Cost-Effective Pavement Roughness Assessment: Implementation and Validation of Solid-State LiDAR for IRI Measurement

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ABSTRACT: This study investigates the potential of solid-state LiDAR (SSL) technology for measuring the International Roughness Index (IRI) as an alternative to inertial profilers. Using a Livox HAP SSL sensor mounted on a vehicle alongside a reference SSI inertial profiler, measurements were conducted on a 100-meter road section exhibiting varying roughness conditions. Point cloud data from the SSL was processed to extract elevation profiles at 30-centimeter intervals, and IRI values were calculated using the quarter-car model. Comparative analysis revealed acceptable agreement between SSL and inertial profiler, with an R^2 of 0.821, MAE of 1.3 (m/km), and RMSE of 1.7 (m/km). While the SSL system showed some limitations in high-roughness zones, the overall results demonstrate its potential as a cost-effective alternative for pavement condition assessment, particularly in moderate roughness conditions.

1 INTRODUCTION

The International Roughness Index (IRI) serves as a standardized mathematical index computed from the longitudinal profile that characterize the ride quality of a road surface. This critical metric has become the global standard for evaluating road surface conditions, playing a vital role in pavement management systems and maintenance decision-making processes. Transportation agencies worldwide rely on IRI measurements to assess road quality, plan maintenance schedules, and allocate resources effectively, as road surface conditions directly impact vehicle operating costs, safety, and user comfort (Sayers, 1995).

IRI measurements are primarily conducted using inertial profilers equipped with high-frequency laser sensors. These systems combine precise laser measurements with accelerometer data to generate accurate road profile measurements while compensating for vehicle dynamics. The laser-based inertial profilers have demonstrated high accuracy and reliability in measuring road roughness, making them the industry standard for pavement condition assessment (Chang et al., 2006). However, these systems come with significant limitations that restrict their widespread adoption, particularly among smaller transportation agencies and contractors. The primary constraints include substantial initial investment costs, ongoing maintenance requirements, and operational expenses. Furthermore, these systems require specialized training and certified operators, adding to the overall cost and complexity of implementation.

In recent years, researchers have begun exploring alternative technologies for IRI measurement to address these limitations (Fares and Zayed, 2023). Various sensing technologies, including RGB-D sensors, depth cameras, and LiDAR systems, have emerged as potential solutions for road roughness measurement (Zhang et al., 2024). These technologies offer promising advantages in terms of cost-effectiveness and ease of use. However, their application in IRI measurement requires further investigation to validate their accuracy and reliability compared to traditional inertial profilers.

This study aims to evaluate the potential of solid-state LiDAR technology, one of the latest advancements in LiDAR systems, for IRI measurement. Solid-state LiDAR represents a significant technological evolution, offering advantages such as no moving parts, compact size, and potentially lower costs compared to traditional mechanical LiDAR systems. In terms of cost comparison to inertial profilers, a typical inertial profiler can exceed $150,000 in purchasing costs, with additional operational and maintenance expenses increasing lifetime costs further. In contrast, the solid-state LiDAR sensor utilized in this study was acquired for approximately $1,500, underscoring its economic advantage for pavement condition assessment. This research focuses on developing and validating a methodology for IRI measurement using solid-state LiDAR, with particular emphasis on comparing its accuracy against conventional inertial profiler measurements. By investigating this emerging technology, this study seeks to contribute to the development of more accessible and cost-effective solutions for road condition assessment while maintaining acceptable levels of accuracy for pavement management applications.

2 METHODOLOGY

2.1 *Data Collection*

The data collection process involved a comprehensive setup combining solid-state LiDAR with traditional inertial profiling equipment for validation purposes. The primary sensor used in this study was a Livox HAP solid-state LiDAR (SSL), which represents the latest generation of LiDAR technology without moving mechanical components. The SSL device was mounted on the rear of the vehicle using a secure suction cup mounting system, oriented in a top-down configuration to capture detailed point cloud data of the pavement surface. This mounting position was specifically chosen to optimize the sensor's field of view and ensure consistent data capture of the road surface profile.

To enhance the data collection process and provide additional contextual information, a GoPro camera was installed directly above the SSL unit. This camera served dual purposes: capturing high-resolution images of the pavement surface for visual reference and documentation, while simultaneously recording GPS coordinates. The GPS data was particularly crucial as it allowed for precise spatial registration of the SSL point cloud data, enabling accurate correlation between different measurement systems and facilitating subsequent data analysis.

For validation purposes, this study employed an SSI inertial profiler, which represents the current industry standard for IRI measurement. The inertial profiler was mounted on the same vehicle to ensure simultaneous data collection under identical conditions, allowing for direct comparison between the SSL measurements and the established reference measurements. Figure 1. shows the data collection equipment and setup. Additionally, a Jetson AGX Orin module was utilized to enable real-time processing and rapid integration of sensor data streams. This real-time processing capability enhances the potential of the systems for efficient implementation in large-scale road network assessments.

The field testing was conducted on a carefully selected 100-meter road section in Columbia, Missouri. This test section was specifically chosen for its diverse range of surface conditions, exhibiting IRI values ranging from low to high. The variability in surface roughness within this single test section provided an ideal environment for evaluating the SSL system's performance across different roughness conditions. This strategic selection of the test section enabled the research team to assess the accuracy and reliability of the SSL-based measurements across a broad spectrum of pavement conditions within a controlled testing environment.

Figure 1. Data collection equipment and setup.

2.2 *Longitudinal Profile Extraction*

The extraction of longitudinal profiles from the collected point cloud data required a systematic approach to transform raw SSL data into meaningful elevation measurements suitable for IRI calculation. The process began with the temporal synchronization of the GoPro camera and SSL data streams, which allowed for the precise mapping of GPS coordinates to each point cloud frame. This synchronization was crucial as it enabled the transformation of the SSL's local coordinate system measurements into global coordinates, providing a standardized reference frame for the entire dataset.

Following the coordinate transformation, a thresholding approach was implemented to isolate the relevant points corresponding to the wheel path on the pavement surface. This selective extraction was essential for focusing the analysis on the specific path that influences vehicle response and ride quality. The thresholding process effectively filtered out peripheral data points while retaining the critical elevation measurements along the wheel path.

To facilitate IRI calculation, which requires regularly spaced elevation measurements, this study established a fixed sampling interval of 30 centimeters (equivalent to 1 foot) along the longitudinal profile (ASTM., 2005). At each sampling point along the longitudinal profile, elevation values were extracted from the point cloud data, creating a discrete elevation profile suitable for subsequent IRI computation. Although a finer interval might offer even more detailed profiling, the 30 cm spacing was selected to balance the sensor’s inherent resolution with data processing constraints.

2.3 *IRI Measurement*

The IRI is calculated using a mathematical model known as the quarter-car model, which simulates the dynamic response of a simplified vehicle suspension system traveling over a road surface. The quarter-car model consists of four primary components that work together to simulate vehicle dynamics. The sprung mass (representing one-quarter of the vehicle body mass), the unsprung mass (representing the wheel assembly), a spring element (simulating the primary suspension system), and a damper (representing the shock absorber) (Sayers, 1995).

The model processes road profile data by simulating the vehicle's response while traveling at a standardized speed of 80 kilometers per hour (50 mph). During this simulation, the system's response to road surface variations is governed by a set of differential equations that describe the dynamic interaction between the vehicle components and the road profile. These equations incorporate specific mechanical parameters that have been standardized worldwide, including precise spring rates, damping coefficients, and mass ratios. The IRI value is ultimately derived from the accumulated suspension motion, calculated as the sum of the relative displacement between the sprung and unsprung masses, normalized by the distance traveled.

For analysis and verification purposes, IRI measurements were obtained through two methods. First, the reference IRI values were extracted directly from the SSI inertial profiler measurements of the test section. Second, a Python script was used to calculate IRI values using the elevation data extracted from the SSL point clouds, implementing the quarter-car model to process these measurements (Šroubek et al., 2021). This dual approach enabled direct comparison between the inertial profiler measurements and the SSL-based results.

3 EXPERIMENTAL RESULTS

The experimental results demonstrate a strong correlation between IRI measurements obtained from the solid-state LiDAR (SSL) system and the reference SSI inertial profiler. The comparison of these two measurement systems was conducted through both longitudinal profile analysis and statistical correlation assessment.

The overall IRI comparison, illustrated as Figure 2., shows the IRI values measured by both systems along the 100-meter test section. The profile reveals that both systems captured similar patterns of road roughness variations throughout the section. The SSL measurements (shown in red) closely tracked the SSI measurements (shown in blue), with mean IRI values of 7.09 m/km and 7.77 m/km respectively. This difference in mean values indicates that the SSL system typically produced slightly lower IRI measurements than the reference system, but the overall difference remained relatively small at 0.68 m/km.

The IRI values show particularly higher agreement in sections with moderate roughness (between 4-8 m/km). Notable variations between the two systems were observed in areas of high roughness, particularly around the 40-meter and 80-meter marks, where IRI values peaked above 14 m/km. In these high-roughness zones, the SSL measurements sometimes underestimated the peak values compared to the SSI system, though they still captured the general pattern of roughness variation. This discrepancy may be due to differences in spatial resolution and measurement patterns between the SSL and SSI systems. The unevenly distributed SSL point clouds, coupled with the relatively larger sampling interval, can smooth out sharp peaks in high-roughness areas, thereby affecting the accuracy of IRI values.

The statistical correlation analysis, presented in Figure 3., provides a quantitative assessment of the agreement between the two measurement systems. The analysis yielded an R-squared value of 0.821, indicating an acceptable positive correlation between the SSL and SSI measurements. This high correlation coefficient suggests that approximately 82% of the variance in SSL measurements can be explained by the SSI reference measurements, demonstrating reliability of the SSL system.

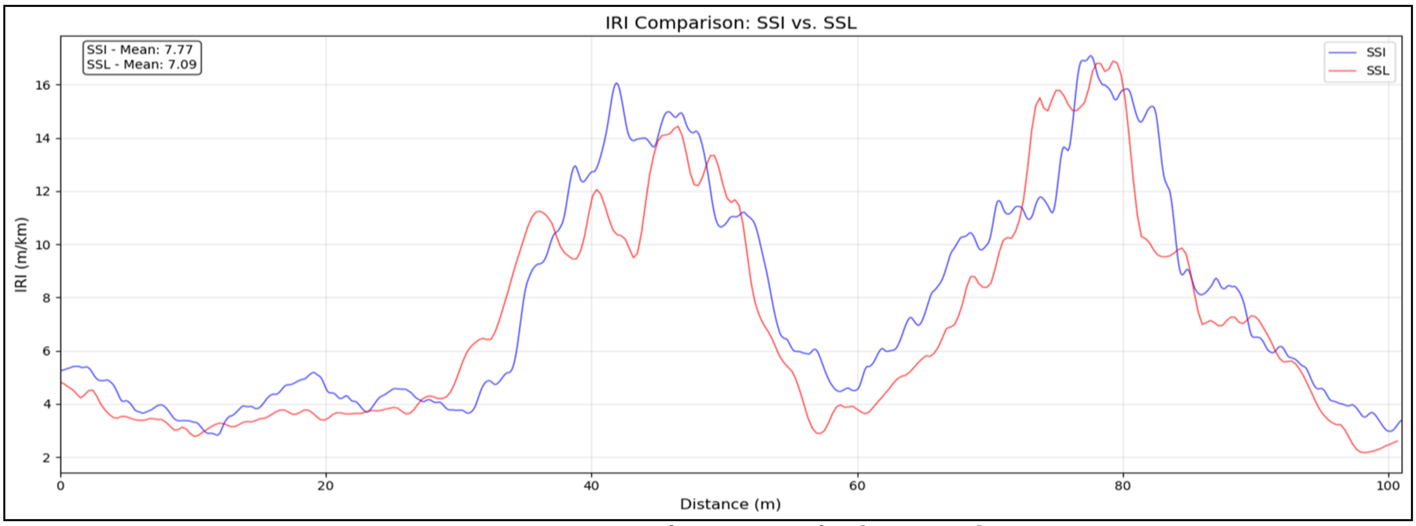

Figure 2. IRI comparison of SSL vs. SSI for the test road section.

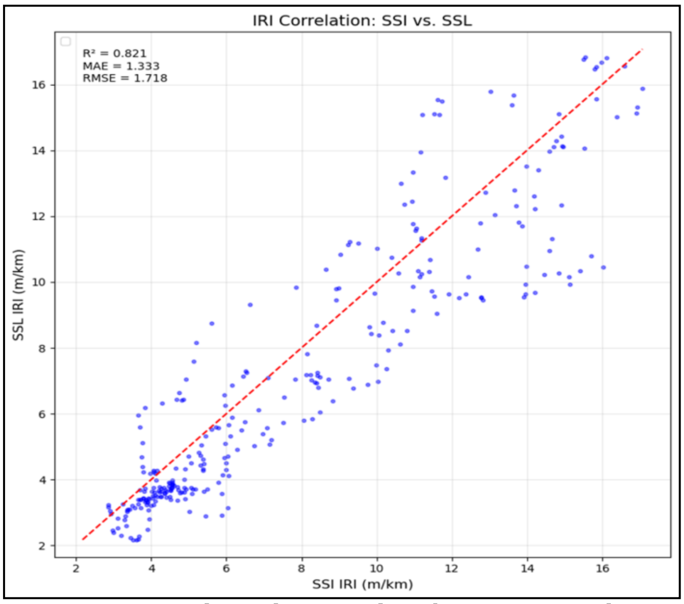

Figure 3. Statistical correlation analysis between SSI and SSL.

The accuracy of the SSL system was further quantified through error metrics. The Mean Absolute Error (MAE) of 1.333 m/km indicates the average magnitude of measurement differences between the two systems. The Root Mean Square Error (RMSE) of 1.718 m/km, being slightly higher than the MAE, suggests the presence of some larger discrepancies, particularly in the high-roughness regions as observed in the IRI profile. These error metrics, while indicating potential for further improvement, demonstrate promising performance for the SSL system, especially considering the complexity of road roughness measurement and the innovative nature of the technology.

4 CONCLUSION

This study demonstrates the potential of solid-state LiDAR technology as a viable alternative for measuring IRI in pavement condition assessment. Through field testing and analysis, the research validates that SSL-based measurements can achieve acceptable levels of accuracy when compared to inertial profiler systems, with a correlation coefficient of 0.821 between the two measurement methods.

The SSL system showed particularly promising performance in sections with moderate roughness levels (4-8 m/km), where it consistently tracked the reference measurements with high fidelity. While some discrepancies were observed in high-roughness regions, the system successfully captured the overall patterns of surface roughness variation. The relatively small difference in mean IRI values between the SSL and SSI systems (0.68 m/km) further supports the potential of this technology for practical applications. The results suggest that solid-state LiDAR could offer a more accessible alternative to traditional inertial profilers, potentially addressing the significant barriers of high cost and operational complexity. Future studies could further enhance accuracy by integrating additional sensors, such as Distance Measurement Instrument (DMI) to complement the LiDAR data and address current measurement limitations.

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