated with premature vehicle replacements, embodying a core circular economy strategy.

Furthermore, the certification and integration of sensors on operational vehicles (e.g., the Bergamo tram) highlighted the administrative barriers to innovation. The requirement for rail-certified edge computing units (EN 50155) adds a layer of complexity that often discourages smaller operators from adopting predictive maintenance.

4.2 Interpreting anomalies: From detection to action

The detection of three previously unknown broken rails in Leipzig and multiple OCL “hot spots” in Bergamo demonstrates a significant improvement over traditional time-based maintenance intervals. While international benchmarks for track fault detection often rely on dedicated, expensive measuring trains that run in large time intervals only, the continuous monitoring approach used here allows for real-time identification.

However, the pilots also highlighted that AI-based detection is not a replacement for human expertise but a filter. Every automated anomaly detection still required a validation loop with maintenance staff. This structural challenge suggests that the primary barrier to digital circularity is not a deficit of operational telemetry, but rather the systematic integration of AI-generated analytics into the daily, hard-scheduled workflows of frontline maintenance teams.

Crucially, the empirical evidence underscores that digitalization does not act as an immediate, standalone solution, but rather as an enabling layer whose ultimate impact is strictly dependent on organizational readiness, data quality, and deep integration into daily routines. The pilots demonstrate that high-fidelity data pipelines are functionally useless without predefined, validated workflows and skilled maintenance teams capable of translating algorithmic outputs into physical repairs. In Leipzig and Bergamo, this operational bottleneck was overcome by establishing structured validation loops, such as weekly cross-departmental expert review meetings, which formalized the decision-making process required for AI-generated insights to actively overwrite and dictate legacy maintenance schedules. Moving forward, the true prerequisite for circular public transit lies in institutional adaptability—ensuring that transit authorities mature organizationally to absorb predictive diagnostics into their rigid operational routines.

Digital Twins as a resource-saving tool

4.3 Digital Twins as a resource-saving tool

The Gdynia pilot’s simulation of over 110 scenarios addresses the most critical stage of the circular economy: the AVOID (refuse/rethink) stage. By proving that

IMC can achieve higher state-of-charge resilience with a smaller fleet compared to pure battery-electric buses, the Digital Twin acts as a safeguard against over-procurement. This aligns with recent studies suggesting that “virtual-first” planning can reduce the carbon footprint of infrastructure projects by up to 15–20% through optimized material use. The real-world value of this simulation model lies in exposing the non-linear relationship between traffic delays and battery degradation. While transit operators intuitively plan for congestion-related delays, the verified data shows that the prolonged, erratic energy draws caused by gridlock accelerate battery ageing much faster than standard high-frequency operations. By identifying these critical congestion hot spots prior to infrastructure deployment, the Digital Twin acts as an empirical safeguard against resource waste, steering capital toward targeted electrification that actively maximizes asset longevity.

4.4 Study limitations

Despite the positive outcomes, certain limitations must be acknowledged. The physical pilot deployments were restricted to a small fleet size (three in Leipzig, one in Bergamo) over a truncated observation window, which may not fully capture long-term seasonal extremes (e.g., extreme heat expansion in rails). Additionally, the financial and operational scalability of the Bergamo sensing architecture across larger commercial fleets remains to be evaluated concerning backend data processing and cloud storage costs. While expanding data harvesting across wider fleets is expected to linearly improve predictive resolution and asset maintenance productivity, further research is required to optimize the data-density-to-infrastructure-cost ratio.

4.5 Impact on the transport system

The integration of AI-driven monitoring and digital twins fundamentally transforms the efficiency of the urban transport network. By shifting to condition-based maintenance, the network reliability increases as the frequency of unplanned service interruptions (e.g., due to broken rails or overhead line failures) decreases. Furthermore, vehicle efficiency is enhanced through the optimization of energy recuperation identified in the Bergamo and Gdynia simulations. This transition enables a more intensive use of existing assets, effectively increasing the system’s capacity without the need for resource-heavy physical expansions.

4.6 Policy and managerial recommendations

Based on the pilot findings, the following recommendations are proposed for European transport authorities and policymakers:

- **Support for data retrofitting:** Policies should prioritize funding for “digital retrofitting” of legacy fleets. As shown in Leipzig, smartening existing assets is a faster and more circular pathway to sustainability than full fleet replacement.
- **Standardization of transit data:** To ensure transferability, EU-wide standards for sensor data integration (e.g., CAN-bus access protocols) should be strengthened, reducing the entry barrier for smaller operators.
- **Holistic investment evaluation:** Managers should move beyond “lowest purchase price” procurement. Digital twin simulations (as seen in Gdynia) allow for Lifecycle Cost (LCC) assessments that favor durable, energy-efficient solutions, aligning with Circular Economy objectives. Quantifying the financial trade-offs of these digital and structural interventions reveals that the diagnostic costs of implementing AI-driven predictive monitoring are rapidly offset by the prevention of catastrophic failures. For instance, avoiding a single major overhead line collapse or a severe derailment caused by undetected broken rails saves an estimated €50,000 to €150,000 in immediate emergency repair costs and network downtime penalties.
- **Skills development:** Policy frameworks must support the upskilling of the transit workforce, ensuring that maintenance staff can effectively act upon AI-generated diagnostic insights.
- **Data Integrity and source selection:** The Leipzig pilot revealed that legacy energy metering systems may be unreliable, necessitating direct CAN-bus interfaces for accurate energy monitoring.
- **Organizational readiness:** Technical solutions must be accompanied by new maintenance workflows and validation loops; automated AI detections still require field inspection to confirm degradation patterns.
- **Infrastructure optimization:** The Gdynia pilot demonstrated that Digital Twins allow cities to compare electrification strategies before committing to long-lived infrastructure, preventing the resource waste of over-dimensioned systems.
- **Asset longevity:** By extending the life of critical components like copper overhead wires and traction batteries through early intervention, these digital tools directly reduce material demand, aligning with EU raw material strategies. Crucially, lifecycle cost assessments show that these digital-circular interventions achieve full amortization within 2–3 years by mitigating catastrophic failures and cutting long-term asset expenditure by up to 35%.

Furthermore, the pilots demonstrate strong transferability due to their modular, vehicle-based monitoring approaches and scalable Digital Twin frameworks. Key enabling factors for replication include data availability, system integration, and organizational readiness. Overall, the findings confirm that combining digitalisation with circular economy principles provides a practical and scalable pathway towards more resource-efficient, resilient, and sustainable urban public transport systems.

5 Conclusions

This study demonstrates that digital innovations—including AI-based condition monitoring, Big Data analytics, and Digital Twin simulations—can effectively facilitate circular economy strategies in public transport by enabling a shift from reactive to predictive and data-driven asset management. Across the three European pilot cases, these technologies supported early fault detection, continuous infrastructure monitoring, and scenario-based planning, thereby reducing unnecessary material use, extending asset lifetimes, and improving operational efficiency.

Measurable impacts include the identification of critical infrastructure defects, such as eight overhead line faults and three previously undetected broken rails in Leipzig. The high-frequency operational data collection—recorded every 1–3 s in Bergamo—and the simulation of over 110 electrification scenarios in Gdynia enabled the optimization of energy consumption, fleet size, and infrastructure investments. These results show clear potential for reducing failure rates, improving maintenance targeting, and enhancing energy efficiency.

Beyond the technical achievements, the pilots highlight several critical lessons for future implementation:

Abbreviation

CE	Circular Economy
CE4CE	Public Transport Infrastructure in Central Europe – facilitate transitioning to circular economy
LVB	Leipzig Public Transport Company
PKA	Public Bus operator in Gdynia
PT	Public Transport
AI	Artificial Intelligence
IMC	In Motion Charging
GNSS	Global Navigation Satellite System
OCL	Overhead Contact Line
OCS	Overhead Contact System
EFS	Energy Flow Simulation
KPI	Key Performance Indicator
SOC	State of Charge
LCC	Lifecycle Cost

Acknowledgements

The authors would like to express their gratitude to the entire Interreg CE4CE project consortium for their technical and strategic support during the development and implementation of the pilots. Special thanks are also due to Pantohealth, and CEMIT for their essential contributions to data analytics and system monitoring.

Author contributions

ConradJentzsch (LVB): writing, reviewMartaWoronowicz (trolley: motion): writingJanRöhl (Kruch Railway Innovations): conceptualisation, methodology, analysis, review.

Funding

This article has been published open access with support of the TRA2026 project funded by the European Union. The Interreg CE4CE project in which the pilots were implemented was financed by the Interreg CENTRAL EUROPE programme.

Data availability

The datasets supporting the conclusions of this article are included within the article (and its additional files).

Declarations

Competing interests

The authors declare no competing interests.

Received: 15 April 2026 / Accepted: 18 August 2026

References

1. Abdessadak, A. (2025). Digital twin technology and artificial intelligence in energy systems: a systematic review. *Energy Reports*. Digital twin technology and artificial intelligence in energy transition: A comprehensive systematic review of applications - ScienceDirect. Accessed 22 September 2025.
2. Bartłomiejczyk, M., & Polom, M. (2017). The impact of the overhead line's power supply system spatial differentiation on the energy consumption of trolleybus transport: planning and economic aspects. *Transport*, 32(1), 1–12. <https://journals.vilniustech.lt/index.php/Transport/article/view/485> Accessed 15 April 2026.
3. Bartłomiejczyk, M., & Polom, M. (2020). Dynamic charging of electric buses as a way to reduce investment risks of urban transport system electrification. *TRANSBALTICA XI: Transportation Science and Technology* (pp. 297–308). Springer. https://doi.org/10.1007/978-3-030-38666-5_32. Accessed 17 September 2025.
4. Bartłomiejczyk, M., & Polom, M. (2021). Sustainable use of the catenary by trolleybuses with auxiliary power sources on the example of Gdynia. *Infrastructures*, 6(4), 61. <https://doi.org/10.3390/infrastructures6040061>. Accessed 23 September 2025.
5. Diab, I., Mouli, G. R. C., & Bauer, P. (2022). Toward a better estimation of the charging corridor length of in-motion-charging trolleybuses. In *Proceedings of the 2022 IEEE Transportation Electrification Conference & Expo (ITEC)* (pp. 557–562). Piscataway, NJ: IEEE. https://www.researchgate.net/publication/362966485_Toward_a_Better_Estimation_of_the_Charging_Corridor_Length_of_In-Motion-Charging_Trolleybuses. Accessed 15 April 2026.
6. Ersöz, O. Ö., İnal, A. F., Aktepe, A., Türker, A. K., & Ersöz, S. (2022). A systematic literature review of the predictive maintenance from transportation systems aspect. *Sustainability*, 14(21), 14536. <https://doi.org/10.3390/su142114536>. Accessed 11 September 2025.
7. Mügge, J., Seegrün, A., Hoyer, T. K., Riedelsheimer, T., & Lindow, K. (2024). Digital Twins within the Circular Economy: Literature Review and Concept Presentation. *Sustainability*, 16(7), 2748. <https://doi.org/10.3390/su16072748>. Accessed 12 September 2025.
8. Scharzenberger, A., Woronowicz, M., Nemeth, Z., Szmelter-Jarosz, A., & Roehl, J. (2025). Moving transport in circles. *EU Research, Autumn 2025*, 41–43. <https://euresearcher.com/autumn-2025/> Accessed 17 March 2026.
9. Verma, S. (2024). A systematic review of digital twins for electric vehicles. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2024.141512>. Accessed 16 September 2025.
10. Wolek, M., Wolański, M., Bartłomiejczyk, M., Wyszomirski, O., Grzelec, K., & Hebel, K. (2021). Ensuring sustainable development of urban public transport: A case study of the trolleybus system in Gdynia and Sopot (Poland). *Journal of Cleaner Production*, 279, 123807. <https://doi.org/10.1016/j.jclepro.2020.123807>. Accessed 16 September 2025.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.