Engineering-Based Early-Life Indicators for Predictive Maintenance in Urban Rail Systems

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Abstract

Predictive maintenance strategies in urban railway systems have increasingly relied on sensor-based monitoring, large datasets, and advanced analytics. While these approaches are effective for mature networks, they present limitations for newly constructed or recently renewed lines, where historical data is scarce and degradation mechanisms are not yet fully developed. This paper proposes an engineering-based approach to predictive maintenance that leverages early-life track behavior as a source of leading indicators for future maintenance demand.

The study focuses on the initial operational phase of urban rail infrastructure, during which the interaction between track design, construction quality, and wheel–rail contact conditions establish the foundation for long-term performance. Rather than relying on extensive monitoring systems, the proposed framework emphasizes observable engineering indicators such as alignment retention, structural response of fastening systems, surface condition development, and asset-specific sensitivity in high-stress locations.

A structured observational methodology is introduced, including asset classification, definition of early-life indicators, and interpretation of their implications for maintenance planning. The approach highlights how deviations from expected early-life behavior can signal accelerated degradation paths, particularly in curves, transition zones, and structurally constrained environments. These indicators are discussed in relation to existing literature on wheel–rail interaction, track degradation, and lifecycle performance.

The findings suggest that early-life engineering observations can significantly enhance predictive maintenance strategies by enabling earlier and more targeted interventions, reducing lifecycle costs, and improving the integration between construction, operation, and maintenance phases. The paper concludes that predictive maintenance should not be treated solely as a data-driven discipline but as an integrated engineering process that begins at the earliest stages of infrastructure operation. Recommendations for further research include the integration of early-life indicators with sensor-based systems and the extension of the proposed framework to other urban rail contexts.

Keywords

Predictive maintenance, urban railways, early-life track behavior, wheel–rail interaction, track design, infrastructure lifecycle, engineering indicators.