



Analysis of Calibration and Validation of Road Roughness Survey Equipment (Hawkeye 2000) Based on SNI 3426:2022

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Abstract: Road roughness measurement using the International Roughness Index (IRI) plays a critical role in road asset management, influencing maintenance prioritization and budget allocation. However, discrepancies between instruments may introduce bias without proper calibration. This study aims to analyze the calibration and validation of the Hawkeye 2000 as a Digital Laser Profiler for IRI measurement based on SNI 3426:2022. Calibration was conducted using a Walking Profilometer as the reference instrument, followed by validation on five test segments (SP1–SP5) with lengths of 100–500 meters under three speed variations (40, 50, and 60 km/h). The results show that the Hawkeye 2000 meets the requirements of SNI 3426:2022, with coefficients of determination (R^2) of 0.9819 (left), 0.9850 (right), and 0.9820 (combined), indicating high accuracy. The coefficient of variation (CV) ranges from 0.0159 to 0.0241 (<5%), reflecting high precision. Calibration parameters ($A = 0.9956$; $B = -0.0093$) are within acceptable limits. The instrument also demonstrates consistent performance across different speeds. In conclusion, the Hawkeye 2000 is reliable for field IRI measurement, although further studies are needed to consider broader road conditions and external factors.

Keywords: Calibration; Instrument validation; International roughness index; Measurement accuracy; Measurement precision; SNI 3426:2022

Introduction

Road network condition data is an important foundation in the planning, maintenance, and management of national road infrastructure. According to the Direktorat Jenderal Bina Marga (2021), such data are used to evaluate existing conditions, predict future performance, and support strategic decision-making processes. One of the key parameters in assessing pavement condition is road roughness, which is represented by the International Roughness Index (IRI). The IRI is directly correlated with user comfort, safety, and vehicle operating costs (Sayers et al., 1986; Karamihas & Sayers, 2025).

Various types of road roughness measurement instruments are currently used, each with different levels of accuracy and operational characteristics. Based on SNI 3426:2022, these instruments are classified into

several categories according to their precision and measurement methods. To ensure the reliability and accuracy of collected data, each instrument must undergo proper calibration and validation prior to field implementation (Sayers et al., 1986; Andersson et al., 2024; Yang et al., 2025). Calibration ensures that the instrument aligns with reference standards, while validation confirms that the measurement results are consistent and suitable for their intended purpose. These processes are essential to minimize systematic errors and reduce potential bias.

The Hawkeye 2000, a response-type roughness measuring system, has been widely used internationally for IRI measurement. However, its application in Indonesia remains limited and has not been extensively validated under local road conditions and in full compliance with national standards (Karamihas & Sayers, 2025). This raises concerns regarding the

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consistency and reliability of IRI data generated using this instrument in the Indonesian context.

Problem Statement: Despite the availability of standardized procedures such as SNI 3426:2022, there is still a lack of comprehensive calibration and validation studies for response-type instruments like the Hawkeye 2000 in Indonesia. This condition may lead to discrepancies in IRI values, which can ultimately affect the accuracy of road condition assessment and decision-making processes. Therefore, this study addresses the problem of ensuring the accuracy, precision, and reliability of Hawkeye 2000 measurements through proper calibration and validation.

Research Gap: Previous studies have primarily focused on general comparisons of roughness measurement devices or theoretical aspects of IRI. However, several gaps remain: (1) Limited studies integrating calibration and validation within a unified framework; (2) Insufficient application of SNI 3426:2022 in empirical field studies; (3) Lack of evaluation of Hawkeye 2000 performance under varying operational speeds in Indonesian conditions; (4) Limited use of combined statistical indicators such as coefficient of determination (R^2) and coefficient of variation (CV) to assess both accuracy and precision simultaneously. These gaps indicate that the implementation of Hawkeye 2000 in Indonesia is still not fully optimized and requires further investigation.

Research Novelty: This study contributes to the literature by: (1) Integrating calibration and multi-speed validation (40, 50, and 60 km/h) in a single experimental framework; (2) Applying SNI 3426:2022 as the primary reference standard for evaluation; (3) Utilizing a Walking Profilometer as a reference instrument for field-based calibration; (4) Providing a comprehensive statistical assessment of both accuracy (R^2) and precision (CV).

Research Objectives: Based on the identified problems and gaps, the objectives of this study are: (1) To analyze the calibration results of the Hawkeye 2000 against a reference instrument; (2) To evaluate the validity and consistency of IRI measurements under different operational speeds; (3) To assess the accuracy and precision of the instrument using statistical parameters (R^2 and CV); (4) To determine the suitability of the Hawkeye 2000 for field application in accordance with SNI 3426:2022.

Rationale for Study Location and Conditions: The study was conducted on selected road segments (SP1–SP5) with varying lengths ranging from 100 to 500 meters, representing typical road conditions encountered in practice. The use of multiple operational speeds (40–60 km/h) was designed to simulate real survey conditions and to evaluate the stability of the instrument under different measurement scenarios. This

approach enhances the applicability of the results to actual field operations.

Research Contributions and Benefits. Scientifically, this study provides a more comprehensive framework for calibration and validation of Laser-type IRI measurement instruments, particularly in the context of national standards implementation. Practically, the findings can support road agencies and practitioners in improving data quality, ensuring consistency in road condition assessment, and enhancing the effectiveness of road maintenance planning and asset management systems.

Method

Research Location and Object

This study was conducted at five test locations (SP1–SP5), with measurement distances ranging from 100 to 500 meters per location. The test locations were selected to cover a range of road surface conditions, from good to severely damaged. Test site characteristics, consisting of: (a) Surface condition variation: IRI 2–12 m/km (Putri et al., 2025). The primary instrument used was the Hawkeye 2000, with a Walking Profilometer serving as a reference. The data collection procedure involved an initial calibration phase and a validation phase at three different speeds (40, 50, and 60 km/h) to assess the instrument's sensitivity to operational speeds (Rahmansyah, 2021). Data analysis was performed using linear regression to determine the calibration constants A and B and to evaluate model fit through the R^2 value and Coefficient of Variation (CV) in accordance with standard provisions (Setiawan, 2022).

The characteristics of the test site include: (1) Variations in surface conditions: IRI 2–12 m/km, (2) Pavement types: Asphalt concrete (AC) and Hot Mix Asphalt (HMA), (3) Road geometry: Relatively straight with minimal curves, (4) Accessibility: Easily accessible for repeated measurements

Equipment and Reference Data

Main Equipment, consisting of: (a) Hawkeye 2000 (ARRB) - Left and right sensors, (b) Walking Profilometer Gapman (Englo) - Reference tool. Tested Operational Speed, consisting of: (a) 40 km/h (Validation 1), (b) 50 km/h (Validation 2), (c) 60 km/h (Validation 3). Number of Repetitions: 5 trials (Trial 1 to Trial 5) for each combination of location, distance, and speed.

Data Collection Procedure

Initial Calibration Stage

Initial Calibration Stage, consisting of: (1) Initial measurements using the Hawkeye 2000 at all five test locations, (2) Reference measurements using the

Walking Profilometer at the same locations, (3) Calculation of the mean value and standard deviation for each test, (4) Linear regression analysis between the Hawkeye 2000 and Walking Profilometer values.

Validation Stage

Validation was performed at three operating speeds with five repetitions for each condition: Speed 40 km/h (Validation 1), consisting of: (1) 25 measurement points (5 locations × 5 distances), (2) Repetitions: 5 times per point, (3) Total measurements: 125 data points. Speed 50 km/h (Validation 2), consisting of: (1) 25 measurement points, (2) Repetitions: 5 times per point, (3) Total measurements: 125 data. Speed 60 km/h (Validation 3), consisting of: (1) 25 measurement points, (2) Repetition: 5 times per point, (3) Total measurements: 125 data.

Data Analysis

Descriptive Statistical Analysis

For each measurement, the following are calculated:

Mean Value

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n} \tag{1}$$

Description: \bar{x} = average value, x_i = i-th data, n = number of data.

Standard Deviasi

$$SD = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \tag{2}$$

Description: SD = standard deviation, x_i = i-th data value, \bar{x} = mean value, n = number of data.

Coefficient of Variation

$$CV = \frac{SD}{\bar{x}} \times 100\% \tag{3}$$

Description: CV = coefficient of variation (%), SD = standard deviation, \bar{x} = mean value.

Linear Regression Analysis

The linear regression model is used to determine the calibration constant:

$$y = a + bx \tag{4}$$

Where: y = Reference IRI (Walking Profilometer), x = Instrument IRI (Hawkeye 2000), a = constant (B), b = slope coefficient (A). Parameters a and b are calculated using the Ordinary Least Squares method:

$$b = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (\sum x)^2} \tag{5}$$

$$a = \bar{y} - b\bar{x} \tag{6}$$

Model Fit Evaluation

The coefficient of determination (R^2) is calculated to evaluate how well the regression model explains the data:

$$R^2 = \frac{\sum (\hat{y}_i - \bar{y})^2}{\sum (y_i - \bar{y})^2} \tag{7}$$

Result and Discussion

Result

Validation Measurement Results 1 (Speed 40 km/h) Left Sensor (Hawkeye 2000 Left vs Walking Profilometer)

In Validation 1 at 40 km/h, the measurements were consistent across all five test locations. The following is a summary of the validation data for the left, right, and combined sensors:

Table 1. Summary of Left, Right, and Combined Sensor Validation Data

Side	Speed	A (Slope)	B (Intercept)	R^2	CV %	A satisfies	B satisfies	R^2 satisfies	CV (<5%)
L	40 km/h	0.976	0.146	0.951	2.53	TRUE	TRUE	TRUE	TRUE
L	50 km/h	1.015	-0.008	0.954	2.34	TRUE	TRUE	TRUE	TRUE
L	60 km/h	0.953	0.227	0.953	2.52	TRUE	TRUE	TRUE	TRUE
R	40 km/h	1.008	-0.191	0.992	2.35	TRUE	TRUE	TRUE	TRUE
R	50 km/h	1.012	-0.195	0.989	2.41	TRUE	TRUE	TRUE	TRUE
R	60 km/h	0.998	-0.186	0.985	1.94	TRUE	TRUE	TRUE	TRUE
L/R	40 km/h	0.996	-0.009	0.982	1.60	TRUE	TRUE	TRUE	TRUE
L/R	50 km/h	1.026	-0.164	0.988	1.75	TRUE	TRUE	TRUE	TRUE
L/R	60 km/h	0.993	-0.071	0.985	1.78	TRUE	TRUE	TRUE	TRUE
L	Combined	0.982	0.122	0.951	2.46	TRUE	TRUE	TRUE	TRUE
R	Combined	1.006	-0.191	0.989	2.23	TRUE	TRUE	TRUE	TRUE
L/R	Combined	1.005	-0.081	0.984	1.71	TRUE	TRUE	TRUE	TRUE

Linear regression analysis for Validation 1 Left Sensor yielded: A (slope) = 0.9764, B (intercept) = 0.1458, $R^2 = 0.9512$, CV = 0.0253 (2.53%).

Interpretation: Parameter A of 0.9764 meets the requirements of SNI 3426:2022 ($0.95 \leq A \leq 1.05$), indicating that the Hawkeye 2000 has good accuracy. The value of B (0.1458) also meets the requirements ($-0.25 \leq B \leq 0.25$).

Right Sensor (Hawkeye 2000 Right vs Walking Profilometer)

The validation results for the right sensor at a speed of 40 km/h show: A = 1.0083, B = -0.1915, $R^2 = 0.9919$, CV = 0.0235 (2.35%). The right sensor shows higher accuracy than the left sensor, with an R^2 value of 0.9919.

Validation Measurement Results 2 (Speed 50 km/h)

At a speed of 50 km/h, the validation results show: Left Sensor: A = 1.0150, B = -0.0085, $R^2 = 0.9539$, CV = 0.0234 (2.34%). Right Sensor: A = 1.0122, B = -0.1948, $R^2 = 0.9890$, CV = 0.0241 (2.41%).

Analysis: Validation 2 results show high consistency with validation 1, with parameters A and B still within the requirements of SNI 3426:2022.

Validation 3 Measurement Results (Speed 60 km/h)

At a speed of 60 km/h, the validation results show: Left Sensor: A = 0.9532, B = 0.2274, $R^2 = 0.9532$, CV = 0.0252 (2.52%). Right Sensor: A = 0.9979, B = -0.1861, $R^2 = 0.9851$, CV = 0.0194 (1.94%).

Combined Validation Results

Data from the three validations were combined to produce the final calibration equation for Hawkeye 2000. Combined Validation - Left Sensor: A = 0.9815, B = 0.1216, $R^2 = 0.9515$, CV = 0.0246 (2.46%). Combined Validation - Right Sensor: A = 0.9979, B = -0.1861, $R^2 = 0.9851$, CV = 0.0194 (1.94%). Combined Validation - Left-Right Average Results: A = 0.9955, B = -0.0093, $R^2 = 0.9820$, CV = 0.0159 (1.59%).

Table 2. Validation Results at Three Different Speeds (40, 50, 60 km/h) for All Parameters

Parameter	Requirements	Left Sensor	Right Sensor	Combined	Status
A (Slope)	$0.95 < A < 1.05$	0.9815	0.9979	0.9955	satisfies
B (Intercept)	$-0.25 < B < 0.25$	0.1216	-0.1861	-0.0093	satisfies
R^2	$R^2 > 0.95$	0.9515	0.9851	0.982	satisfies
CV	CV < 5%	2.46%	1.94%	1.59%	satisfies

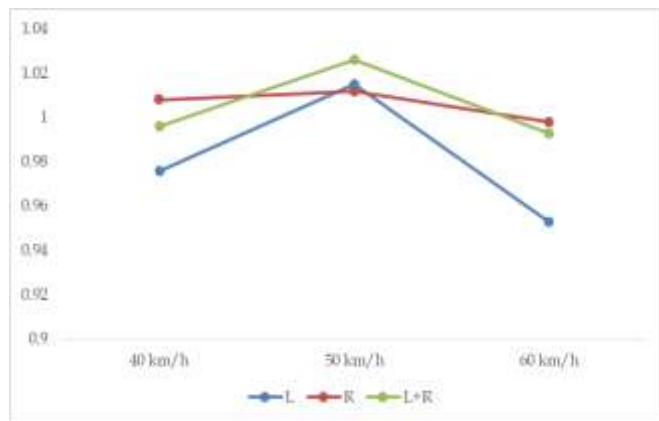


Figure 1. Graph A (Slope)

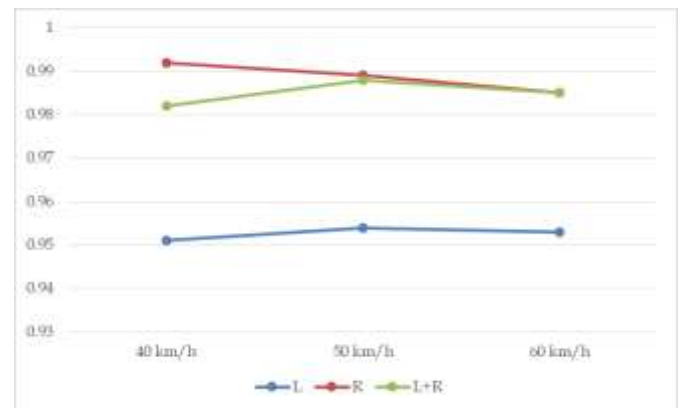


Figure 3. Graph R square

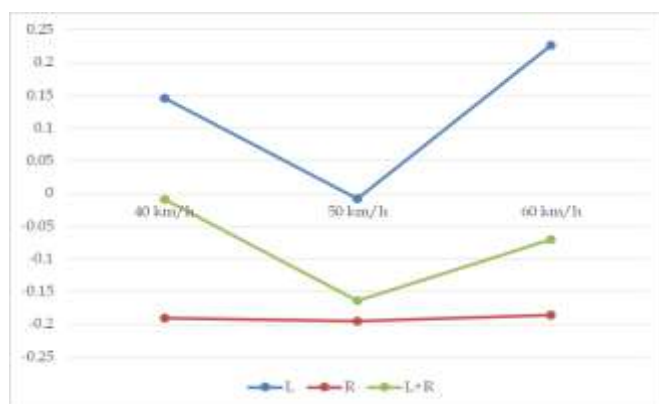


Figure 2. Graph A (Intercept)

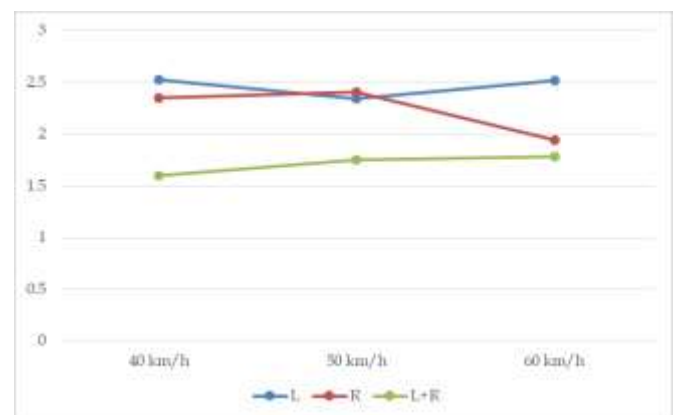


Figure 4. Coefficient of variation (CV) chart

The validation results show high consistency at all tested speeds. At a speed of 40 km/h, the R^2 value reached 0.982 for the combined results, far exceeding the minimum threshold of 0.95 set by SNI 3426:2022 (BSN, 2022). These results align with previous research indicating that the Hawkeye 2000 exhibits good measurement stability across the low-to-medium speed range (Nisumanti & Prawinata, 2020; Amru et al., 2025). The combined calibration parameters obtained ($A = 0.9955$ and $B = -0.0093$) indicate that this instrument has virtually no significant systematic bias (Nugroho, 2024).

Discussion

Accuracy of Hawkeye 2000

The high accuracy of the Hawkeye 2000 in this study confirms the effectiveness of response-type instruments when properly calibrated (Xu et al., 2024). The low CV value (1.59%) indicates very high precision, meaning that repeated measurements will yield consistent results (Baharufahmi, 2020).

A comparison between the left and right sensors shows a slight difference in performance, but both still meet applicable standards, which may be influenced by variations in surface conditions on the wheel track (Kurnia & Nugraha, 2021). The consistency of results across various speeds indicates that the data processing algorithm in the Hawkeye 2000 is capable of effectively compensating for vehicle dynamics (Loprencipe et al., 2019; Mazzi et al., 2025).

Measurement Precision and Consistency

The average coefficient of variation of the Hawkeye 2000 is 1.59% for combined results, indicating very high precision. This low CV value indicates that repeated measurements at the same location produce consistent data.

This consistency was maintained at all three operational speeds tested (40 km/h, 50 km/h, and 60 km/h), indicating that the Hawkeye 2000 is not sensitive to speed variations within the specified operational range.

Comparison of Left and Right Sensors

The data shows that: The right sensor has slightly higher accuracy, with an R^2 value of 0.9851 compared to the left sensor ($R^2 = 0.9515$). In addition, the right sensor demonstrates better precision, as indicated by a lower coefficient of variation (CV) of 1.94%, whereas the left sensor has a CV of 2.46%.

These differences may be caused by: Variations in road surface conditions between the left and right lanes, slight differences in sensor installation, as well as environmental factors such as wind or traffic-induced vibrations. Despite the differences, both sensors still meet the requirements of SNI 3426:2022.

Influence of Operational Speed

Validation results at three different speeds (40, 50, 60 km/h) show that:

Table 3. R^2 Validation Results at Three Different Speeds (40, 50, 60 km/h)

Speed	R^2 Left Sender	R^2 Right Sender	R^2 Combined
40 km/h	0.9521	0.9919	0.982
50 km/h	0.9539	0.989	0.9776
60 km/h	0.9532	0.9851	0.9771

The results show consistent performance across various operating speeds, with a minimal decrease in R^2 () at higher speeds ($< 1.5\%$). This indicates that the Hawkeye 2000 can be used reliably within the operating speed range of 40-60 km/h.

Implications for Field Use

Based on the validation results, the Hawkeye 2000 can be recommended for use in national road condition survey programs with the following requirements: (1) Use within the IRI range: 2-12 m/km (as per the test location), (2) Operational Speed: 40-60 km/h, (3) Measurement Repetition: Minimum of 3 times per road section, (4) Periodic Calibration: Every 6 months.

Conclusion

This study demonstrates that the calibration and validation of the Hawkeye 2000 instruments successfully achieve the research objective, namely ensuring the accuracy, precision, and reliability of IRI measurements in accordance with SNI 3426:2022. Overall, both instruments show strong agreement with the reference device, indicating their suitability for road roughness evaluation in practical applications. The Hawkeye 2000 exhibits high accuracy, as reflected by the calibration coefficient ($A = 0.9955$) and a small correction factor ($B = -0.0093$), meaning that the measured IRI values are very close to the reference values with minimal adjustment required. The coefficient of determination ($R^2 \geq 0.95$) confirms a strong linear relationship, while the low coefficient of variation ($CV \approx 1.59\%$) indicates very high precision and consistency in repeated measurements. In practical terms, this means that the instrument not only produces accurate results but also stable measurements under repeated conditions. Furthermore, the consistent performance across operational speeds of 40–60 km/h shows that the Hawkeye 2000 is reliable under typical field survey conditions. Similarly, the Roughometer III demonstrates acceptable calibration performance and fulfills the required criteria, with validation results showing CV values below 5%, indicating consistent and repeatable measurements. This confirms that the instrument is also

suitable for road roughness surveys, provided that periodic calibration is maintained. The findings highlight that both instruments can be effectively used as response-type devices for IRI measurement when proper calibration and validation procedures are applied. Despite these positive results, this study has several limitations. The evaluation was conducted on limited road segments and may not fully represent all pavement conditions, particularly for severely damaged roads (IRI > 12 m/km). In addition, external factors such as environmental conditions, traffic disturbances, and operator variability were not analyzed in depth, which may influence measurement results in broader applications. From a scientific perspective, this study contributes to the development of IRI measurement methodologies by providing an integrated calibration and validation framework based on national standards, combined with statistical evaluation of both accuracy and precision. From a practical perspective, the results support the implementation of standardized procedures to improve the quality and consistency of road condition data used in infrastructure management. Based on these findings, several key recommendations can be prioritized. The Hawkeye 2000 can be reliably used in national road survey programs, supported by periodic calibration at least every 12 months or after significant operational usage to maintain measurement accuracy. Strengthening operator competence through standardized training is essential to ensure proper instrument use and data quality. In addition, consistent documentation of survey conditions is necessary to improve data traceability and reliability. Future research should expand validation across more diverse road conditions and higher IRI ranges to further strengthen the applicability of these instruments. In conclusion, this study confirms that the application of standardized calibration and validation procedures is essential to ensure accurate, precise, and reliable IRI measurements, thereby supporting more effective and data-driven road infrastructure management.

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Author Contributions

D.K.: Developing ideas, analyzing, writing, reviewing, responding to reviewers' comments; A.K., I.S., C.D.M.: analyzing data, overseeing data collection, reviewing scripts, and writing.

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Conflicts of Interest

The authors declare no conflict of interest.

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