Invisible surveyors pave the way to ATO

Trials on the Berlin S-Bahn have demonstrated how continuous monitoring of railway infrastructure using normal service trains can be paired with a dynamically updated digital twin to support predictive maintenance, and also offer a first step towards implementing higher grades of automation.

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Across the world, there is a significant 'insight gap' in understanding the condition of railway infrastructure, in order to inform both operations and maintenance policies. Notwithstanding the push toward digitalisation and advanced signalling systems over the past couple of decades, many parts of the physical railway network have still not been mapped in a usable digital format. Operators find themselves managing complex systems while dealing with blind spots regarding the exact condition of their infrastructure.

Dedicated survey trains are costly upfront and can be expensive to run. As they are hard to fit into busy timetables, they might only check a specific corridor once every six months. The data may be highly accurate, but it quickly becomes outdated. A one-off snapshot loses value as soon as the train leaves the track. For example, a minor landslip caused by a storm the day after the survey train passes might not be recorded officially for another half-year.

The alternative is the manual track walk, which takes a lot of time, often requires track closures and puts staff in potentially hazardous environments. A maintenance crew walking a line late at night, in the rain, may be hard pressed to spot small changes in track geometry or shifts in the overhead lines. It is an inefficient process.

In many cases, however, no regular inspections take place at all. This leaves the infrastructure managers relying entirely on reactive maintenance, fixing things when they break. And that is far from satisfactory for the train operators.

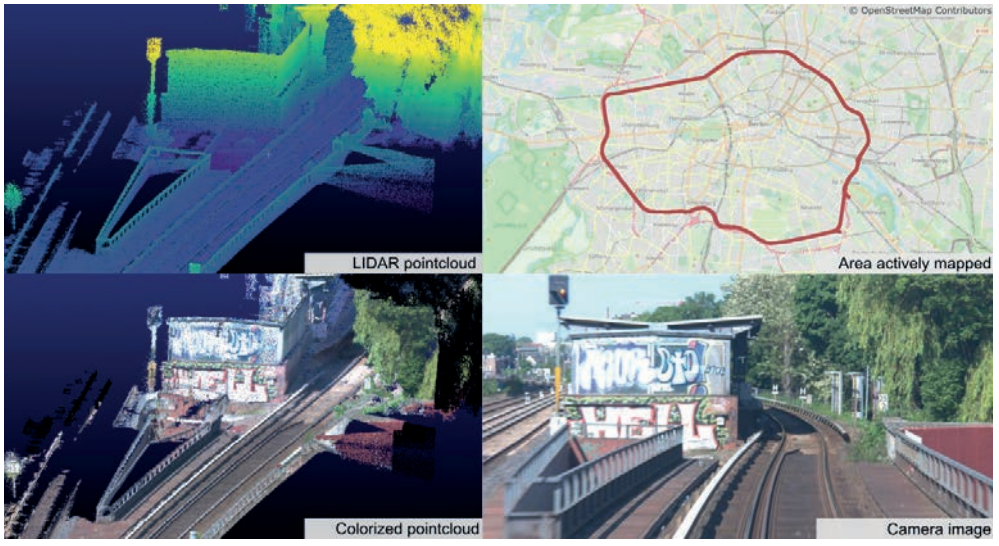


Fig 1. Examples of the near-real time data now being collected on the Berlin S-Bahn.

The true cost of blind spots

The cost of this 'insight gap' goes beyond emergency repairs. When a critical asset fails unexpectedly, the effects on the network are immediate and can be expensive. Consider a minor defect that goes unnoticed until it causes operational disruption or forces a speed restriction. The infrastructure manager not only faces the expense of deploying emergency crews to replace the damaged infrastructure quickly, but must divert or delay other services until the line can be reopened. Meanwhile, the train operator is faced with all the costs associated with passenger compensation, the provision of alternative transport, and damage to their brand reputation.

The lack of continuous data also forces railway companies into a conservative time-based maintenance strategy, where components are replaced on the basis of their expected lifespan rather than their actual condition. This can lead to premature disposal of functional assets, tying up capital in unnecessary inventory and increasing labour costs.

By moving to a predictive model based on continuous data collection, railway operators and infrastructure managers can optimise maintenance schedules, extend the safe operational life of assets, and reduce life-cycle costs. It is altogether a more efficient process.

The Invisible Surveyor

Digital twins are becoming increasingly common as virtual representations of physical assets, but they are only useful when the data is fresh and reflects the actual state of the network. However, a new approach is emerging to address the problem of outdated data, making use of the trains that are already running.

Siemens Mobility has been developing its own mapping solution, inspired by Alexander von Humboldt who emphasised the value of continuous observation over static snapshots to understand complex systems. This uses regular passenger trains fitted with

lightweight onboard sensors, specifically LiDAR and optical cameras, to capture infrastructure data continuously during their normal daily operation.

The mechanics are straightforward. As a sensor-equipped train runs over its normal route, the LiDAR measurement system creates an accurate, three-dimensional point cloud of the surrounding environment, while the cameras capture high-definition visual imagery. Advanced software brings all the data together to update the 3D digital twin constantly in near real time. This enables a shift in infrastructure maintenance practices from reactive repairs based on old information to predictive, data-driven insights.

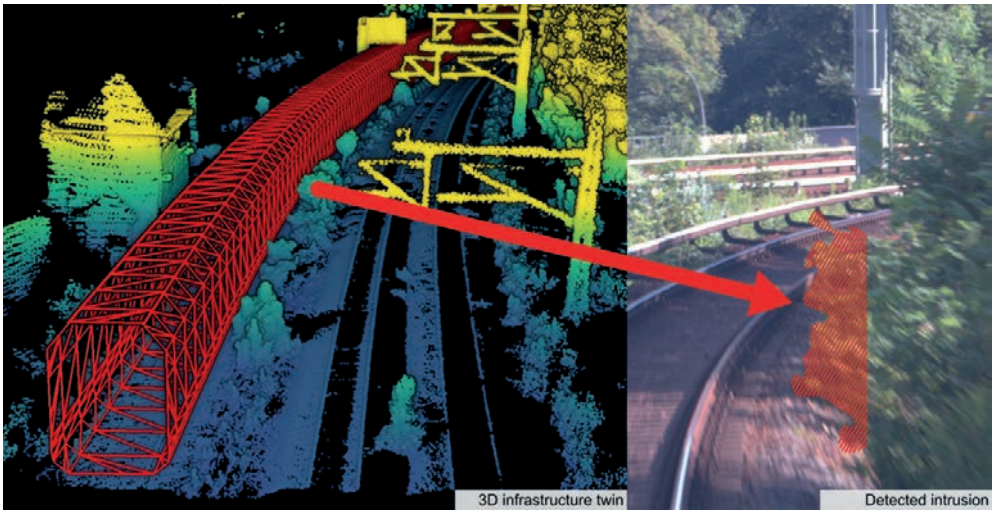


Fig 3. Vegetation incursion on the railway alignment has been detected by digital twin-enabled trains in revenue service.

Riding a wave of innovation

This ability to turn passenger trains into continuous monitoring tools is a direct result of how sensor technology has evolved. In the past, the sensors needed for precise infrastructure mapping were expensive, bulky, and fragile, which is why they were only fitted on dedicated trains.

Development in other industries, particularly the automotive sector and industrial robotics, has led to better sensor technologies, making LiDAR and high-resolution cameras more robust, compact, and affordable. The sort of high-definition sensors found in advanced robotics and autonomous vehicles can be fitted to passenger fleets at a reasonable cost, so the hardware is no longer the main obstacle.

By using these standardised, durable sensors, the system can capture reliably both the geometric structure and the visual context of the railway environment every day. This makes continuous, fleet-wide monitoring practical, and provides the hardware foundation for a future transition to GoA3/4 automated operation.



Fig 2. An S-Bahn Berlin trainset has been equipped with cameras and sensors for automation trials, but these are also able to collect asset condition information in revenue service every day.

Managing data with AI

Capturing infrastructure data continuously is only the first step. The real challenge is making the resulting volumes of information usable. Every sensor-equipped train generates terabytes of data during a standard shift. Without a way to process it all, operators would just be trading a lack of information for an unmanageable amount of raw data.

Artificial Intelligence provides a practical way to manage this data and extract value, using Machine Learning algorithms as an automated filter. Instead of requiring engineers to review hours of footage or complex 3D point clouds manually, the AI continuously analyses the incoming data streams, identifying patterns and flagging up any anomalies.

This approach allows the system to be tailored to customer needs. The AI systems can be trained to look for the issues that matter to an individual operator or infrastructure manager, whether that's vegetation encroachment, loading gauge clearance violations, or specific asset monitoring requirements. The system translates the raw data into targeted insights, allowing maintenance teams to focus on solving problems rather than searching for them.

Real-world validation

The robustness of the algorithms has already been proven by processing more than 4 500 track-km of infrastructure data across Germany, successfully automating the extraction of track geometry and asset locations at scale.

The 'invisible surveyor' concept is now being applied in complex urban environments. Siemens Mobility has equipped one trainset on the Berlin S-Bahn with cameras and LiDAR sensors for testing obstacle detection, and this has been validated in regular passenger service. The feeds from the sensors have been used to update the digital twin continuously as the train runs around the S-Bahn Ring Line, proving that high-quality infrastructure data can be gathered day after day without disrupting regular operations (Fig 2).

Platform multiplier effect

The digital twin functions not as a single-purpose tool, but as an extensible platform. This creates a multiplier effect: once the data has been collected, it can be used for many different purposes across the organisation. Typical use cases include:

- Clearance Intrusion Detection: The system automatically analyses the 3D point cloud to detect objects intruding into the clearance space. If a retaining wall begins to bulge or a temporary construction barrier shifts too close to the track, the system will flag it.
- Vegetation Management: Rather than sending crews to check manually for overgrown branches, the digital twin monitors vegetation growth over time (Fig 3).
- Catenary Wire Monitoring: Checking the tension and positioning of overhead catenary wires is traditionally difficult. The system can track the precise alignment of the wires, issuing warnings about any sagging or misalignment.
- Next-Generation Simulators: The visual data collected can be used to

generate photorealistic 3D models for route-specific driver training simulators. Drivers can learn on digital replicas of the routes they will drive, complete with current signal positions and trackside landmarks, before taking to the controls.

- Automated Asset Inventory: Railways own millions of assets. Because the system logs the exact GPS location and visual condition of each asset every time a train passes, this reduces the need for manual inventory audits. The underlying AI models have been trained to recognise and locate up to 145 different infrastructure components.



Fig 4. A mobile sensor attached to a windscreen can be used to prove the inspection concept before committing to a full deployment.

Breaking the barrier to entry

The adoption of new technology in the rail sector is often hindered by concerns about lengthy deployments, high initial costs, and complex certification processes. Our approach is designed to bypass these traditional hurdles by using a mobile sensor setup to undertake a proof of concept. This requires minimal commitment from operators who may be concerned the cost and complexity of modifying their trains permanently.

Every network is different, of course, and so is every deployment. Rather than offering a rigid, one-size-fits-all, product, Siemens Mobility favours a 'co-creation partnership' that adapts to each customer's individual priorities, infrastructure, and pace of adoption. That unfolds in three phases.

The first is a Rapid Proof of Concept, using a mobile sensor kit and immediate AI-based processing to validate a priority use case. The operator simply has to define its initial use case and provide access to a suitable vehicle during its regular commercial service. There is no need to modify the vehicle, no complex approvals, and no disruption to revenue operations.

Once the value of the insights has been demonstrated on the operator's own tracks, the second phase is System Hardening. Here, Siemens Mobility moves the sensors from their temporary mounting to a permanent retrofit within the vehicle and automates the data capture pipelines, integrating them into the customer's existing IT systems. Depending on data governance requirements, the digital twin can be computed either on-premises or in the cloud. The operator, in turn, co-ordinates the vehicle integration process and begins adapting its management workflows to incorporate the new data streams.

The Platform Expansion phase shifts the focus from proving the technology to scaling its impact. Siemens Mobility implements additional use cases drawn from the same underlying data platform, while the operator prioritises which new use cases matter most and integrates the resulting insights into their day-to-day workflows. What begins with a lightweight trial on a single route can grow into a network-wide digital infrastructure backbone, but at the customer's own pace.

Foundation for automation

Continuous infrastructure monitoring is a powerful tool for today, enabling a shift toward predictive maintenance and improved operational efficiency. But looking ahead strategically, it can also serve as the essential first step toward autonomous railway operations.

As the rail sector moves toward highly automated and fully unattended train operation at Grades of Automation 3 and 4, the requirements for environmental awareness increase. In many cases, these advanced systems require more than just sensors on the train; they depend on having highly detailed, machine-readable 'HD maps' of the entire network.

Crucially, an autonomous train cannot rely on a map that was last updated six months ago. ATO requires precise, continuously refreshed data to ensure safe operation. An autonomous train needs to know exactly where the signals are, the precise track geometry, and the current clearance profile on any given day. A static map is insufficient for dynamic operations.

This is a common hurdle for many operators: how do they justify the investment in the digital infrastructure required to support future automation before the autonomous fleets arrive?

The digital twin approach can solve this conundrum by providing immediate tangible value today. Turning the existing passenger fleet into a network of invisible surveyors helps the operator solve current maintenance challenges and reduce infrastructure costs while simultaneously building the continuously updated HD landscape required to support GoA3/4 operation in the future. In effect, they are creating a cost-effective, foundational data layer, ensuring that when the next generation of automated trains arrives, the digital infrastructure is already in place and waiting for them.

The hidden benefit

Beyond building the necessary data foundation, deploying a continuous monitoring system offers another significant, yet often overlooked strategic advantage: it serves as a practical, low-barrier point of entry into the technologies that will define GoA3/4. ATO systems typically use the same calibre of LiDAR and camera sensors, coupled to similar AI-driven perception software, so using them for infrastructure monitoring enables the operators to gain invaluable, hands-on experience with these critical technologies much sooner.

Rather than waiting years to interact with the complex hardware and software required for high-level automation, engineering and operations teams can begin familiarising themselves with sensor data management, AI analysis, and digital twin integration. This offers a gentle learning curve, enabling the organisations to build its internal competence and adapt its workflows using a system that delivers an return on investment through lower maintenance costs, long before the first fully autonomous train is ever commissioned.