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Development of an Ultrasonic Surface Roughness Meter for Road Maintenance: A Prototype for IRI Measurement

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Abstract. The importance of the road network in Indonesia as a vital infrastructure that connects various regions has made road maintenance a top priority in development planning. However, various challenges such as ineffective handling methods, limited experts, and minimal equipment have caused road management to not be optimal. Therefore, innovations are needed in road condition measurement, one of which is through the development of an ultrasonic sensor-based surface roughness measuring instrument as a prototype of International Roughness Index (IRI) measurement to support more accurate road maintenance evaluation and planning. The purpose of this research is to measure road roughness through IRI and pavement modulus values to improve road condition assessment.This study employs the International Roughness Index (IRI) to assess the functional condition of roads and the Pavement Modulus to evaluate the structural strength of the pavement. The IRI is measured through road surface roughness surveys using a roughness meter, with the results used to classify the severity of road damage. The IRI calculation is based on a quarter-car simulation model that utilizes vehicle dynamic parameters in response to road surface profiles, following the mathematical approach developed by Sayers, Gillespie, and Paterson (1986). The research results show that the prototype Ultrasonic Surface Roughness Meter was able to measure IRI values ranging from 4 to 8 at three different locations. These measurements fall within the "Good–Fair" classification, indicating relatively mild surface roughness. Based on these findings, the Directorate General of Highways recommends light rehabilitation and periodic maintenance, and the prototype device has the potential to serve as an effective, low-cost alternative for road condition monitoring, especially in areas with limited access to conventional IRI measurement tools.

Keywords: ultrasonic measurement, road infrastructure, pavement condition, road roughness measurement technology

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1. Introduction

Road networks play a vital role as essential infrastructure that supports the connectivity and mobility of people and goods across Indonesia's vast archipelago [1]. They act as the backbone of economic activity, linking rural areas to urban centers, facilitating trade, and enabling access to education, healthcare, and other basic services. A reliable and well-connected road system not only enhances logistical efficiency but also stimulates regional development and reduces economic disparities among regions [2].

However, the performance of road infrastructure declines over time due to factors such as increasing traffic volume, heavy vehicle loads, extreme weather conditions, and the natural aging of construction materials. Without proper and timely maintenance, road conditions can deteriorate rapidly, leading to higher repair costs, reduced safety, and negative economic impacts [3]. To ensure effective maintenance, it is essential to have accurate, up-to-date data on the condition of road pavements. This data-driven approach enables better planning, prioritization, and allocation of resources, ensuring that maintenance efforts are both efficient and sustainable in the long term [4].

In practice, however, road maintenance efforts in Indonesia still face several challenges, including ineffective handling methods, a lack of skilled personnel, and limited availability of adequate measuring equipment [5]. Road management that is not based on real-time data often results in inefficient budget allocation and poor maintenance outcomes. Thus, there is a need for a more practical, efficient, and affordable road condition monitoring system that can be implemented widely, especially in areas with limited resources.

One commonly used method to evaluate road conditions is surface roughness measurement using a roughness meter, which calculates the International Roughness Index (IRI). IRI is an internationally recognized indicator for assessing road comfort and safety based on the longitudinal surface profile [6], [7]. However, existing IRI measurement tools are generally expensive and require complex technical operation, limiting their use in the field.

Previous studies have emphasized the importance of improving road maintenance management due to various persistent challenges, such as ineffective implementation methods, a shortage of skilled personnel, and limited availability of equipment [5] To assess road pavement conditions, existing methods typically use a roughness measuring device, or rough meter, which evaluates the surface profile and calculates the International Roughness Index (IRI) as an indicator of road quality [6], [7], [8]. These methods, while standardized, often rely on costly and less accessible technologies, particularly in regions with limited infrastructure.

This study introduces a novel approach by developing a prototype Ultrasonic Surface Roughness Meter that utilizes ultrasonic sensors to measure IRI values more efficiently and affordably. The innovation lies in offering a portable, low-cost alternative to traditional rough meters, making it more accessible for use in remote or resource-constrained areas. By integrating ultrasonic technology with IRI-based road evaluation, this research contributes a new tool for enhancing road maintenance strategies through accurate, real-time surface condition monitoring.

This study aims to measure road unevenness using various tools and research approaches, specifically utilizing a rough meter equipped with an ultrasonic sensor, referred to as the ultrasonic surface rough meter. The findings from this study can serve as a reference for experts in planning highway maintenance at the study location and contribute to the development of an IRI-based road function performance evaluation using the "Ultrasonic Surface Rough Meter."

2. Methods

Road conditions serve as an index that objectively applies specific criteria or ranges to assess the extent of road damage, with various methods available for measuring road conditions. Among these indices, distinctions exist between the functional and structural conditions of sidewalks.

However, these variations can be integrated into a single index when assessed based on Remaining Life. The estimated remaining service life is determined by analyzing the total number of vehicles passing through in a given year while ensuring the surface remains in both functional and structural condition with only routine maintenance [9].

This study utilizes the International Roughness Index (IRI) to measure road functionality, while the Pavement Modulus is employed to assess the structural strength of the pavement. The IRI value is obtained through road surface roughness surveys using a roughness meter [7], [8].

Road pavement damage, in terms of both volume and severity, is evaluated through the Road Survey (SRD), which aims to facilitate the development and expansion of the road network. Additionally, the longitudinal roughness of the road surface is quantified using the International Roughness Index (IRI), expressed in meters per kilometer (m/km) (SNI 03-3426-1994, 1994).

The condition of road pavement is also assessed using the Surface Disturbance Index (SDI), a visually based evaluation system that serves as a guideline for maintenance planning. This visual assessment enables the classification of road damage according to its severity level [10], [11], [12], [13].

Furthermore, road damage conditions are classified based on IRI values: an IRI value below 4 indicates good condition or minor damage, a value between 4 and 8 represents light damage, a range of 8 to 12 signifies moderate to severe damage, and an IRI value between 12 and 16 indicates heavy damage [14].

2.1. Iri Calculation

M. W. Sayers, Gillespie, and Paterson (1986) introduced a method for calculating the International Roughness Index (IRI), which relies on four key parameters derived from the road surface profile. These parameters reflect the dynamic response of vehicles moving across the measured surface. The calculation applies to all elevation points except the first, where initialization is based on the average slope over the initial 11 meters or 0.5 seconds, assuming a vehicle speed of 80 m/km with a predetermined value [15].

Once the above equation is solved, the next step is to compute the four recursive equations from point 2 to point n. For a more efficient calculation, Sayers (1995) proposed a simplified formula to determine the IRI value [16].

$$\text{IRI} = \frac{1}{(n-1)} \sum_{i=2}^{n} RSi \qquad 11$$

The next step is to calculate the coefficient of the IRI equation to solve equations 4 to 7 are as follows: [15].

$$\frac{dz(t)}{dt} = \underline{A} * z(t) + B * y(t) \quad [16] \qquad 1$$

where:

z = is vector of 4 Z variables from Equations 1 – 7

A = 4 x 4 description of model dynamics

B = 4 x 1 vehicle description with profile interaction

y(t) = input for profiles on moving vehicles.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -K2 & -C & K2 & C \\ 0 & 0 & 0 & 1 \\ K2/u & C/u & -(K1+K2)/u & -C/u \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ K1/u \end{bmatrix} \ldots\ldots \qquad 2$$

The S coefficient can be determined based on the values of the four constants [16]. $ST = e^{A*dt}$
3

The image below illustrates and verifies the accuracy of the IRI calculation while also serving as input.

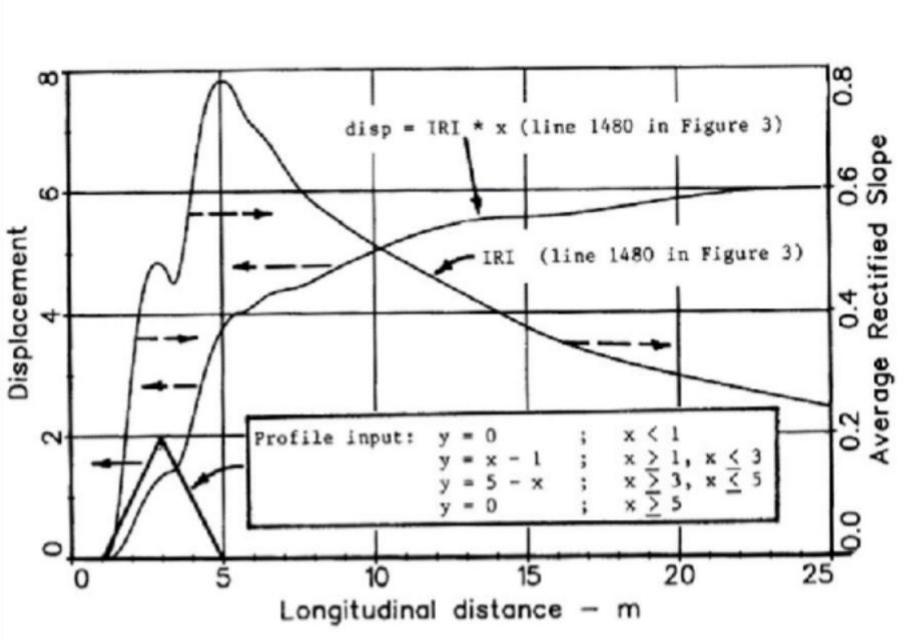

Figure 1. Special profile inputs used to check the IRI calculation program
Source: M. W. Sayers, Gillespie and Paterson, 1986 [15]

The IRI value is calculated using a quarter-car simulation model, which consists of spring mass and non-spring mass components, as depicted in Figure 2. In further detail, Chen et al. (2020) formulated the following equation, based on the work of Michael W. Sayers, Gillespie, and Paterson (1986) [17], [18]:

$$m_s Z''_s + c_s (Z'_s - Z'_u) + k_s(Z_s - Z_u) = 0, \quad 4$$

$$m_s Z''_s + m_u Z''_u + k_t(Z_u - y) = 0 \quad 5$$

By simultaneously dividing both segments of Equations (4) and (5) by \(m_s \), the equation of motion can be simplified into Equations (6) and (7) [17].

$$Z''_s + (Z'_s - Z'_u) + K_2(Z_s - Z_u) = 0, \quad 6$$

$$Z''_s + u\ddot{Z}_u + K_1 Z_u = K_1 y \quad 7$$

where

C	=	c_s/m_s	=	$6(1/s)$
u	=	m_u/m_s	=	0,15
K_1	=	k_t/m_s	=	65,3 $(1/s^2)$
K_2	=	k_s/m_s	=	63,3 $(1/s^2)$

Equation (8) to calculate the IRI value

$$IRI = \frac{1}{L}\int_0^L \left| Zs - Zu \right| dx, \quad 8$$

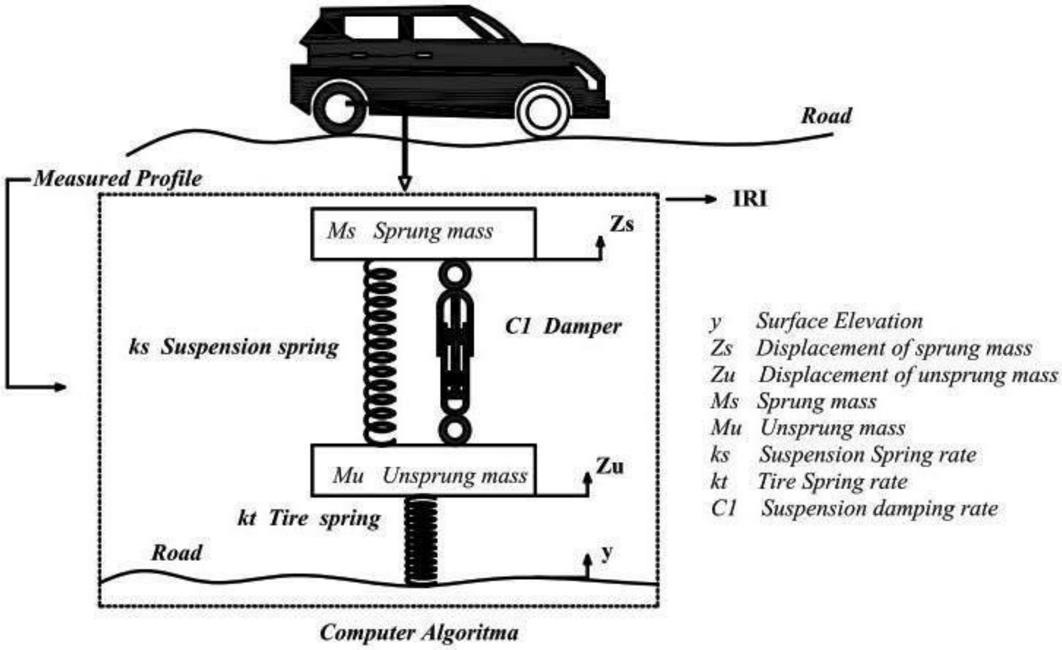

Figure 2. Illustration of IRI value calculation
Source: Chen et al., 2020

One of the limitations or potential challenges in using ultrasonic-based surface roughness measuring devices is their sensitivity to surrounding environmental conditions, such as dust, water, or extremely uneven and rough road surfaces. These factors can interfere with the reflection of ultrasonic waves and affect the accuracy of data readings. Additionally, the lack of widely standardized calibration procedures and the device's limited ability to handle various types of road surfaces may restrict the generalizability of measurement results in more diverse road contexts or in areas with different geographic and climatic characteristics.

Ultrasonic-based surface roughness measurement tools offer a more economical alternative compared to conventional technologies such as laser profilometers or high-standard IRI measurement vehicles, which are typically expensive and require specialized technical operations. In terms of accuracy, while this prototype may have a slightly higher margin of error compared to professional-grade devices, its measurement results remain within an acceptable range for routine maintenance and preliminary road condition surveys. Regarding scalability, the device has great potential for widespread implementation, especially in remote areas or regions with budget constraints, as its simpler design and minimal operational requirements allow for efficient distribution and user training.

3. Results and Discussion

Results

The unevenness measuring instrument used is a Prototype Ultrasonic Surface Rough meter designed and designed using the HC-SR04 Ultrasonic Sensor.

a. Research Location

The research was conducted at several locations in Garut Regency, West Java. The first site was on Jalan H. Hasan Arif, Sukasenang, Banyuresmi District (44191), starting at coordinates 7°10'50.1"S 107°55'33.0"E and ending at 7°10'49.2"S 107°55'42.7"E (SP 2). The second site was on Jalan Prof. KH. Anwar Musaddad (left side), Tj. Kamuning, Tarogong Kaler District (44151), beginning at 7°10'37.5"S 107°54'19.2"E and concluding at 7°10'28.6"S 107°54'15.1"E (SP 3). The third site was on Jalan Prof. KH. Anwar Musaddad (right side), also in Tj. Kamuning, Tarogong Kaler District (44151), spanning from 7°10'30.1"S 107°54'16.2"E to 7°10'38.9"S 107°54'20.4"E (SP 4).

Figure 3. Map of the coordinates of the research location

b. Data Acquisition

The next step, measurements are taken on a site and marked. The marking was in the form of dots with white paint on the vehicle's radio path with a distance of 25 cm for each dot along 3x100 m (300 m), as shown in the image below. Measurements were made with an Ultrasonic Surface Rough meter that had been installed in the vehicle (see figure 5) and measurements were made at a vehicle speed of between 30 – 40 km/h.

Figure 4. Research locations SP 2, SP 3 and SP 4 (start-finish)

Figure 5. The Ultrasonic Surface Rough meter that has been installed on the vehicle

The measurement data was in the form of vertical height data between the road surface point and the ultrasonic sensor on the Ultrasonic Surface Rough meter device installed on the front horn of the vehicle. The amount of data obtained is as many as 1200 high data and 1200 acceleration data. At each location that is 300 m away.

c. Data Calculation

To make it easier to calculate the IRI value by using equations 1 to equation 7 and then calculating the coefficient of the IRI equation to solve equations 4 to 7 by using equation 12 which first solves equations 13 to d as the coefficient. Only the 11-value equation from IRI. To simplify and accelerate the calculation of the IRI by using a computer program. The results of the calculation are as follows:

Table 2. IRI Calculation Results and Classification

No	Location	IRI Value	Surface Type	Information
1	SP 2, 0-100 m	5.80	Asphalt	Good-fair
2	SP 2, 100-200 m	6.70	Asphalt	Good-fair
3	SP 2, 200-300 m	7.50	Asphalt	Good-fair
4	SP 3, 0-100 m	6.84	Asphalt	Good-fair
5	SP 3, 100-200 m	6.84	Asphalt	Good-fair
6	SP 3, 200-300 m	7.33	Asphalt	Good-fair
7	SP 4, 0-100 m	5.01	Concrete	Good-fair
8	SP 4, 100-200 m	5.75	Concrete	Good-fair
9	SP 4, 200-300 m	4.93	Concrete	Good-fair

The results of the calculations and analysis of data obtained during measurements with the ultrasonic surface rough meter prototype are the IRI values obtained at the H. Hasan Arif road section (SP 2), is 5.80 for the 0 – 100m section, 6.70 for the 100 – 200 m section and 7.50 for the 200 – 300 m section which has an IRI value ranging from 4 to 8 so that it can be said to be included in the Good-fair classification category, while for the Prof. KH Road section. Anwar Musaddad on the left (SP 3), is 6.84 for the 0 – 100m section, 6.84 for the 100 – 200 m section and 7.33 for the 200 – 300 m section which has an IRI value ranging from 4 - 8 so that it can be said to be included in the Good-fair classification category and for the Prof. KH Road section. Anwar Musaddad on the right (SP 4), is 5.01 for the 0 – 100m section, 5.75 for the 100 – 200 m section and 4.93 for the 200 – 300 m section which has an IRI value ranging from 4 – 8 so that it can be said to be included in the Good-fair classification category and according to the recommendation of the Directorate General of Highways is light rehabilitation and periodic maintenance.

Discussion

The use of a prototype Ultrasonic Surface Rough Meter, designed with the HC-SR04 ultrasonic sensor, has proven effective in measuring road surface roughness (IRI – International Roughness Index) at several locations in Garut Regency, West Java. The study was conducted at three different sites: H. Hasan Arif Street (SP 2), the left side of Prof. KH. Anwar Musaddad Street (SP 3), and the right side of the same road (SP 4). These locations represent different surface types SP 2 and SP 3 being asphalt, and SP 4 being concrete.

Data acquisition was carried out systematically by marking vehicle tracks every 25 cm along a 300-meter stretch at each site. Measurements were conducted while the vehicle maintained a consistent speed of 30–40 km/h. The vertical height between the road surface and the sensor was recorded, yielding 1,200 height and acceleration data points per location. These measurements were processed using a computer program to calculate IRI values based on a series of predefined mathematical equations.

The results show that all tested road sections had IRI values ranging from 4 to 8, which, according to the classification by the Directorate General of Highways, fall under the "Good-fair" category. On H. Hasan Arif Street (SP 2), the IRI values increased from 5.80 to 7.50 over the 300-meter segment, indicating a slight decline in surface quality with distance. A similar pattern was observed at SP 3, with consistently high IRI values ranging from 6.84 to 7.33. Meanwhile, SP 4 (concrete surface) showed relatively lower and more stable values, ranging from 4.93 to 5.75.

From these findings, it can be concluded that the prototype device is capable of accurately identifying road surface irregularities across different surface types. The obtained IRI values confirm that all three locations are in relatively good condition but require light and periodic maintenance. This aligns with recommendations from the Directorate General of Highways, which suggest light rehabilitation and regular upkeep to maintain road service quality. Moving forward, improvements to the device in terms of data stability and automated calculation integration will be essential to support sustainable and efficient road monitoring efforts.

The application of an Ultrasonic Surface Rough Meter prototype in this study is supported by previous research emphasizing the importance of road roughness measurements as a key indicator of road quality and user comfort. The International Roughness Index (IRI) has long been established by the World Bank as a standardized and widely adopted metric for assessing pavement smoothness. It is directly correlated with vehicle operating costs, safety, and ride quality (Tamagusko &Ferreira, 2023). Higher IRI values typically indicate deteriorating pavement conditions, leading to discomfort for road users and increased maintenance costs.

Ultrasonic sensors, such as the HC-SR04 used in this study, have been increasingly utilized in surface roughness detection due to their affordability, ease of integration, and non-contact measurement capabilities. According to studies by Ashgari, (2025) ultrasonic sensors can provide reliable displacement data for pavement monitoring when installed on moving platforms. The integration of this sensor into a mobile prototype aligns with the recent trend toward developing cost-effective and portable roughness measuring instruments, which can offer alternatives to more expensive tools like laser profilometers or inertial profilers [19].

Furthermore, related research by Abdallah et al., (2024) demonstrated that low-cost sensors, when properly calibrated and processed using appropriate algorithms, can produce IRI measurements with acceptable levels of accuracy for road condition assessments in developing regions [20]. The use of vehicle-mounted systems for dynamic data collection, as applied in this study, is also in line with approaches taken by Pratama & Safrilah (2021) who highlighted the effectiveness of continuous road monitoring using in-motion data acquisition techniques [21].

This study's findings where all IRI values across various sites fall within the "Good-fair" classification range are consistent with other similar works that validate the reliability of ultrasonic sensor-based systems for roughness evaluation. The consistent performance across different pavement materials (asphalt and concrete) further supports the versatility of the prototype. With values consistently under 8, the roads are deemed serviceable but in need of regular maintenance, which aligns with the maintenance thresholds outlined by the Directorate General of Highways.

Thus, the use of the ultrasonic prototype in this study is strongly supported by existing theoretical frameworks and empirical research. It demonstrates how low-cost technology, when combined with thoughtful methodological design and proper data processing, can yield valuable insights for infrastructure management. Further refinement and calibration may enhance the precision and scalability of this approach, making it a promising tool for broader applications in road network monitoring and smart transportation systems.

4. Conclusion

The results of the IRI measurement with the prototype Ultrasonic Surface Rough meter from the three research locations ranged from 4 - 8 so that it can be said to be included in the Good-fair classification category and according to the recommendation of the Directorate General of Highways is light rehabilitation and periodic maintenance.

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