Pavement Condition Assessment using Smartphone Accelerometers

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***Abstract*— The vast road networks and limited resources make the prioritization of roads for maintenance purposes very difficult. Routine pavement condition monitoring is inevitable for ensuring comfortable and safe travel experience for the road users. Roughness is one of the significant road conditions as it directly affects the safety of the users as well as the vehicle costs. Road roughness is generally measured using expensive or time-consuming instruments like roughometer, and MERLIN. The present work discusses a novel, low-cost and easy method using smartphone sensors for road roughness measurement. Smartphone is fixed on the dashboard of a vehicle to collect the vertical vibrations caused when it is driven over the pavement. Quarter car simulation model is employed to convert the smartphone-based vertical acceleration values to International Roughness Index (IRI). Roughness survey is conducted using a standard Roughometer and a Smartphone on 19 roads in Tiruchirappalli city, as it is one among the 12 cities selected for implementing Smart-City project in Tamilnadu state of India. An R2 value of 0.82 between the results from smartphone and roughometer is a standing testament to its applicability in pavement condition assessment. The relation was further validated by applying it for the data collected for a second trial on the same set of roads.**

Keywords*— IRI estimation model, Roughness, Roughometer, Smartphone Sensors, Quarter Car Simulation Model component; formatting; style; styling; insert (key words)

I. INTRODUCTION

A smart city is a municipality that makes use of communication and information technologies to escalate operational efficiency and share the information with the public in order to improve both the welfare of the citizen as well as the quality of Government. Tiruchirappalli, being one of the 12 cities selected for implementing Smart city project in Tamilnadu state of India has a vast road network of 715.85 km [1, 2]. Adequate and timely maintenance of these roads is a prerequisite to avoid irreversible damages. The in-service performance of the pavement depends on cost-effective, consistent, and accurate condition monitoring for early scheduling of maintenance and repair. This involves, analyzing its structural condition, roughness, skid-resistance, etc. Roughness is one of the crucial pavement characteristics since it affects the ride quality, fuel consumption; maintenance costs, etc. It is normally measured using expensive or time-consuming instruments like roughometer, bump integrator, laser profilometers, MERLIN, etc. [3].

Longitudinal road profiles are generally measured to obtain the International Roughness Index (IRI) values, and the recommended units are m/km or mm/m. International Road Roughness experiment was conducted in Brazil (1982) by the World Bank and the conventional roughness measuring techniques were divided into four classes. Class I equiment such as rod and level, MERLIN, etc. give highly accurate results and thereby enable a precise measurement of road roughness. However, such methods are rather tedious and time-consuming. Direct measurement of road profile from each wheel track is carried out by Class II devices like Laser Road Surface Tester, APJ Trailer, etc. The accuracy of such methods is very less when compared to Class I equipment. Class III devices such as Roughometer or Bump Integrator study the response of the vehicle or the trailer used in the experiment to evaluate the pavement roughness. Even though a reasonable level of accuracy is obtained with the use of Class III equipment, they are very expensive. Class IV method usually quantifies pavement roughness in terms of Present Serviceability Rating (PSR) [4], [5]. PSR is defined as 'the judgment of an observer as to the current ability of the pavement to serve the traffic it is meant to serve' [6]. The observers ride over the test track, and the ride quality is rated on a quantitative scale to generate the PSR score. The rating scale ranges from 0 (essentially impassable) to 5 (excellent). As road roughness largely affects the ride quality, PSR and roughness are said to be related. However, this road condition appraisal method is highly subjective and is therefore not a reliable measure of road roughness.

To surmount these drawbacks, modern smartphones equipped with different efficient sensors such as proximity sensors, gyroscope, accelerometer, etc. can be used for pavement roughness surveys (Liu 2013). The number of smartphone users around the world is exponentially increasing, and it is expected that smartphones will become the leading handset type in almost all countries by 2025 [8]. Smartphones have proved their applicability in various walks of transportation engineering. In recent years, smartphone sensors are being harnessed in the field of travel time estimation, vehicle speed monitoring, least cost or shortest route identification, traffic congestion studies, etc. (Neeft 2017; Nawaz and Mascolo 2014; Prasanth and Karthikeyan 2016; Wunnava et al. 2007; Yoo, Park, and Kang 2005).

In the present work, an attempt is made to develop a novel, low cost, and easy alternative to measure road roughness with the aid of smartphone sensors. Many researches have been conducted in the to use smartphones as a tool to estimate road roughness. [4], [14] manually double integrated the acceleration data to obtain the pavement profile, and it is then given as the input of ProVal software to get the International Roughness Index (IRI). [5], analyses the standard deviation of the acceleration values to analyze the road roughness and ghats complexity. [6], deploys the root mean square value of the acceleration data and the gravity component to estimate the road roughness. Very few researches are conducted for determining the IRI by considering the effect of suspension characteristics of the vehicle. In this work, quarter car model that takes suspension characteristics of the vehicle in account is used to convert the vertical acceleration values captured using the smartphone sensors to its power spectral density (PSD). An equation is derived to convert this PSD to IRI values. Smartphone as well as roughometer data is collected simultaneously for 19 roads within Tiruchirappalli District. The roughness values captured using the standard roughometer is used to validate the results from smartphone sensors.

II. STUDY AREA

The study area comprises of 19 urban roads in Tiruchirappalli city of Tamilnadu State, India with a total length of 15. 25 km. Tiruchirappalli, is ranked first among 12 cities selected for implementing Smart-City project in Tamilnadu state of India. It provides good connectivity between all major cities in Tamilnadu. The details of the selected roads are shown in Table 1 and Figure 1. Two rounds of lane wise roughometer as well as smartphone roughness survey was conducted for the whole road stretches. Therefore, roughness data for a total of 72 kms were collected.

Fig 1. Study Roads.

TABLE I. DETAILS OF THE STUDY ROADS

Road No.	Road Name	Length (km)	No. of Lanes	Length for 2 runs (km)
1	Anna Nagar Main road	1	2	4
2	Bharathithasan Road	1.300	4	10.4
3	Bishop Road	1.050	2	4.2
4	Collector Office Road	1.675	2	6.7
5	Convent Road	0.525	2	2.1
6	Hospital Road	0.550	2	2.2
7	Lawson's Road	0.500	2	2
8	Mc Donald's Road	0.350	2	1.4
9	Pattabiraman Street	0.850	2	3.4
10	Puthur EVR Road	0.725	4	5.8
11	Puthur Main Road	0.725	4	5.8
12	Reynold's Road	0.375	2	1.5
13	Rockins Road	0.525	2	2.1
14	Royal Road	0.625	2	2.5
15	Salai Road	1.250	2	5
16	Sastri Road	1.025	2	4.1
17	Thillai Nagar Main Road	1.050	2	4.2
18	Victoria Road	0.275	2	1.1
19	William's Road	0.875	2	3.5
	Total	**15.25**		**72**

III. METHODOLOGY

The methodology adopted for the present work is depicted in Figure 2.

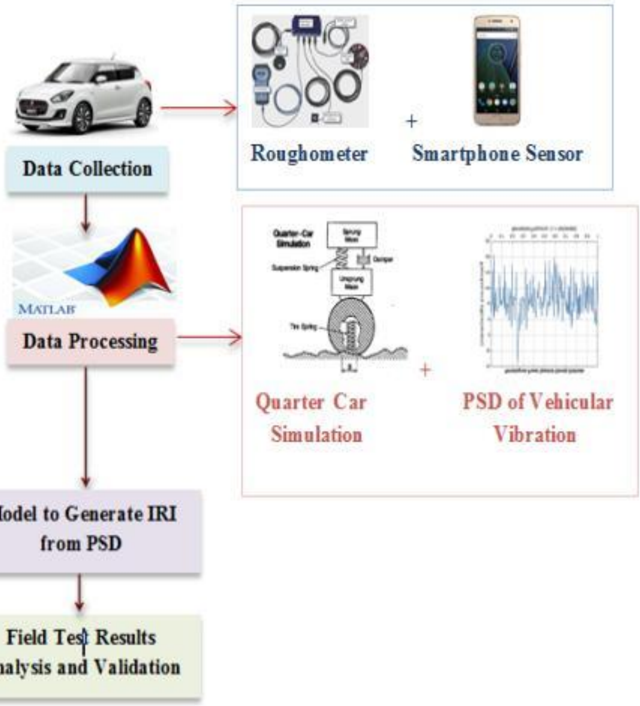

Fig 2. Project Approach

Smartphone used for the survey is fixed on the dashboard of a Tavera car (SUV model) using thin and strong double-sided adhesive tape. The head and face of the smartphone were pointing to the front and roof of the vehicle respectively. Therefore, the left-right motion, front-rear motion and up-down motion of the car are identified by x, y, and z-axes of the smartphone accelerometer respectively. AndroSensor application is used to collect the data from the smartphone accelerometer which has a capacity of 200 Hz. Five different smartphones were used for the data collection, and the acceleration data from one smartphone was used for further data processing after considering various aspects such as the type of accelerometer used in the smartphone, specifications, accuracy, etc. As those details are beyond the scope of this paper, it is not explained in detail. Two rounds of lane-wise smartphone based vertical acceleration and roughometer based IRI values of the study roads were captured simultaneously. The concept of Quarter Car Simulation model was deployed to develop a relationship between Power Spectral Density (PSD) and IRI. This relation was used to generate a model with the first set of data. The model was validated by applying it to the second set of data. The accuracy was further checked by analyzing the correlation between the predicted (Smartphone-based) and obtained (Roughometer-based) IRI values.

IV. SMARTPHONE BASED IRI ESTIMATION

Quarter car simulation is the most employed as well as a useful model of the suspension system of a vehicle [15]. A general representation of a quarter-car model with two degrees of freedom is shown in Figure 3.

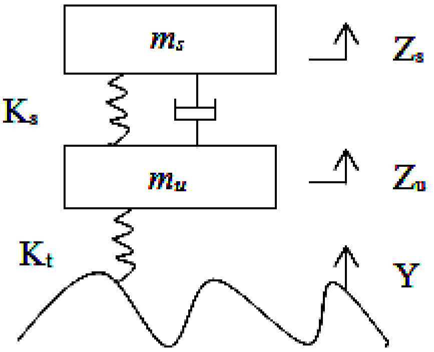

Fig 3. Quarter Car Simulation Model

By applying Newton's second law, differential equations (1) and (2) are obtained.

$$\ddot{Z}_s + C_s(\dot{Z}_s - \dot{Z}_u) + K_s(Z_s - Z_u) = 0 \tag{1}$$

$$m_u\ddot{Z}_u + C_s(\dot{Z}_u - \dot{Z}_s) + K_s(Z_u - Z_s) + K_t(Z_u - Y) = 0 \tag{2}$$

m_s and m_u are the sprung and unsprung mass respectively. The suspension system is the combination of a linear spring of stiffness K_s and a linear damper with a damping rate C_s. Alinear spring of stiffness K_t is used to represent the tire.Zs, Zu and Y are the vertical displacements from static equilibrium of sprung mass, unsprung mass and road respectively. The response of the Quarter Car Model can be used to estimate IRI using (3) [16].

$$\mathrm{IRI} = \frac{1}{L}\int_0^L |Z_s - Z_u|\, dx \tag{3}$$

Where, *L* is the length of the road on which the experiment is performed.

Power Spectral Density describes the way in which the power of a signal is distributed over different frequencies. Therefore, it is used for random vibration analysis. This can be explained using Wiener-Khinchin Theorem. The theorem, states that the autocorrelation function of a wide-sense-stationary random process has a spectral decomposition given by the power spectrum of that process as shown in (4).

$$R_{XX}(\tau) = \int_{-\infty}^{\infty} S_{XX}(\omega)e^{j\omega T}\, d\omega \tag{4}$$

where, is the autocorrelation function, is the PSD and is the angular frequency.

According to the concept of a Linear Time-Invariant System and considering Y(t) as systematic excitation, $Z_s(t)$ and $Z_u(t)$ as systematic response, the frequency response function is solved by Laplace transform as shown in (5) to (7) [9, 10].

$$H_{Z_sY}(\omega) = \frac{K_t(jC_s\omega + K_s)}{\Delta(\omega)} \tag{5}$$

$$H_{Z_uY}(\omega) = \frac{K_t(-m_s\omega^2 jC_s\omega + K_s)}{\Delta(\omega)} \tag{6}$$

$$\Delta(\omega) = (-m_s\omega^2 jC_s\omega + K_s)(-m_u\omega^2 jC_s\omega + K_s + K_u) - (jC_s\omega + K_s)^2 \tag{7}$$

As the systematic response is also a stationary random variable, IRI can be estimated from (8).

$$\mathrm{IRI} = A \text{ x } \sqrt{\int_{-\infty}^{\infty} |H_{Z\,Y}(\omega)|^2 \left(\frac{\omega}{v}\right)^4 S_a(\omega)\, d\omega} \tag{8}$$

$$\mathrm{IRI} = A\sqrt{\mathrm{PSD}} \tag{9}$$

Therefore, it was identified that there is a linear relationship between the IRI and the square root of the PSD function. MATLAB code is used to determine the PSD, and the relation between PSD and IRI that is obtained using the first set of data is shown in figure 4.

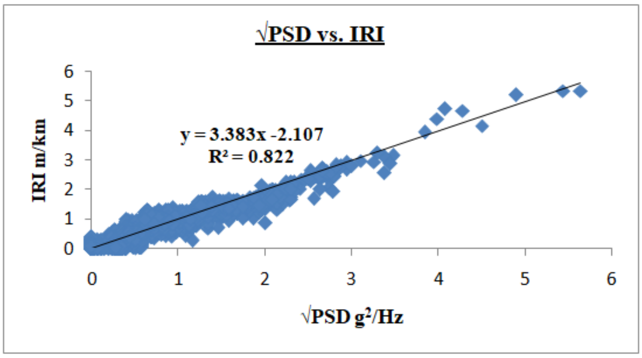

Fig 4. Plot for √PSD vs. IRI

The IRI-PSD model developed is shown in (10) and the R^2 obtained with the roughometer based IRI values was 0.822. Therefore, the fit of the model was good.

$$\mathrm{IRI} = 3.383\sqrt{\mathrm{PSD}} - 2.107 \tag{10}$$

The validation of the model was performed using the second set of data. The IRI- PSD model developed was used to derive the IRI values for the second run on the test section. The actual road wise consolidated IRI values obtained using roughometer and the corresponding smartphone based values obtained for rounds 1 and 2 are depicted in figure 5.

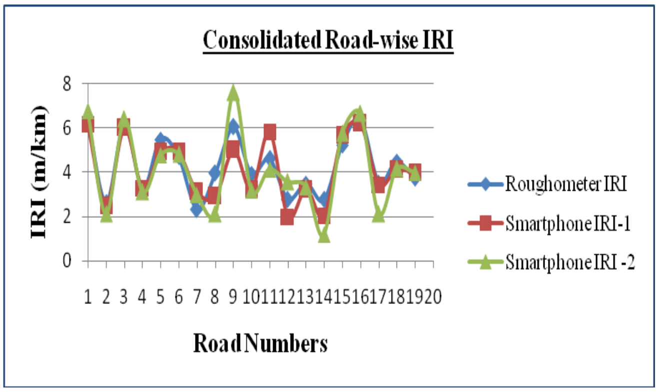

Fig 5. Consolidated Road-wise IRI

The correlation of consolidated road wise IRI values collected using Roughometer and smartphone for both round 1 and 2 is shown in figures 6 and 7.

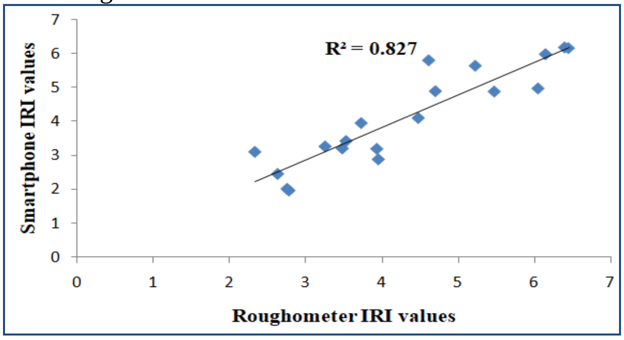

Fig 6 Roughometer vs. Smartphone IRI values- Trial 1

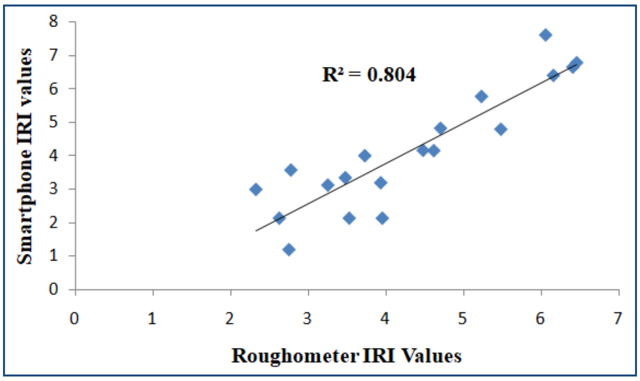

Fig 7 Roughometer vs. Smartphone IRI values- Trial 2

The high correlation values of 0.827 and 0.807 for trials 1 and 2 respectively shows that the model developed is repeatable and reproducible.

V. CONCLUSIONS

The relation between International Roughness Index and the Power Spectral Density of smartphone based acceleration values are explained and a model is developed for the same. The accuracy of the model was validated by applying it for the data collected on 19 roads within Tiruchirappalli district of Tamilnadu state, India. The correlation value as high as 0.82 is a stand testament for a strong relationship between the IRI and PSD of smartphone based acceleration values. This proves that there is a high potential for utilizing smartphones in pavement condition assessment. One of the significant advantages of this method is that it considers the suspension characteristics of the vehicle while estimating the IRI. The rapid growths in number of smartphone users all around the world, its ease of usage and low cost have helped pave the way to a novel and welcome change in the pavement condition assessment. This technique offers promising potential for engineers to reliably assess large areas in less time. The work can be further improved by analyzing the results when the smartphone is not kept in a fixed position as in the present case. The outcomes of the present work are expected to benefit pavement maintainers and researchers although some aspects of the study need to be expanded and improved, particularly with reference to the effect of driving speed in the results. A smart city can be called as an urban area that utilizes various electronic sensors for collecting data as well as supplying this information to the concerned authorities in order to help them in managing the resources and assets efficiently. Deploying accelerometer sensors present in smartphones for monitoring the condition of the pavements is not only smart but also less time consuming, low cost and easy.

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