Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 7.3
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.7.3

Analytic Temporal Tracker Sensor Monitoring System - Case Study

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Abstract

This paper introduces the Analytic Temporal Tracker (ATT) sensor system and its application in a railway section. The equipment provides high-frequency tracking of vibration, acceleration, inclination, and temperature, delivering processed data such as dynamic deflection and track modulus. The system operates in both stationary and campaign modes, allowing multiple point measurements with the same portable hardware. A case study was conducted at four critical points of interest along a railway section located in Rio de Janeiro, Brazil. Using a portable ATT sensor, it was possible to monitor all four locations within a single day. The methodology involved temporary mechanical fixation to the rail and data recording during train passage. Results indicated that deflection and track modulus were outside the ideal design parameters, potentially influenced by significant rainfall during the three days preceding the tests. The ATT sensor offers a practical alternative for remote railway monitoring through continuous or programmed readings. Its automated alerts and limit configurations facilitate prompt actions. The results of the case study confirmed the system's effectiveness in identifying critical deviations in track performance, highlighting the immediate need for maintenance intervention.

Keywords: railway monitoring, track modulus, deflection, case study, infrastructure maintenance, vibration sensors.

1 Introduction

The strategic management of railway assets has progressively shifted from predominantly reactive maintenance practices towards predictive track condition monitoring strategies. This transition is driven by the need to enhance operational safety, optimise maintenance planning and reduce uncertainty associated with the condition and performance of track components, particularly in sections subjected to variable geotechnical and environmental conditions.

Track deflection and track modulus are essential metrics for evaluating the structural performance of the permanent way. As defined by Selig and Waters [1], track deflection refers to the immediate elastic vertical displacement of the rail under dynamic wheel loads, reflecting the integrated response of all track components. Complementarily, the track modulus (u) represents the overall stiffness of the track support system. According to the classification established by Ahlf (1975) [2], a track modulus below 14 MPa is considered poor, while values exceeding 28 MPa represent a good track condition. Furthermore, Selig and Li (1994) [3] highlight that the subgrade's resilient modulus is the primary driver of this overall stiffness. A critical aspect of track behaviour is its non-linear load-deflection relationship; initial deflections often account for the "voids" or "slack" between components before the linear elastic response of the subgrade is fully engaged.

Central to this evolution is the ability to transform raw physical measurements into actionable operational intelligence. In this context, this paper evaluates the application of the Analytic Temporal Tracker (ATT) sensor monitoring system in a railway environment. The ATT is a multifunctional instrumentation suite designed to reduce uncertainty regarding track behaviour by capturing, processing and analysing temporal variations in key physical parameters associated with the performance of the railway track and its foundation.

The ATT designation reflects the system's core capability: the high-frequency analytic processing of temporal data to track behaviour and identify early anomalies. By capturing a continuous track response signature through triaxial measurements, the system enables the monitoring of both slow-onset processes, such as gradual settlement and geometric variation, and rapid dynamic events associated with train passages, including vibration peaks and transient deflections.

This dual capability is particularly relevant under adverse environmental conditions. Periods of intense or prolonged rainfall, such as those observed during the case study presented herein, can lead to subgrade saturation, loss of stiffness and degradation of the track modulus, directly affecting track performance and operational safety. The ability to detect changes in track response under such conditions is therefore critical for informed engineering decision-making.

The ATT system operates as an autonomous and wireless monitoring solution, enabling deployment in remote or operationally constrained railway sections where traditional cabled instrumentation is often logistically unfeasible. Furthermore, the sensor can be employed in both stationary and campaign-based monitoring modes. The latter allows the same equipment to be sequentially installed at multiple points of interest along the track, enabling rapid assessments over extended sections within limited time windows.

The primary objective of this paper is to present and evaluate the application of the ATT sensor system in a campaign-based monitoring programme conducted at four points along a railway section. The study focuses on the interpretation of measurements obtained during train passages and the assessment of parameters such as deflection and track modulus under wet conditions. The results demonstrate the potential of the ATT system as a practical and effective tool for railway monitoring and support the identification of sections requiring maintenance intervention.

2 Methods

The methodology adopted a campaign-based monitoring approach, taking advantage of the portability and autonomous operation of the ATT sensor ecosystem.

The ATT Sensor

The core of the instrumentation comprised autonomous ATT sensors developed for structural and geotechnical monitoring applications. From a technical perspective, the ATT is defined as an integrated system for structural signature analysis, consolidating sensing, local data acquisition and preliminary processing within a single compact and robust device. The sensing architecture is consistent with that typically associated with Micro-Electro-Mechanical Systems (MEMS) technology, which is widely employed in modern monitoring applications due to its capability to detect small-scale mechanical responses with high sensitivity, low power consumption and long-term operational stability.

The ATT sensors are capable of simultaneously measuring multiple physical parameters, including triaxial acceleration, vibration, linear displacement, inclination (tilt) and temperature. The concurrent acquisition of these complementary quantities allows a comprehensive characterisation of both dynamic response and long-term behavioural trends. In practice, this multi-parameter approach supports the correlation between rapid operational events—such as train-induced vibrations—and slower processes, including gradual geometric variations, settlement and rotational trends.

Unlike conventional wired instrumentation systems, the ATT units operate as fully self-contained sensing nodes, incorporating an internal battery bank and wireless data transmission. This autonomous architecture eliminates the need for cabling along the structure, reducing installation complexity, potential points of failure and operational interference, which is particularly advantageous in active railway environments.

A key operational feature of the system is the “Wake on Rail” technology, which enables automated triggering of data acquisition during train passage. By activating high-frequency measurements only when dynamic loading is detected, this mechanism optimises energy consumption while ensuring that critical events are fully captured. As a result, the integrated battery bank can support an estimated service life of approximately 7 to 10 years under typical operating conditions.

The ATT system can be deployed in two distinct modes:

- Stationary Mode: For long-term monitoring of specific critical assets.
- Campaign Mode: Utilised in this study as a mobile solution. It allows for rapid relocation, where a technician installs the sensor by tightening two bolts, captures data from a safe distance of up to 300 metres using a mobile terminal, and relocates the unit within minutes.

In the campaign-based monitoring mode, adopted in this study, the sensors were deployed as mobile instrumentation units, allowing multiple locations along the track to be monitored sequentially. The acquisition parameters were configured with a high sampling rate to capture rapid dynamic phenomena, such as vibration peaks and transient vertical displacements associated with train passages, while preserving sensitivity to slow-onset and long-term trends related to track geometry and foundation behaviour.

Field Setup

For accurate transduction of the "temporal signature" of the track, rigid coupling is mandatory. The sensors were secured to the rail foot using a bespoke mechanical clamping system. This device allows for a non-invasive installation, requiring the tightening of only two bolts to ensure the sensor acts as a monolithic part of the rail during train passage. This method eliminates signal damping typically found in magnetic or adhesive mounts, ensuring the integrity of the data used for track modulus calculations. The mechanical coupling is achieved through a bespoke clamp that anchors the ATT sensor directly to the rail foot (see Figure 1).

Figure 1: View of the ATT sensor coupled to the rail using the quick-release mechanical clamping system.

All necessary components for the campaign, including sensors, clamping devices, and the gateway, are transported in a dedicated rugged case, ensuring rapid deployment and organization in the field (see Figure 2).

Figure 2: Portable instrumentation kit for field campaigns, containing ATT sensors, mechanical clamps, mini gateway, and the mobile management terminal.

Local Connectivity (Sysrail)

The field operation utilized a decentralized communication architecture to ensure operator safety. Once the sensors were positioned, the technical team withdrew to a safe zone, maintaining a distance of up to 300 metres from the active track.

Data transmission was handled via a localized Mini Gateway, which established a wireless link (LoRaWAN protocol) with a mobile terminal running the Sysrail management software. The Sysrail interface facilitated:

- Point Management: Georeferencing and naming of the four points of interest.
- Session Control: Manual or automated triggering of data recording synchronized with train arrival.
- Real-time Verification: Preliminary validation of signal strength and axle-by-axle impact detection before sensor relocation.

Analytical Processing (LeadPro)

The final stage involved the transfer of field datasets to the LeadPro analytical platform. LeadPro acts as the central processing engine, applying domain-specific algorithms to the raw triaxial data. The methodology focused on three primary analytical outputs:

- Dynamic Deflection Analysis: Transformation of vertical acceleration and inclination into millimetric displacement.
- Track Modulus Calculation: Integration of deflection data with known load parameters to determine the global stiffness (N/mm²) of the track-subgrade system.
- Early Anomaly Detection: Comparison of current structural signatures against a baseline to identify "early anomalies".

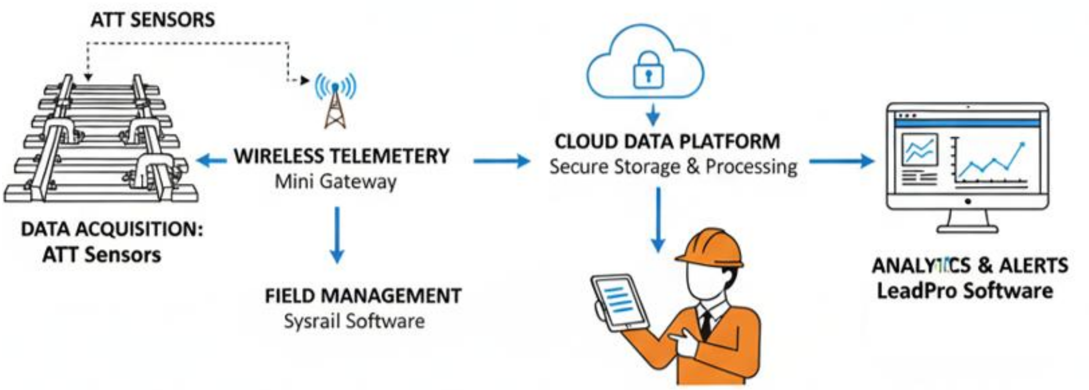

Figure 3: Data acquisition and processing flowchart for the ATT sensor ecosystem.

3 Results

The field campaign monitored four points along a railway section located in Rio de Janeiro, Brazil, to validate the sensor's efficacy in detecting structural deviations under operational loads. Data were recorded following three days of continuous rainfall, a factor that significantly influenced subgrade saturation.

Point	Location (km)	Track Feature	Ballast Condition	Max. Deflection (mm)	Track Modulus u (MPa)
1	124+540	Tangent - Low Line	Partially Fouled	7.3	10
2	123+679	Circular Curve	Partially Fouled	3.2	30
3	123+600	Ballasted Bridge	Clean (New)	2.4	46
4	123+610	Spiral - High Line	Partially Fouled	2.7	37

Table 1: Case study monitoring results and parameters.

The monitoring results revealed a significant disparity in structural performance across the points. Point 1 (km 124+540) presented the most critical condition, with a maximum deflection of 7.3 mm and a track modulus of 10 MPa. According to the Ahlf (1975) criteria, this section is classified as "poor", indicating a severe loss of support stiffness.

The high deflection at Point 1 suggests that the subgrade saturation compromised its load-bearing capacity. As argued by Selig and Waters [5], when the subgrade's resilient modulus is reduced by moisture, the overall track modulus drops precipitously. In contrast, Point 3 (Bridge section) exhibited a modulus of 46 MPa, placing it within the "optimal" range (34–69 MPa) defined by Raymond (1985), likely due to the superior drainage and stiffness of the ballasted bridge structure.

Furthermore, the ATT sensor’s high-frequency capture allowed for the identification of "axle-by-axle" impact signatures. The automated alerts generated by the LeadPro platform for Point 1 flagged the deviation from safety limits, facilitating immediate maintenance prioritisation to address the fouled ballast and subgrade instability.

4 Conclusions

The Analytic Temporal Tracker (ATT) is an effective solution for reducing operational uncertainty in railway infrastructure. The case study demonstrated that the system successfully identified structural instabilities exacerbated by environmental factors (rainfall). By accurately distinguishing between component "slack" and subgrade weakness through millimetric deflection tracking, the ATT system serves as a powerful predictive maintenance tool. These data-driven insights ensure that interventions are prioritised accurately to prevent asset failure and ensure operational safety.

Acknowledgements

The authors would like to thank MRS Logística for the support and for providing access to the railway infrastructure, which made the field data acquisition possible. Special thanks are also due to Solver Tecnologias for their technical collaboration, the supply of the Analytic Temporal Tracker (ATT) instrumentation, and for the analytical support provided through the LeadPro platform.

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