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Searching for Precision in Pavement Evaluation: A Comparative Analysis of Smartphones for Measuring the International Roughness Index (IRI)

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Abstract **-** This study assesses the feasibility of using smartphones to measure the International Roughness Index (IRI) by comparing them with the Roughometer III instrument on a section of the Loja-Malacatos highway. Data on IRI were collected using a mobile app on 51 smartphones mounted in 51 different vehicles, which were then compared with measurements from the Roughometer III to evaluate accuracy and reliability. The results indicate that although the smartphones did not achieve the precision of the specialized device, with a maximum R^2 of 0.334 (RMSE = 1.6 m/km) certain models showed potential for making quick and cost-effective IRI estimates. The study revealed significant variations in accuracy among the devices, influenced by the type and condition of the vehicle, the technical specifications of the smartphone, and the environmental conditions during data collection. The mean absolute error (MAE) and the root mean square error (RMSE) were calculated for each smartphone, identifying those whose measurements deviated least from those obtained by the Roughometer III. Despite the observed limitations, the results suggest a moderate potential of smartphones for estimating IRI, particularly in contexts where specialized equipment is unavailable. The research emphasizes the need to optimize calibration methodologies and to develop specific software that improves the accuracy of data collected with these devices. In conclusion, smartphones represent an accessible and promising tool for the preliminary evaluation of pavement roughness, enabling more frequent and economical monitoring of road infrastructure and allowing greater community involvement in pavement quality management.

Keywords**:** International Roughness Index (IRI), Highways and Roads, Pavement Management, Smartphones.

1. Introduction

Pavement quality significantly influences multiple aspects, including the final cost of goods and services, the safety of both drivers and pedestrians, as well as the comfort during a driver's journey [1]. It also has a direct impact on vehicular maintenance costs, fuel consumption, and travel comfort [2]. Proper maintenance of road infrastructure is essential for the economic development and quality of life of the inhabitants of any country. However, the costs associated with monitoring and maintaining pavements are notoriously high. Moreover, pavement conditions substantially impact user costs, as poor pavement increases fuel consumption, tire wear, and maintenance costs [1].

The regularity of the pavement surface is commonly measured by the International Roughness Index (IRI), which interprets vehicle behavior based on the pavement's longitudinal profile. The IRI is typically measured using various pavement monitoring equipment, but the operational cost associated with these devices is significantly high [3], not cost-effective, and often requires considerable field expertise [2], making these traditional methods inefficient and expensive [4].

Modern smartphones are equipped with an array of integrated sensors, such as accelerometers, gyroscopes, GPS, proximity sensors, and magnetic sensors [5], which enable the collection of motion data, positional information, and environmental characteristics. Recent research has demonstrated that data collected by smartphones can be used to assess pavement conditions with promising results. Consequently, it is suggested that smartphones could significantly reduce the costs associated with pavement monitoring and ensure proper road maintenance.

Some researchers point out that the data generated by these sensors can vary depending on the smartphone's features, sensor conditions, driver behavior, and vehicle dynamics [4]. They also identify certain challenges and limitations, such as differences among phone types, operating systems, hardware and software, and other physical properties. One of the limitations of sensor technology based on smartphones is that the data collected are not directly obtained from the pavement surface but are inferred from the interaction between the vehicle, the driver, and the pavement [2]. Therefore, further research is recommended to better understand the effects of different types and conditions of vehicles, driver behaviors, and smartphone types and conditions to achieve more accurate data [4].

This article examines the accuracy of measuring the International Roughness Index (IRI) using smartphones on a specific road segment. It compares IRI values obtained with a precision roughness meter (Roughometer III) against those recorded by 51 smartphones. The study takes into account various characteristics of the mobile devices, as well as the different types and conditions of the vehicles involved.

2. Materials and Methods

Study Section

A section of the Loja-Malacatos road, specifically between the Redondel del Soldado (699 717E; 9 556 114N) and the intersection of the Paso Lateral road (700 277E; 9 551 354N), with a total length of 4.9 km, was selected for the measurement of the International Roughness Index (IRI) in meters per kilometer (m/km). The reason for selecting this section of road was the variability of the conditions for the study. Measurements were taken in both directions to ensure a thorough evaluation of road roughness.

Population and Sample

In this study, two complementary methods were employed to collect International Roughness Index (IRI) data in meters per kilometer (m/km). Initially, measurements were taken using the professional Roughometer III instrument, manufactured by ARRB Group Ltd. These values served as a baseline for comparison with data collected using smartphones. Concurrently, smartphone data was gathered with the assistance of student volunteers using their own mobile devices and vehicles, which included a variety of cars and a motorcycle. A purposive sample of 51 vehicles and 51 smartphones was selected, ensuring a diverse range of types, brands, models, and years of manufacture for both smartphones and vehicles. This strategy enabled the study to address a wide range of vehicle conditions and mobile device capabilities, facilitating a comprehensive evaluation of the performance of the IRI measurement application under different circumstances. It is important to note that the selection of smartphones and vehicles was constrained by the availability provided by student collaborators, introducing an element of selection bias into the study. This limitation should be considered when interpreting the results, as the diversity in device and vehicle conditions reflects the inherent variability within the sample group used.

Data Collection Equipment

Two types of equipment were used for the IRI measurements: Roughmeter III and smartphones equipped with the IRI-Calc-Free application in meters per kilometer (m/km).

The Roughmeter III is a device known for its accuracy, ease of use and consistency of IRI measurements. Prior to use, it was calibrated according to the user's manual to ensure the accuracy of the data collected.

On the other hand, smartphones equipped with the IRI-Calc-Free application were used, chosen to use the internal sensors for roughness measurements. Stability during data collection was ensured by the mandatory use of smartphone holders in the vehicles. The selection of mobile devices was based on compatibility and correct functioning of the application, excluding those in which measurement malfunctions were detected.

Data Collection Procedure

Data collection with the Roughmeter III followed the manufacturer's guidelines, using a 4x4 vehicle and conducted by by university professors, with measurements taken every 100 meters in both directions. For the smartphone measurements, measurements, the process began with an informational session for the participants on how to properly mount the phone in in the vehicle mount and how to properly use the IRI-Calc-Free app. The measurement route was shared and start and end end coordinates were provided to improve accuracy. Participants were instructed to record the IRI every 100 meters while maintaining a constant and safe speed in both directions to ensure comprehensive data collection.

Furthermore, volunteers were asked to fill out a detailed form including: telephone company, weather conditions, vehicle information (brand, model, year of manufacture, cellphone placement in the vehicle), collection session data (date, app name used), and cellphone details (brand, model, battery level, approximate price, and operating system). This meticulous approach to documentation was supplemented by taking photographs at key points to validate the setup and measurement conditions. Special care was taken to avoid data collection during adverse weather conditions that could affect the results negatively. Mechanisms were also established for reporting and resolving any technical issues that arose during the measurement process, ensuring the reliability and precision of the collected data.

Data Processing

Statistical tools were used for data analysis, allowing an objective interpretation of road roughness based on the measurements obtained JASP software [6] and Spyder [7] were used for the statistical analysis.

To evaluate the accuracy of the International Roughness Index (IRI) measurements obtained by smartphones compared to those obtained by the dedicated Roughometer III device, a methodological approach was adopted, structured in two main phases. First, basic descriptive statistics, such as the mean and median of the IRI measurements of the five most accurate mobile devices from the right and left lanes, as well as the reference measurements from the Roughometer III, were calculated. This preliminary analysis was complemented by the application of the normality test (Shapiro-Wilk test), whose p-value made it possible to evaluate the distribution of the measurements and to determine the suitability of subsequent statistical tests.

The next step was to quantify the measurement error of the mobile devices in relation to the Roughometer III precision instrument. To this end, the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE) were calculated for each of the 51 smartphones evaluated in both lanes (right and left). These error metrics provided a quantitative assessment of the precision of the devices and facilitated the identification of those whose measurements showed the least deviation from the high-precision standard. In addition, Pearson's square correlation (R^2) was estimated for each mobile device against the Roughometer III, providing a measure of the strength and direction of the linear relationship between the measurements of both methods.

3. Results.

Descriptive Statistics

Table 1 presents a statistical summary of the values obtained from the International Roughness Index (IRI) measurements made with both the Roughometer III precision instrument and the cellular devices selected as the best performers (lowest MAE values). It shows the top five values obtained with the cellular devices for both the right and left lanes. In addition, it includes Shapiro-Wilk test values to assess the normality of the IRI distribution, where the associated p-values indicate deviations from normality in several devices.

Table 1: Summary of statistical values. IRI in meters per kilometer (m/km).

Variables	Roughometer III - right	32 right	40 right	49 right	6 right	2 right	Roughometer III - left	33 left	40 left	49 left	45 left	48 left
Median	2.500	1.600	1.260	1.300	1.280	3.950	1.800	0.200	1.400	1.260	0.860	1.000
Mean	2.537	1.796	1.312	1.310	1.269	4.034	2.005	0.213	1.378	1.227	1.247	0.995
Std. Deviation	0.721	0.568	0.267	0.389	0.364	0.646	0.667	0.136	0.215	0.352	0.740	0.165
Coefficient of variation	0.284	0.317	0.204	0.297	0.287	0.160	0.333	0.642	0.156	0.287	0.594	0.166
Shapiro-Wilk	0.927	0.935	0.855	0.963	0.952	0.976	0.940	0.598	0.944	0.966	0.887	0.974
P-value of Shapiro-Wilk	0.012	0.021	1.022×10-4	0.203	0.081	0.528	0.031	2.170×10-9	0.045	0.246	7.136×10-4	0.463
Minimum	1.400	0.710	0.910	0.660	0.120	2.870	1.000	0.100	0.980	0.200	0.200	0.670
Maximum	4.900	3.590	2.410	2.010	2.210	5.380	4.000	0.900	2.100	1.990	2.750	1.490

The figure 1 compares the measurements of the International Roughness Index (IRI) obtained through the five most precise mobile devices, selected based on the lowest mean absolute error (MAE), for each of the lanes, right and left, in comparison to the standard measurements conducted by the high-precision Roughometer III equipment. For each cellular device, two bars are shown: the first represents the MAE between the device's measurements and those of the Roughometer III, and the second illustrates the root mean square error (RMSE), offering a comprehensive view of the accuracy of each device. Additionally, Pearson's squared correlation values, R^2, are indicated above each pair of bars, highlighting the strength and direction of the linear relationship between the device measurements and those obtained by the reference equipment.

The inclusion of both, MAE and RMSE, allows for the evaluation not only of the average precision of the devices in terms of absolute deviations from the actual values but also the variability of these errors, respectively. The Pearson's squared values (R^2), in turn, provide valuable information about the alignment of trends between the measurements of the mobile devices and the high-precision equipment. In general, devices with lower values of MAE and RMSE, along with high Pearson correlation values, are indicative of greater accuracy and reliability in measuring the IRI compared to the Roughometer III equipment.

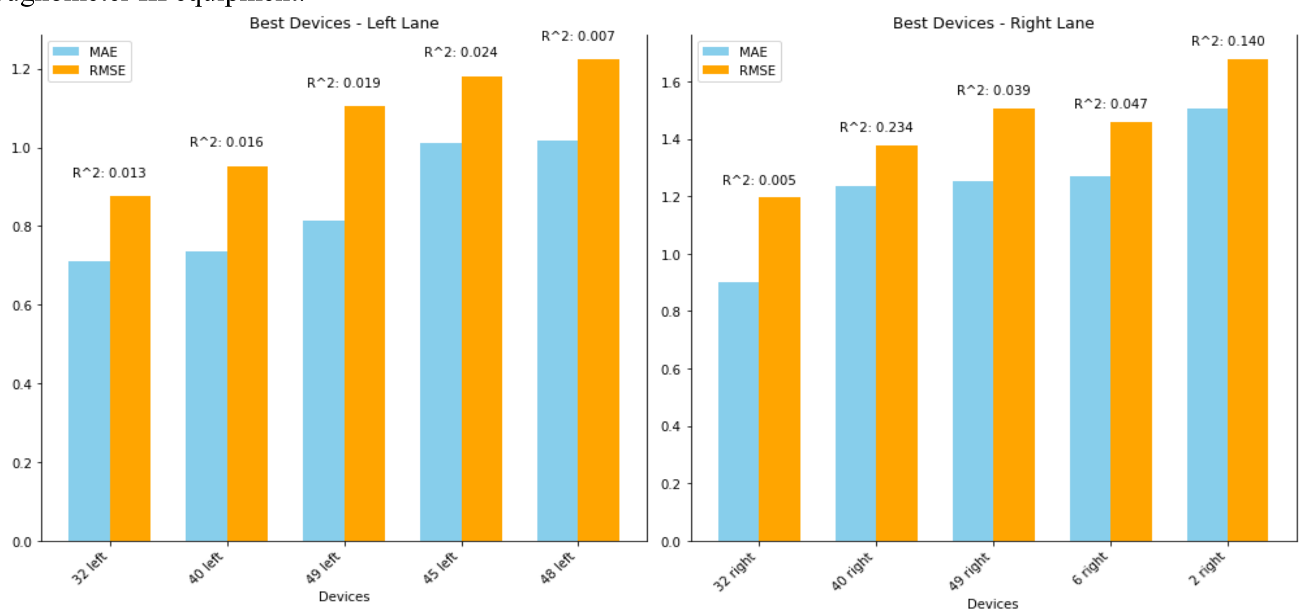

Fig. 1: Comparative Analysis of Mobile Devices' Precision in Measuring IRI against Roughometer III Standards

Upon identifying the top five smartphones from both the left and right lanes, Table 02 presents a compendium of complementary data aimed at identifying patterns from the best measurements. The dataset includes the brand and model of of the smartphones used, as well as the battery charge percentage at the time of measurement, and the market price of each each device. Additionally, the precise location within the vehicle where each smartphone was placed during data collection collection is specified, along with the prevailing weather conditions at the time. The characteristics of the vehicle used for for the measurements are also documented, including the brand, model, and year of manufacture. To quantify the accuracy of the IRI measurements obtained with each smartphone, key statistical metrics are incorporated: MAE, RMSE, and R^2.

Table 2: Supplementary Data on Top Performing Smartphones for IRI Measurement

Best Devices	Brand - Cell	Model - Cell	Battery	Price - Cell	Location - Cell	Weather Conditions	Brand - Vehicle	Model - Vehicle	Year - Vehicle	MAE	RMSE	R^2
32 left	Xiaomi	Redmi 12	39%	$160	Front Right Side	Partly Cloudy	Nissan	NP300	2006	0.71	0.95	0.013
40 left	Samsung	A54	86%	$400	Front Right Side	Clear	Hyundai	Verna	2005	0.73	0.98	0.016
49 left	Samsung	A52	86%	$200	In the Front Central Part	Partly Cloudy	Suzuki	Forsa 2	1997	0.81	1.05	0.019
45 left	Samsung	S9+	48%	$ 1 100	Front Right Side	Clear	Nissan	Datsun 1200	1989	1.01	1.2	0.024
48 left	Samsung	Galaxy A32	96%	$ 300	In the Front Central Part	Partly Cloudy	Chevrolet	Spark	2011	1.02	1.22	0.007
32 right	Xiaomi	Redmi 12	39%	$ 160	Front Right Side	Partly Cloudy	Nissan	NP300	2006	0.9	1.1	0.005
40 right	Samsung	A54	86%	$ 400	Front Right Side	Clear	Hyundai	Verna	2005	1.23	1.4	0.234
49 right	Samsung	A52	86%	$ 200	In the Front Central Part	Partly Cloudy	Suzuki	Forsa 2	1997	1.25	1.46	0.039
06 right	Samsung	A10	83%	$ 100	Front Center	Clear	Ford	Escape	2014	1.26	1.45	0.047
02 right	Samsung	A20	50%	$ 200	Front Center	Clear	Daytona motorcycle	Scrambrel	2022	1.5	1.7	0.014

4. Discussion.

Researchers have conducted a series of studies to determine the International Roughness Index (IRI) using smartphones in various contexts, achieving mostly satisfactory results. A literature review covering 49 relevant articles found that the accuracy of smartphone-based IRI measurements ranged from 0.60 (R^2= 0.36) to 0.95 (R^2= 0.90) compared to IRI obtained through traditional methods [4]. In other instances, correlations higher than 0.86 (R^2= 0.74) were found between smartphone-derived IRI and roughometer-measured IRI [8], and a correlation of 0.97 (R^2= 0.95) with the Rod and Level method [9]. In our research, the highest R^2 value was 0.334 (RMSE = 1.61 m/km (smartphone: 2-left)), which is considerably lower compared to findings from previous studies reviewed.

The significant discrepancy in R^2 values in our study compared to the literature could be attributed to several factors, including differences in device calibration, the environmental conditions under which measurements were made, or specific features of the phones used, or tire pressure and suspension stiffness as suggested by previous studies [10]. Although the performance observed in this study is lower than documented in prior literature, it still suggests a moderate potential for smartphones to estimate IRI cost-effectively and accessibly, especially in contexts where quick estimates are required and specialized equipment is unavailable. However, it is evident that to achieve precision levels comparable to traditional methods, optimizing both hardware selection and data processing methodologies is critical.

After selecting the top 10 devices based on their performance (the lowest MAEs), we observed RMSE values ranging from 0.95 to 1.70, which are considered within an acceptable range. Previous studies have reported RMSE values of 0.75 and 1.14 [11], and an RMSE of 0.60 [12]. These figures highlight the variability and challenges associated with obtaining accurate measurements.

Analyzing battery percentage, we see a moderate correlation between the smartphone's battery percentage and the coefficient of determination (R^2), with a correlation value of 0.311. This suggests that a higher battery level might be associated with more reliable IRI measurements. Since accuracy is not significantly affected by the battery percentage, as indicated by the weaker correlations MAE (0.114) and RMSE (0.121), it can be inferred that, although a fully charged smartphone might provide slightly more consistent results, battery charge is not a critical determinant of accuracy in road roughness data capture.

Vehicle Year: The correlation between the vehicle's year and both MAE (0.445) and RMSE (0.462) indicates that older vehicles tend to be associated with less precise IRI measurements. This trend may reflect how the vehicle's features, such as suspension technology, affect the quality of the measurements. However, the weak negative correlation between the vehicle's year and R^2 (-0.036) suggests that the vehicle model alone is not a strong predictor of the ability to perform consistent IRI measurements, emphasizing the influence of a combination of factors on data collection accuracy. Previous studies indicate that the accuracy of data collected via smartphone can vary due to various variables, including vehicle type [12]. Although very close IRI values can be obtained through cellphone and an inertial profiler, it is suggested that the calibration of vehicle suspension systems should be considered when measuring IRI [13].

Smartphone Price: The price of the device showed a weak negative correlation with MAE (-0.085) and RMSE (-0.117), and a weak positive correlation with R^2 (0.088). These findings indicate that, although more expensive smartphones may offer marginally higher consistency in measurements, the impact of price on accuracy is limited. This result suggests that investing in higher-priced devices does not necessarily guarantee a substantial improvement in the quality of IRI measurements, emphasizing the viability of using a broader range of devices for these applications.

While our study collected data from different trips under various conditions, as previous research suggests [14], one limitation was the omission of speed analysis. This data was not recorded adequately; however, it will be considered in future studies. Speed is a crucial factor in this type of research; for instance, previous studies assessed the IRI across three different speed ranges. The results indicated that the best correlation between the IRI measured by smartphones and that obtained by a roughometer is achieved at speeds of 31 to 50 km/h, with correlation values of 0.75 and an RMSE of 1.14 [11].

The various studies reviewed suggest that using smartphones for data collection is a reliable, cost-effective, and efficient technique, especially in terms of the time required for data collection and processing in pavement roughness assessment [2]. However, the results obtained in our research do not reflect the same reliability. This indicates the need for more in-depth research to understand the parameters.

5. Conclusion

In this study, the feasibility of using smartphones to measure the International Roughness Index (IRI) on a section of the Loja-Malacatos highway was evaluated by comparing it with measurements obtained using the specialized Roughometer III instrument. The results indicated that, although smartphones did not achieve the precision of specialized devices, they present an economical and accessible alternative for preliminary IRI estimates. It is crucial to verify the IRI measurements obtained with smartphones on a road section under known conditions to calibrate the application used, as some measurements showed suspiciously constant and inaccurate values. The factors that most influenced accuracy included the type and condition of the vehicle, the characteristics of the smartphone (especially battery charge), and the environmental conditions during the measurements.

For future research, it is suggested not to rely exclusively on pre-existing applications but to develop specific software that directly utilizes the raw data from the mobile devices' sensors, which could significantly improve the precision of the measurements. The limitations observed, such as the influence of vehicle speed which was not adequately considered, highlight the need for methodological adjustments that could be refined in subsequent studies.

Further exploring the calibration of mobile devices, operating conditions, and the development of more robust applications for data collection could consolidate the use of smartphones in monitoring the condition of roads, providing a valuable tool for maintenance and planning of road infrastructures, especially in contexts with limited resources.

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