



OPERATIONAL VALIDATION OF SPACE-ENABLED RAIL BUCKLING RISK MONITORING IN THE SPATRA RAILWAY PILOT

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Abstract - SPATRA project developed and demonstrated a Railway Pilot (RWP) that combines Earth Observation (EO)-derived land-surface temperature, meteorological forecasts, in-situ rail and environmental measurements, and track data to predict rail-track temperature and heat-related buckling risk. This paper summarises the integrated rail-pilot results. The RWP was operated from 1 July to 31 August 2025 on a 22 km Red Cross-Jasenovik section of the Niš-Svrljig line. The reported pilot results showed that 15 of 17 rail-temperature predictions were within ± 5 °C of in-situ measurements. Retrospective analysis of 22 hot-weather slow-order days indicates that risk-based restriction windows would reduce slow-speed operation from 264 to 146 h, a reduction of 118 h (about 45%). The system also identified the documented 24 July 2025 buckling location as high risk in advance. After interface refinements, all user-oriented KPIs exceeded 90% satisfaction, with section scores between 4.64 and 4.90/5. The results support more targeted speed restrictions, inspection prioritisation and traceable hot-weather decision-making, while wider deployment requires sustained sensor coverage, up-to-date asset data and integration with Railway Infrastructure Manager procedures.

Keywords - Railways, heat-related buckling, Earth Observation, rail track temperature, decision support.

1. INTRODUCTION

Increasing summer temperatures create a growing operational challenge for continuous welded rail, because high rail temperature can increase compressive thermal forces and the probability of lateral instability. Conventional hot-weather procedures are intentionally conservative, but they are often based on forecast air temperature and broad rules that have limited spatial and temporal resolution. The SPATRA project (Space-Based Applications for Transport Monitoring and Management) [1] addresses this gap by combining satellite-derived information with local measurements and operational data in decision-support services for land transport. Its

Railway Pilot (RWP) focuses on prediction and management of heat-related rail buckling risk [2].

This paper summarises the rail workstream pilot results, which evaluates the end-to-end behaviour, integrated performance and user acceptance of the pilot under operational conditions [2]. The evaluation builds on the pilot plan and KPI framework defined in [2], the integrated component validation reported in [4], and the user and system requirements defined in [5]. The objective is not to repeat module-level algorithm validation, but to present the evidence most relevant to railway infrastructure management: prediction performance, ability to localise high-risk periods and segments, potential impact on slow-speed orders, end-user acceptance, and prerequisites for

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wider deployment.

2. RAILWAY PILOT SETUP AND EVALUATION

2.1 Pilot corridor and integrated service

The RWP was demonstrated on a 22 km section of the Niš-Svrljig-Knjazevac-Prahovo corridor between Red Cross (Crveni Krst, Niš) and Jasenovik stations. The corridor combines high summer temperatures, small-radius curves, mixed cut-and-embankment geometry and strongly varying shading conditions. Eight representative sites were characterised by curvature, sleeper and fastening configuration and micro-climatic exposure. For risk assessment, the test track was divided into 234 homogeneous segments (Fig. 1). In-situ stations provided rail temperature, lateral displacement and local environmental measurements, while additional track and asset parameters were used to characterise segment susceptibility [1]

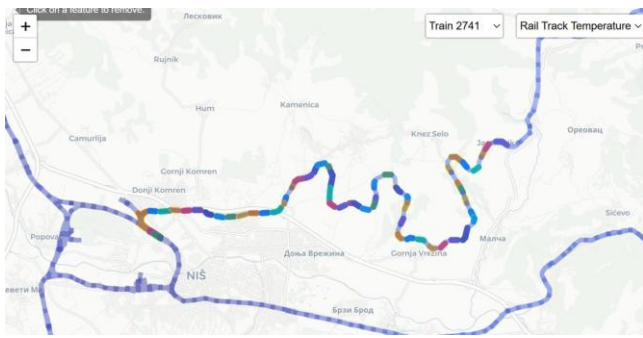


Fig. 1. Pilot demonstration track between stations Red Cross (Niš) and Jasenovik.

During the 1 July-31 August 2025 campaign, the integrated back-end operated in production-like mode. The processing chain combined a high-resolution EO-based Land-Surface-Temperature (LST) processor, Rail Track Temperature Prediction (RTTP), classical buckling-risk estimation using a Zarembski–Grissom–Lees-type buckling-risk index [6], which combines the rail-temperature increase above the neutral temperature with supplementary track-related risk factors, and an ANN-based lateral-displacement assessment. EO-derived LST and meteorological inputs provide spatial coverage, while in-situ measurements provide local calibration and ground truth [7]. Hourly RTT, risk and lateral-displacement outputs were delivered to Serbian Railway Infrastructure (ISR) users through the RWP WebGUI, where staff could inspect maps, segment-level time series, threshold exceedances and alerts [2].

2.2 Operational reference data and KPIs

Pilot interpretation used ISR operational records for the same summer period. Twenty-eight hot-140

weather telegrams were issued for the demonstration track, while the retrospective slow-order efficiency comparison reported covers 22 days with the standard 12-hour restriction window. One buckling incident was officially documented on Section 153 at km 9+040 on 24 July 2025, providing a real-world reference case. The key integrated KPIs addressed RTT prediction accuracy, buckling-risk assessment, efficiency of slow-order application and user satisfaction with the WebGUI, visual analytics and alerts [2].

3. PILOT RESULTS

3.1 Rail-temperature prediction and buckling-risk indication

For the pilot retrospective comparison, predicted and measured RTT values were examined for 17 dates in July associated with ISR slow-order telegrams. Fifteen of the 17 observations (about 88.2%) were within the ± 5 °C tolerance used for the integrated comparison. The two exceedances remained limited, at approximately 5.1 °C and 5.9 °C absolute error. RWP Results and Analysis Report therefore concluded that the RTT model performed reliably under the vast majority of observed pilot conditions.

The documented 24 July 2025 buckling case is the most important operational reference. The RWP identified the affected segment as high risk before the incident and predicted buckling risk above 70% during the late morning and early afternoon. In [2], the high-risk period is reported around 10:00-15:00, whereas Train 2743 entered the section at 17:05 and the deformation was then reported. The case demonstrates that the RWP could provide an earlier, segment-specific warning layer to complement field inspection and existing hot-weather rules. Risk values are nevertheless sensitive to local parameters such as rail-neutral temperature, track quality and fastening type, so the output is intended as decision support rather than an automatic safety decision [2].

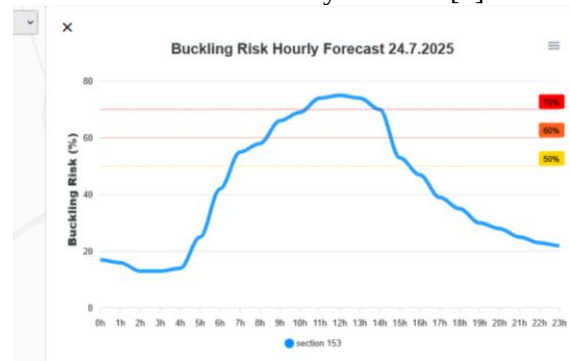


Fig. 2. Buckling-risk forecast for Section 153 on 24 July 2025 (adapted from [2], Fig. 8).

3.2 Potential reduction of heat-related slow-speed operation

Current ISR hot-weather practice applies precautionary slow-speed orders when forecast air temperature exceeds an internal threshold of approximately 33 °C. On the analysed days, restrictions were generally imposed from 10:00 to 22:00. Study reported in [2] compares this conservative 12-hour window with a risk-based approach in which reduced speed is associated with periods when the RWP buckling-risk indicator exceeds 70%. Across the 22 analysed days, the conventional approach corresponds to 264 hours of slow-speed operation, whereas the RWP-derived high-risk windows total 146 hours. The difference is 118 hours, or approximately 45%. On most days, the risk-based windows were 4-7 hours shorter than the standard block [2].

The results also indicate that timing can be refined in both directions. For example, on 1 July the standard 10:00-22:00 slow order could, according to the retrospective RWP result, have been focused on 10:00-16:00. Conversely, a vulnerable segment may require action earlier than a generic standard window if its risk rises rapidly. The operational value is therefore not simply shorter restrictions: it is the possibility to target where and when risk is elevated, while retaining ISR responsibility and established safety procedures.

3.3 Integrated KPI summary

Taken together, the integrated results presented in [2] show five points of direct operational relevance. First, 15 of 17 RTT observations in the retrospective sample were within ± 5 °C. Second, the risk-based slow-order windows totalled 146 h compared with 264 h under the standard 12 h windows, a reduction of about 45%. Third, the documented 24 July 2025 incident location was identified as high risk in advance. Fourth, after GUI refinements all user-oriented KPIs exceeded the 90% satisfaction targets. Finally, system logs reported threshold exceedance detection within 30 s and completion of processing within 1 min in more than 95% of cases.

3.4 User acceptance and operational relevance

ISR staff used the WebGUI during the summer campaign and in structured workshops. The first questionnaire round was already positive, but users requested clearer risk scales, better explanation of thresholds and greater visibility of live sensor data. The project consequently added intermediate risk thresholds, integrated live in-situ information and refined alert presentation. In the second round, all

user-oriented KPIs were reported as achieved: overall satisfaction 4.67/5 (93.4%), data visualisation and analysis 4.73/5 (94.6%), alerts and notifications 4.64/5 (92.8%), and interface usability 4.90/5 (98%) [2].

Feedback shows that the main operational benefits are the ability to localise critical segments in space and time, prioritise inspections, and document the rationale for hot-weather measures. ISR experts considered a two-stage workflow natural: first review a daily line-level risk map, then drill down into hourly RTT, risk and sensor traces for flagged segments. They also highlighted the value of archived risk maps and alert histories as a traceable record for post-event analysis, threshold refinement and longer-term climate-adaptation planning [1].

4. OPERATIONAL IMPACT FOR RAILWAY INFRASTRUCTURE MANAGEMENT

4.1 Inspection planning and recurrent thermal hotspots

The same segment-level information used to refine slow-speed orders can support inspection and maintenance planning. During the campaign, short curves and transition sections repeatedly reached higher risk levels than adjacent track under comparable meteorological forcing. SPATRA results therefore propose using recurrent high-risk segments as thermal hotspots in asset-management practice. Such locations can be assigned higher inspection frequency during the hottest months and can be prioritised for ballast cleaning, tamping, sleeper renewal or additional stabilisation measures where justified by field condition. On individual hot days, the hourly risk forecast can also help route patrol teams first to segments expected to enter the high-risk regime earliest, rather than relying only on uniform patrol patterns and static vulnerable-section lists [2].

4.2 Traceable risk history and decision rationale

A further result of the integrated service is systematic digital documentation. For each hot day, the RWP can retain predicted RTT and buckling risk by segment and hour, together with threshold exceedances, active alerts and recorded operational responses. ISR feedback identified this as an important complement to current documentation, which is largely textual and distributed across different systems. A georeferenced risk archive can provide traceable justification for past restrictions and non-actions, support post-incident and near-miss analysis, and create a data source for refining thresholds and identifying repeatedly critical locations for climate-adaptation and reinvestment planning [2].

4.3 Requirement coverage and maturity at pilot scale

[2] assesses the main functional and non-functional requirement groups as fully or largely met at pilot scale. The core processing chain is fully implemented: thermal downscaling, RTT prediction, buckling-risk and lateral displacement assessment, quality control, threshold monitoring and WebGUI delivery all operated as an integrated service. User-facing workflows for map exploration, segment time series and alert review were also demonstrated. Performance and usability were considered adequate for the pilot, while the principal open issues concern parameter sensitivity, extension of the lateral-displacement model to different track typologies, richer configuration and explanations, and deeper integration with ISR control-room tools. The overall demonstration therefore supports the SPATRA project conclusion of TRL6 and technical readiness for pre-operational use, not yet network-wide autonomous operation.

5. LESSONS AND DEPLOYMENT REQUIREMENTS

The SPATRA rail pilot confirms that EO and in-situ data are complementary rather than interchangeable. Satellite and meteorological products provide spatial continuity over the corridor, while local stations provide ground truth and measurements, such as lateral displacement, that cannot be obtained directly from EO. [2] and [4] also report that the complete RWP chain operated reliably at pilot scale; threshold exceedances were detected within 30 s and processing completed within 1 min for more than 95% of cases in the validation logs, supporting near-real-time use during heatwaves.

At the same time, network-wide use requires conditions that go beyond the successful pilot. A sparse but representative sensor network is needed for different climatic and track typologies, together with regular maintenance of rail-neutral temperature, geometry, fastening, ballast and track-quality data. Risk alerts should be integrated into ISR dispatch, traffic-management and asset-management environments so that they appear alongside existing operational information. Formal procedures must define responsibilities and threshold-to-action mappings, and users require concise training on interpretation of risk indices and confidence levels [2].

SPATRA final report [2] therefore recommends a phased transition: formalise RWP-supported operating procedures; standardise role-specific WebGUI views and legends; link alerts directly to the affected

segment and time context; use the digital archive systematically in safety reviews; incrementally extend reference sensors; and, in the medium term, integrate the service with ISR operational and asset databases. Multi-year data should then be used to refine site-specific thresholds and sustain model calibration as part of normal service lifecycle management.

6. CONCLUSION

The SPATRA Railway Pilot demonstrated an end-to-end EO-enabled service for heat-related rail buckling risk under realistic operating conditions on the Niš-Svrljig demonstration corridor. The project integrated evidence reported shows reliable rail-temperature prediction in the pilot sample, correct identification of the documented 24 July 2025 high-risk segment, a substantial potential reduction in the duration of heat-related slow-speed operation, and very high user acceptance after interface refinement. The principal operational contribution is not automated replacement of existing Railway Infrastructure Manager procedures, but a more spatially and temporally specific evidence layer for speed restrictions, inspection planning and documentation. The pilot achieved the project target of TRL6, while progression towards sustained operational use depends on sensor and asset-data governance, formal workflow integration, model maintenance and continued validation on additional lines and seasons.

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