Onboard track stiffness variation monitoring using hybrid signal processing techniques

Reza Naseri, Brennan L. Gedney, Dimitris C. Rizos
University of South Carolina, Columbia, SC, USA

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Introduction

Railway networks face growing demands due to heavier loads and faster trains, making infrastructure health assessment more important than ever. Subtle variations in track stiffness caused by issues like ballast fouling, tie deterioration, or subgrade failure often precede more serious failures such as mud pumping, hanging ties, or settlement. Yet, most railroads still rely on costly, periodic inspections that often miss early-stage problems.

Vibration-based monitoring using onboard sensors has emerged as a promising alternative for continuous assessment. However, existing methods struggle with signal complexity, environmental noise, and massive data loads that limit real-time application.

To address these gaps, we propose a hybrid signal processing framework shown in Figure 1 that uses onboard acceleration data to detect localized stiffness changes with high precision.

This method was tested on acceleration data from in-service railcars and validated through simulation and field studies, demonstrating its ability to reveal subtle structural variations using instantaneous energy signatures.

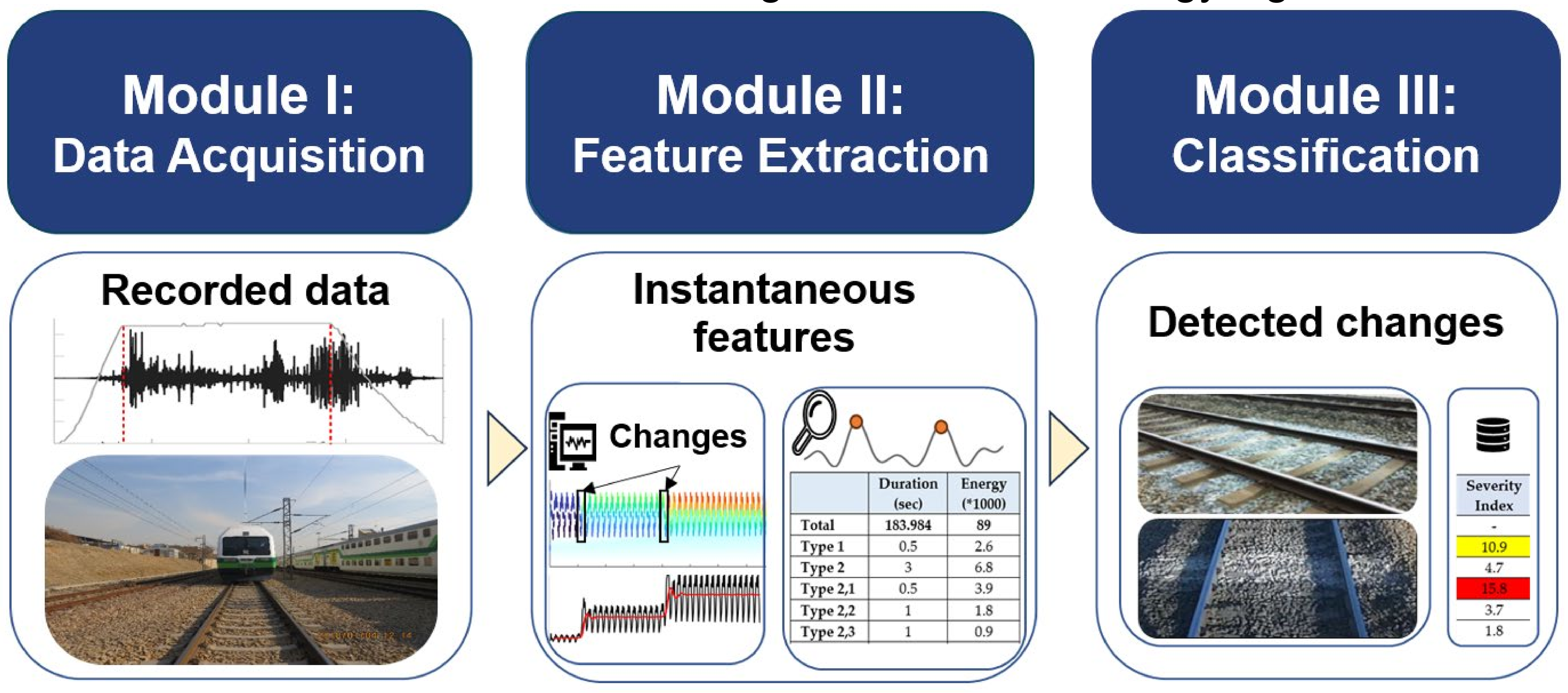

Figure 1: The three key modules of the proposed system

Experimental work

This study used acceleration and GPS data from in-service light rail vehicles in Pittsburgh collected by Liu et al. (2019). Tri-axial accelerometers were mounted on the non-powered bogie frame to record vertical dynamics at 1.6 kHz, with GPS sampled at 1 Hz. Multiple runs were performed over the track segment between Bon Air and Denise stations, which includes a bridge section. Figure 2 shows the instrumented train, the track segment, the bridge, and an example of the recorded signal.

For signal processing (Module II), Wavelet Packet Analysis decomposed the data across frequency bands to localize stiffness-related transients. Empirical Mode Decomposition extracted intrinsic mode functions to isolate non-stationary features, and the Hilbert Transform quantified instantaneous energy and frequency.

Processed signals were analyzed over time. Unsupervised clustering helped distinguish normal track behavior from zones of potential degradation.

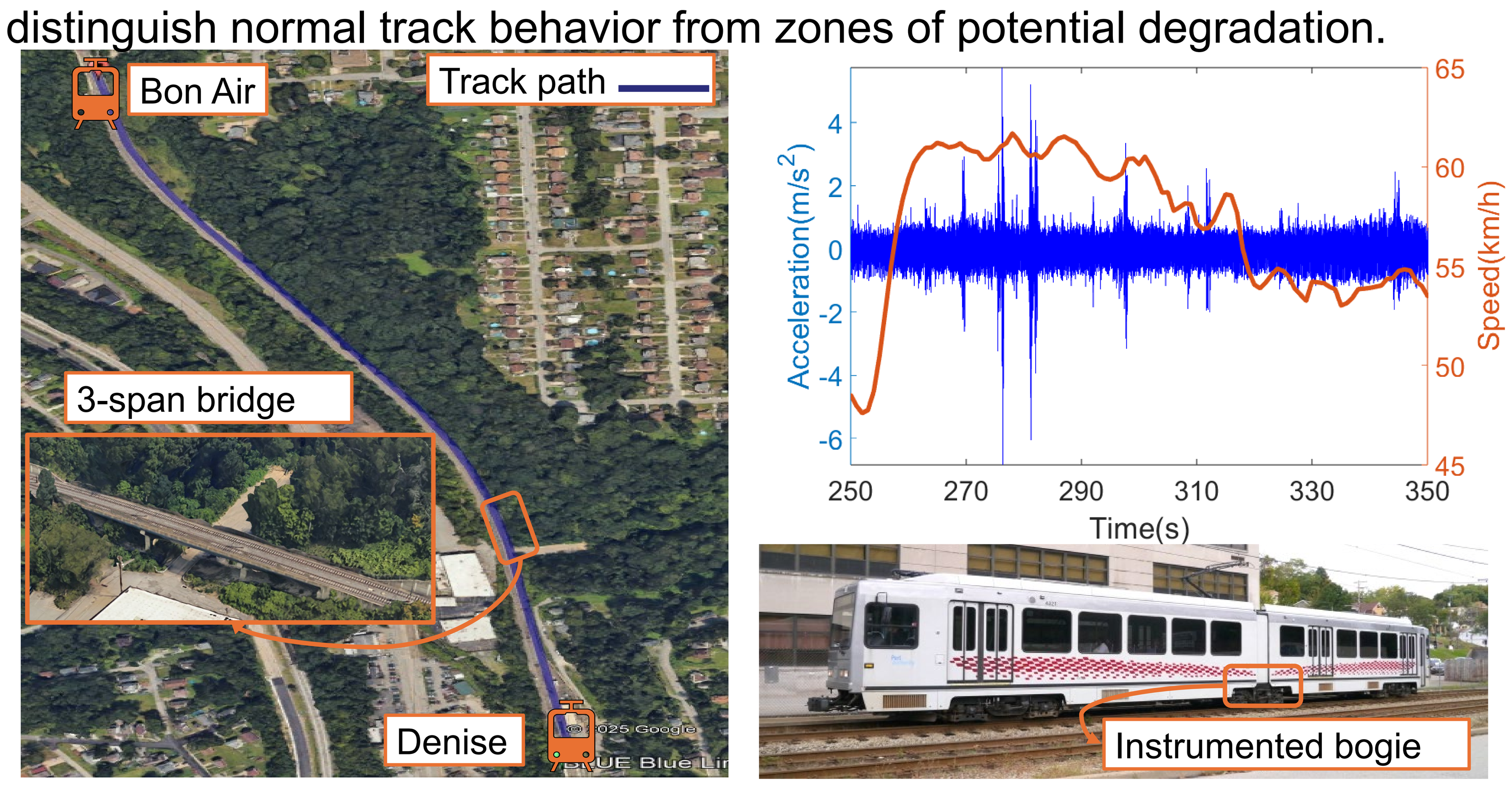

Figure 2. Field test: Instrumented train, track section, and recorded data

Results

Figure 3 shows how instantaneous energy varied along the track segment, using signals compacted by over 95%. The graph compares measurements collected before and after tamping and resurfacing maintenance. Two main peaks (2 and 5) near 4890 m and 4990 m indicate the bridge (80m long) and its transition zones (10 m each). Smaller fluctuations between them correspond to intermediate piers where stiffness changes are expected due to structural supports.

While maintenance reduced energy across most of the track, the bridge area showed only slight improvement, suggesting its dynamic response remained largely unchanged. Before the bridge, energy levels remained high near the switch, indicating a locally stiffer or dynamically distinct region.

Overall, energy levels dropped, confirming better track conditions. However, some spikes (6, 9, and 10) persisted after maintenance, likely reflecting persistent subgrade irregularities or soft spots contributing to localized settlement. In contrast, spikes 7 and 8 were successfully addressed, showing localized maintenance benefits.

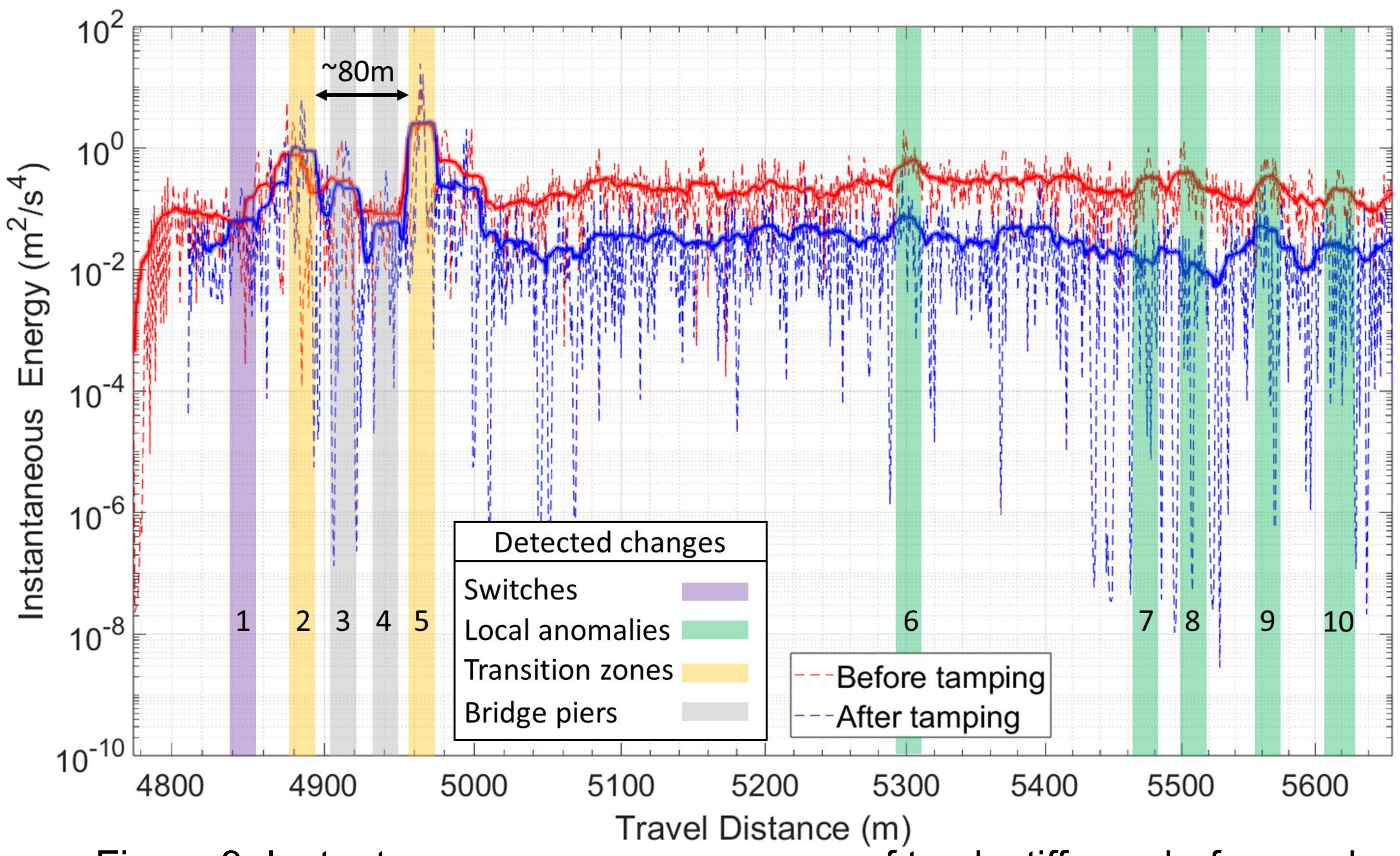

Figure 3: Instantaneous energy as a proxy of track stiffness before and after maintenance

Conclusions

This study demonstrated that instantaneous energy, derived from vertical acceleration, serves as a stiffness-sensitive proxy for identifying track condition during normal train operations. Combining Wavelet Packet Analysis, Empirical Mode Decomposition, and Hilbert Transform enabled precise identification of weak spots without intrusive inspections. The results confirm that this approach is both compressible and interpretable, supporting near real-time monitoring. These findings align with recent research and suggest strong potential for improving maintenance, reducing risks, and extending track life. Future work will include additional dynamic measurements and advanced classifiers to broaden application across varied rail environments.

References

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For further information please contact:
Reza Naseri, University of South Carolina, rnaseri@email.sc.edu

University of South Carolina

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