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EMPHASIZING STATISTICAL RELATIONSHIPS BETWEEN PAVEMENT SURFACE ROUGHNESS INDEX AND SUBGRADE GROUND PROPERTIES ON SPATIAL FEATURE EXTRACTION

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The structural assessment of asphalt pavements is critical for efficient road maintenance and resource allocation. Traditional techniques, such as Falling Weight Deflectometer (FWD) testing, while accurate, are costly, labour-intensive, and disruptive to traffic flow, presenting major draw backs. This study explores the potential of estimating the structural capacity of asphalt pavements by leveraging functional parameters, specifically the International Roughness Index (IRI), a widely accessible and cost-effective metric for surface roughness. Utilizing data from six road sections across Ghana, totalling 219 km, the research develops a framework for predicting the Effective Structural Number (SN_{eff}) based on decomposed IRI data. The Robbins-Monro Kalman Filter was utilized to decompose IRI measurements into trend and random components, effectively isolating latent patterns obscured in raw data. Additionally, simple logarithmic transformations were applied to optimize data normalization for improved correlation analysis. The findings indicate that the decomposed IRI data exhibits significantly stronger correlations with SN_{eff} compared to raw IRI. While individual road sections demonstrated varying correlation strengths, the combined dataset,which includes diverse traffic, material, and climatic conditions,yielded a more predictive relationship.

Keywords: Spectra analysis, Fallingweight deflectometer, International roughness index, Flexible pavements, Structural evaluation, Decomposition.

1. Introduction

The effective maintenance of asphalt pavements is critical for developing countries, where road infrastructure remains a fundamental component of national transportation systems. This is particularly true in regions like Ghana, where limited resources underscore the need for optimized pavement management strategies. Among the various indices used to assess pavement conditions, the International Roughness Index (IRI) has gained prominence due to its ability to provide a measurable indication of pavement surface roughness, which is directly correlated with ride quality and pavement distress levels. Simultaneously, Falling Weight Deflectometer (FWD) testing is frequently employed to evaluate the stiffness and structural integrity of underlying pavement layers and the subgrade.However, while both IRI and FWD data are valuable for pavement condition assessment, acquiring comprehensive FWD data across extensive road networks can be financially prohibitive due to the high cost of FWD testing equipment and procedures.

Recent advancements in data-driven techniques, including machine learning, have revolutionized the scientific landscape (Otake et al., 2024) and opened promising avenues for using simpler, widely available data, such as IRI, to infer complex pavement parameters that would otherwise require costly FWD measurements. Prior research has explored the potential for leveraging large datasets from IRI measurements, yielding mixed results. For instance, the Federal Highway Administration (FHWA, 2012) analyseddata from Long-Term Pavement Performance (LTPP) to investigate whether IRI variations could indicate changes in Effective Structural Number(SN_{eff}), which is a measure of the pavement's structural capacity, along flexible pavement wheel paths. Despite employing normalized plots and comparative analyses, the study concluded that no clear correlation existed, emphasizing that good ride quality does not necessarily indicate structural soundness. Similarly, AI-Omari and Darter (1995) found weak correlations between IRI and rut depth for individual pavement sections in LTPP database. However, aggregated analyses of IRI ranges revealed stronger statistical relationships, suggesting the potential for deeper insights when considering broader datasets.Chandra et al. (2013) demonstrated that Artificial Neural Networks (ANNs) could accurately model relationships between pavement roughness and distress parameters such as potholes and rutting, outperforming traditional regression approaches. Nearly all these investigations relied on raw IRI data, whether studying surface distresses like potholes and cracking or exploring structural relationships with parameters such as SN_{eff}. Despite these advances, there remains a critical need to understand the statistical relationship between IRI and FWD data, particularly in varying site conditions characteristic of Ghana's diverse road network.

This study aimed to address this gap by investigating the statistical relationship between IRI and FWD data across a section of Ghana's road network to establish a foundation for a more resource-efficient pavement management system. We hypothesized that IRI data, which can be collected more frequently and cost-effectively, may serve as a proxy for certain pavement layer structural properties and subgrade as determined by FWD testing. By analyzing spatial and temporal variations in IRI data alongside FWD derived layer modulus values, this research sought to uncover trends and correlations that could facilitate predictive modeling and support strategic maintenance planning.

A notable challenge in using IRI data for structural assessments lies in its inherent components: IRI measurements are influenced by both trend(non-stationary) components, associated with subsurface settlement or pavement design, and random (stationary) components, such as localized surface irregularities or measurement noise. Disentangling these elements could reveal underlying patterns linked to pavement deterioration,enhancing predictive modeling for pavement management, whichis a key element of network-level pavement management systems (Mizutani et al. 2020). In this study, we separated the trend and random components of IRI data and examined their correlation with FWD-measured pavement stiffness to assess the feasibility of using IRI as a surrogate indicator for structural integrity over extended road sections

The research also addressed the statistical properties of IRI-FWD relationships under different site-specific conditions by examining individual road sections and aggregating data across multiple sections to discern broader trends. Such a dual-level analysis, localized and generalizedmay reveal fundamental interdependencies that inform targeted maintenance and forecasting practices across varying environmental and design conditions. Ultimately, this study lay the groundwork for a cost-effective, data-driven pavement management approach by enabling a more strategic use of IRI data to infer essential geotechnical properties, thereby extending the lifespan of pavements and optimizing resource allocation for infrastructure maintenance in Ghana.

2. Data

2.1. *Data Description*

This study utilizes data from six road sections spanning four regions in Ghana, totaling 219 km in length. The individual road section lengths are 42 km, 14.9 km, 70.6 km, 31.9 km, 28.8 km, and 31.7 km, respectively. Sections 1 to 3 are situated in the Eastern Region, Section 4 in the Central Region, Section 5 in the Bono Region, and Section 6 in the Greater Accra Region. For each section, both IRI data (collected from 2021-2024) and FWD deflection data (collected from 2017-2024), providing the basis for analysing the relationship between surface roughness and structural strength.The selection of these road sections was driven by the diverse characteristics of the data, offering variability in terms of traffic volumes, climatic conditions, and material composition. Each region presents unique factors influencing pavement deterioration. This diversity provides a comprehensive dataset that enhances the robustness of the analysis, allowing for a more in-depth investigation into the relationship.

2.2. *Data Collection*

The deflection testing for all sections was conducted using the Dynatest FWD Model 8002-288, a standard device for measuring pavement deflection under controlled loads, providing data on individual pavement layers and subgrade strength. The in-situ structural condition of the pavement was assessed through the deflection bowl at each test location. Deflection tests were conducted along the external wheel path at 100-meter intervals in both directions of the road, with test points staggered at 50-meter intervals. A maximum load of 40 kN was applied during the tests, ensuring that the measurements accurately reflected the pavement's load-bearing capacity. IRI data was collected at 50-meter intervals using pavement roughness measuring devices to align with the FWD measurements.

2.3. *Material Composition*

The material composition of pavement layers is a fundamental aspect of road construction, directly influencing the structural capacity, durability, and long-term performance. Each road section in this study incorporates a unique combination of materials tailored to meet the specific demands of traffic loads, climatic conditions, and expected service life. Typically, pavements consist of several layers, including an asphalt concrete (AC) wearing course, binder course, base, and subbase, with some sections utilizing dense bitumen macadam (DBM) or cement-stabilized materials to enhance structural integrity. The variations in layer thicknesses and material types across the different sections reflect both regional construction practices and the specific engineering requirements for each road.

3. Methodology

3.1. *Robbins-Monro Kalman Filter*

IRI data, being non-stationary, exhibits local observation errors and fluctuations due to various factors such as road conditions, traffic load, and environmental changes. Non-stationary data, like the IRI in this study, cannot be modelled with simple static techniques because the data's statistical properties, such as mean and variance, change over time. To address this challenge, we utilize the Robbins-Monro Kalman Filter (Robbins & Monro 1951), a variation of the Kalman filter that is specifically designed for handling non-stationary data and dynamic systems. Unlike the traditional Kalman filter, which operates within a Bayesian framework and assumes that the underlying system is linear with gaussian noise, in this approach, the filter iteratively updates parameter estimates to optimize a function based on noisy observations and modifies the update equations to accommodate real-time changes in the system.The application of the Robbins-Monro Kalman Filter enables the decomposition of IRI data into trend, random components, as shown in Fig. 1.

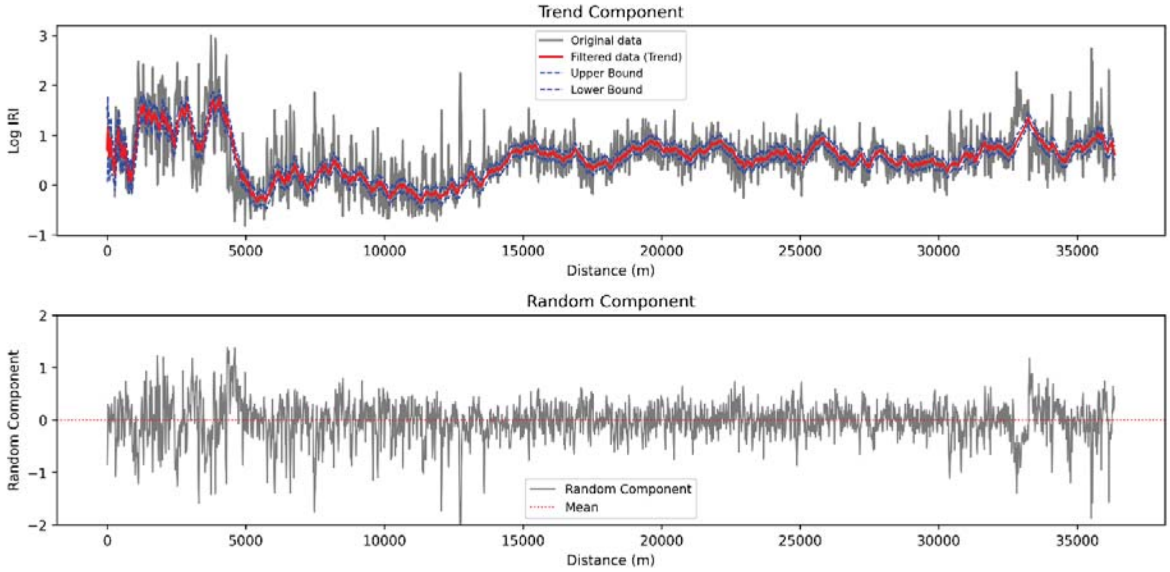


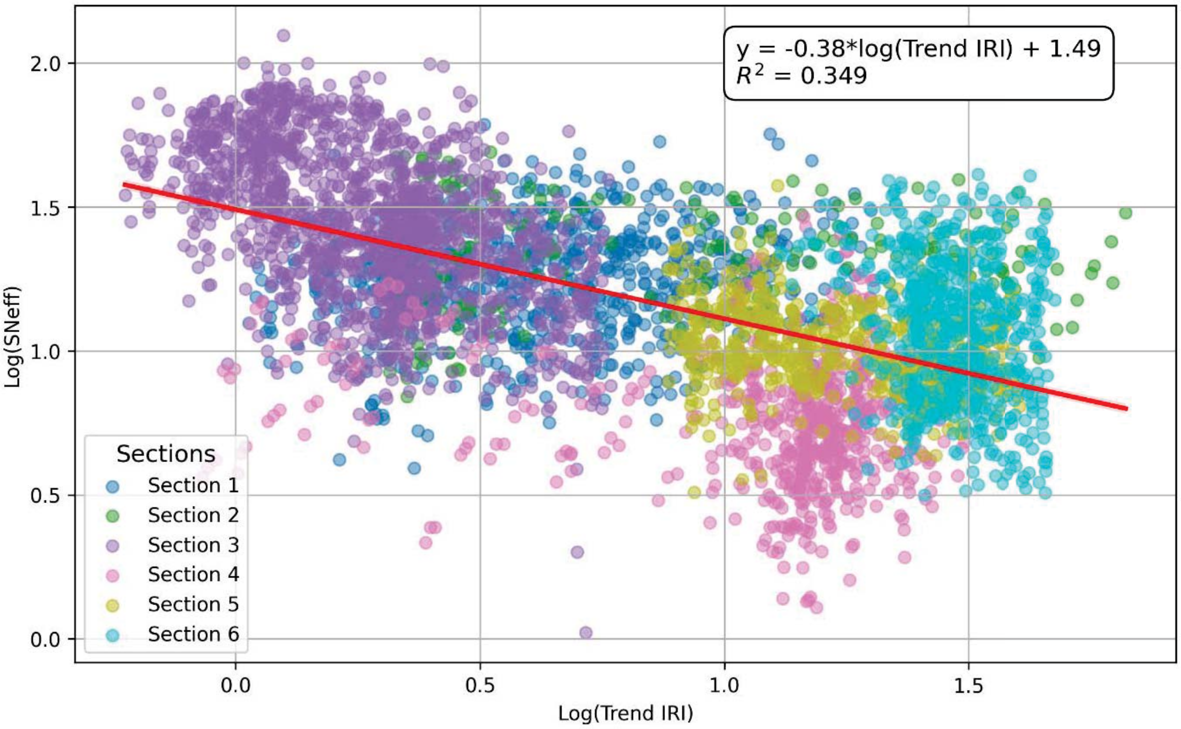
Fig. 1. Visualization of the decomposition of IRI(m/km). (Top panel) Original IRI data (gray) and filtered trend component (red) with upper and lower bounds (blue and dashed red). (Bottom panel) Random components of the decomposed data, showcasing residual variations post-filtering.

3.2. *Effective Structural Number (SN$_{eff}$) Determination*

The effective structural number (SN$_{\text{eff}}$) was computed as described in the 1993 AASHTO Empirical Pavement Design Guide (AASTO, 1993). The study adapted the simplified model proposed by Kavussi et al. (2017), which estimates SN$_{\text{eff}}$using FWD deflection data alone.The model, originally developed from 2,453 FWD test points in Khuzestan province in southern Iran, uses deflection bowl parameters to strongly correlate with SN$_{\text{eff}}$ values. Abd El-Raof et al. (2018) calibrated the regression coefficients of the model K_1, K_2 and K_3 and recommended for general application based on its efficiency and simplicity.

4. Results

The analysis of the relationship between the raw IRI and SN$_{\text{eff}}$, revealed a weak correlation $(R^2 = 0.136)$, suggesting that raw IRI data alone may not adequately capture the structural properties represented by SN$_{\text{eff}}$. Decomposing IRI into its trend and random componentssignificantlyimproves the correlation$(R^2 = 0.301)$, emphasizing the value of isolating the trend to reduce noise. A further improvementwas observed with a simple logarithmic transformationof both trend IRI and SN$_{\text{eff}}$, as illustrated inFig.2, achieving a higher correlation$(R^2 = 0.349)$ and suggesting a non-linear relationship. Whilethis correlation remains moderate, the observed improvement highlights the potential of further refinement to enhance predictive accuracy. These results emphasize the importance of preprocessing and transformation in uncovering meaningful structural relationships.



5. Conclusion

This study demonstrates how the decomposition of IRI data effectively reveals hidden structural relationships that are not apparent in raw datasets. Analysing the correlation between FWD data and the IRI on a section-by-section basis suggests an absence of a strong correlation. The fundamental property of layer and subgrade capacity, clearer relationship emerged, despite significant site variability. This tendencywas more pronounced when focusing on the trend component alone, as opposed to using raw data without decomposition.. This suggests that variability across sites plays a significant role in highlighting correlations when data from diverse environmental contexts are pooled.These results imply that additional factors, such as site-specific environmental conditions, traffic loads, and pavementdesignswhich vary across sections and were not considered in this studymay contribute to an interdependent relationship. These influences potentially manifest as non-linear correlations between FWD and IRI.Although this study did not isolate the source of these interdependencies or non-linear relationships, it suggests the potential utility of advanced methodologies in addressing such challenges. Approaches like neural networks, hierarchical Bayesian modelling for site-specific analysis, and similarity assessmentstools gaining traction in geotechnical researchmay provide valuable insights by accommodating site variability and complex interdependencies.Consistent with findings from Sollazzo et. al.(2017), these insights suggest that integrating both intrinsic and extrinsic factors of pavement structures could enhance the predictive capability of using IRI data to estimate subgrade characteristics. Such a model could highlight fundamental differences between sections, aiding in identifying inherent weaknesses and susceptibility to deterioration.

Fig. 2. Regression analysis of log-transformed Trend IRI and log-transformed SN_{eff} across six sections, represented by different colors. The scatter statistics vary by section, highlighting site-specific variabilitywith fitted regression line, illustrating a negative linear relationship. The logarithmic transformation improves correlation and reveals a non-linear trend.

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