**MTech Thesis Progress Report**

**Evaluation of IRI using Smartphone Application**

**PROJECT**

***By***

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**ARGUL, JATNI -752050, ODISHA**

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**Evaluation of IRI using Smartphone Application**

**A PROJECT**

***Submitted in partial fulfillment of the***

***requirement for the award of the degree***

***of***

**MASTERS OF TECHNOLOGY**

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***By***

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**14 SEPTEMBER 2021**

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CANDIDATE’S DECLARATION

We hereby certify that the work which is being presented in the project entitled **“Eevaluation of IRI using Smartphone Application”**, in the partial fulfilment of the requirement for the award of the Degree of Master of Technology in Civil Engineering and submitted in the School of Infrastructure, Indian Institute of Technology Bhubaneswar, is an authentic record of my own work carried out during a period from to under the supervision of **Dr. Anush K. Chandrappa**, IIT Bhubaneswar.

The matter presented in the project has not been submitted by me for the award of any degree of this or any other Institute/ University

**PRANAV YOGESH BARADKAR (17CE02012)**

This is to certify that the above statement made by the candidates is correct to the best of our knowledge.

**Signature of Supervisor (S) Signature of H.O.S.**

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Chapter 1

# Introduction

## General

Continuously increasing rate of economic and infrastructure development in several countries like India causes increase in road traffic which further leads to road devastation. Also, funding for the infrastructure development is not appropriate with highly increasing maintenance demands, lack of which is one of the primary causes for large deterioration. It is one of the reasons to study about pavement deterioration or roughness.

Many of us have experienced a bumpy ride at some point, whether on a rural road or a city side street. We can say roughness is probably one of the better-understood properties of pavements, both in a qualitative way by the driver or passenger, and in a quantitative way by road engineers. Roughness simply means how bumpy or smooth a road can be, which is an indicator of not only how comfortable your ride is, but also the wear and tear on your vehicle, its fuel efficiency, and the maintenance needs of the road. Studies have suggested that increase in the road roughness increases fuel consumption. It can increase your vehicle operating cost by 4 - 5% (Islam et al. 2014)

International roughness index (IRI) is the parameter to measure road roughness. The United States National Cooperative Highway Research Program (US-NCHRP) initiated a research project to help state agencies improve their use of roughness measuring equipment. The work was continued by The World Bankto determine how to compare or convert data obtained from different countries (mostly developing countries) involved in World Bank projects. Findings from the World Bank testing showed that most equipment in use could produce useful roughness measures on a single scale if methods were standardized. The roughness scale that was defined and tested was eventually named the International Roughness Index. The World Bank. The IRI is used for managing pavements, sometimes used to evaluate new construction to determine bonus/penalty payments for contractors, and to identify specific locations where repairs or improvements (e.g., grinding) are recommended. The IRI is also a key determinant of vehicle operating costs which are used to determine the economic viability of road improvement projects.

The IRI was defined as a mathematical property of a two-dimensional road profile (a longitudinal slice of the road showing elevation as it varies with longitudinal distance along a travelled track on the road). As such, it can be calculated from profiles obtained with any valid measurement method, ranging from static rod and level surveying equipment to high-speed inertial profiling systems.

Pavement Management System (PMS) tool helps to allocate the budget and available resources for the reconstruction and maintenance for pavements in many countries optimally. The international roughness index (IRI) is considered a critical pavement condition parameter along with other pavement distresses like pavement condition index (PCI), rut depth, and pavement service ability index (PSI).

## Pavement Management system

A pavement management system (PMS) is a planning tool used to make pavement management decisions. PMS software programs predict future pavement deterioration due to traffic and weather, and recommend maintenance and repairs to the road's pavement based on the type and age of the pavement and various measures of existing pavement quality. Measurements can be made by persons on the ground, visually from a moving vehicle, or using automated sensors mounted to a vehicle. PMS software often helps the user create composite pavement quality rankings based on pavement quality measures on roads or road sections. Recommendations are usually biased towards predictive maintenance, rather than allowing a road to deteriorate until it needs more extensive reconstruction.

1. Typical tasks performed by pavement management systems include:
2. Inventory pavement conditions, identifying good, fair and poor pavements.
3. Assign importance ratings for road segments, based on traffic volumes, road functional class, and community demand.
4. Schedule maintenance of good roads to keep them in good condition.
5. Schedule repairs of poor and fair pavements as remaining available funding allows.

Research has shown that it is far less expensive to keep a road in good condition than it is to repair it once it has deteriorated. This is why pavement management systems place the priority on preventive maintenance of roads in good condition, rather than reconstructing roads in poor condition.

## International Roughness Index.

In order to address specifics of roughness measurement, or issues of accuracy, it is first necessary to define the roughness scale. In the interest of encouraging use of a common roughness measure in all significant projects throughout the world, an International Roughness Index (IRI) has been selected. The IRI is so-named because it was a product of the International Road Roughness Experiment (IRRE), conducted by research teams from Brazil, England, France, the United States, and Belgium for the purpose of identifying such an index. IRRE was held in Brazilia in Brazil under controlled measurement of different road surfaces under different road conditions using and various roughness measurement devices. The roughness scale selected as a IRI was best suitable for criteria of being relevant, transportable, and time-stable, while also easily used by practitioners.

The IRI is a standardized roughness measurement related to those obtained by response-type road roughness measurement systems (RTRRMS), with recommended units: meters per kilometre (m/km). The measure called by RTRRMS is also called by Average Rectified Slope (ARS) which is measure of average accumulated suspension motion of a vehicle divided by the distance travelled by the vehicle during the test. Reference RTRRMS used for the computation of IRI is a mathematical model in place of mechanical model and this model applied to road profile. The computational mathematical model is called as a quarter-car simulation (QCS) because it represents a RTRRMS having a single wheel. The measure is obtained from the simulation is called reference ARS. ARS is speed dependent therefore a standard speed of 80kmph is specified in IRI definition. The IRI is directly related to the opinions about road roughness. Figure 1.1 shows the range of IRI on different types of roads.

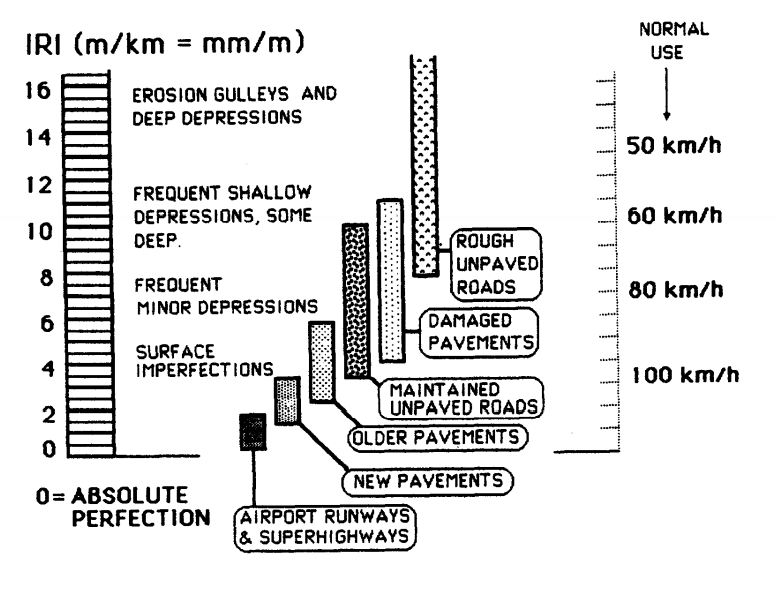


Figure 1.1.1: Range of IRI on different types of roads. (Source: IRC SP 16 2019)

## Problem statement

A high level of profile variation can increase vehicle operating cost by 4%-6%. Increasing population requires greater vehicular needs and therefore it is necessary to talk about maintenance of pavements and the economic losses due to road roughness.

According to US federation, each state needs to have his own PMS system. PMS help to allocate available resources for maintenance optimally. IRI is consider as very critical parameter for calculation of PMS.

One study reported pavement profile data collection and analysis involve agency costs in the range of $2.23 to $10.00 per mile with an average cost of $6.12 per mile (Islam 2014). In US, the cost of measuring IRI varies in the range of $1.40– $6.20 per kilometre (McGhee 2004) and in some areas like Wyoming, the cost of collecting roughness and video logs of pavement sections is around $31 per kilometre. However, many are relying on the IRI for the maintenance and reconstruction of the pavements.

On the other hand, methods which are used for determining IRI are either time consuming or expensive. Therefore, it is necessary to study about different methods which consume less time and cost. Inertial Profiler is one type of high speed profilometer based roughness measuring instruments which is used to calculate IRI at higher speeds. Inertial Profiler finds road profile using laser and vertical acceleration and converts it to IRI. A main drawback of the inertial profiler is that its operating and maintenance costs are very high.

The use of smartphones appears to be an appealing approach for reducing the cost of measuring roads roughness. These smartphones are equipped with many useful sensors such as gyroscopes, global positioning system (GPS), and three-dimensional (3D), or three-axis, accelerometers. But the calibration and validation of roughness data using smartphone is under investigation. In this study ability and consistency of smartphones data to calculate the IRI has been investigated.

## Objective and scope

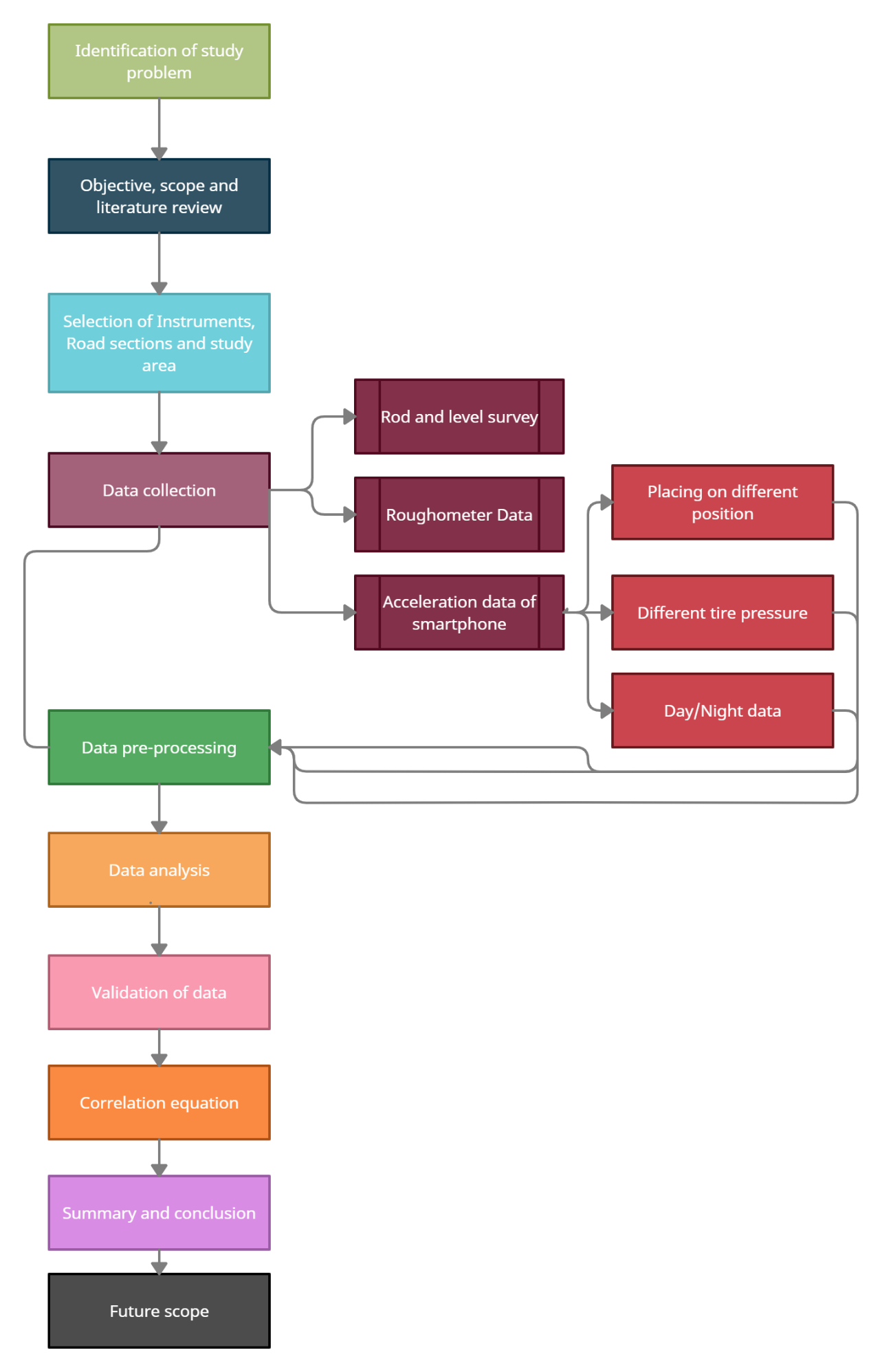
The present research was focused on calibration and validation of roughness data using smartphone application. The broad objectives of the research are:

1. Calculate of the IRI using smartphone application.
2. Effect of tire pressure on road roughness in RTRRMS methods.
3. Estimating best position to place smartphone.
4. Validation of smartphone for different pavement materials.

To accomplish the research objective, the scope of research was established which included

1. Selection of stretch of pavement as study area.
2. Data collection using class 1 method.
3. Data collection using roughometer and smartphone.
4. Calibration of roughometer.
5. Calculation of IRI using roughometer.
6. Determining profile of the road using smartphone.
7. Determining IRI using smartphone.
8. Calibration and validation of roughness data.
9. Effect of tire pressure.
10. Effect of smartphone positioning.
11. Effect of smartphone type.

## Methodology



Chapter 2

# Literature Review

## General

A wide review of literature was undertaken to comprehend various aspects of road roughness. Literature review begins with the definition of road roughness, background of the International Roughness Index and its importance. Next, discussed various methods to calculate road roughness and IRI. This section is followed by discussion about pros and cons of different methods and latest research. Various investigation of low-cost methods to calculate IRI and several aspects of analysed data are the farthest section.

## Road Roughness

Though there is not a single definition for pavement roughness, it is generally defined as an expression of irregularities in the pavement surface that affects the ride quality of the vehicle. American Society of Testing and Materials (ASTM) definition (E867) for roughness is “The deviations of pavement surface from a true planer surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage, for example, longitudinal profile, transverse profile and cross slope”. However, it is found that the drainage and ride quality is unrelated to each other. Roughness is an important indicator of pavement riding, comfort and safety. However, the different wave lengths on the surface profile affect differently on the ride quality depending on vehicle characteristics and driving speed. Generally, roughness may cause due to one or more of the following factors;

* + construction techniques,
  + Traffic loading. (For example, repeated loads in a channelized area may cause pavement distortion by plastic deformation),
  + environment effects,
  + construction material, and
  + non uniform initial compaction and built in construction irregularities.

Short wave length roughness is normally caused by localized pavement distresses such as depressions and cracking. On the other hand, long wave length roughness is normally caused by environmental process in combination with pavement layer properties.

## Roughness Measurement Methods

Roughness measurements are used to

1. Helps in measuring acceptability of repaired or newly constructed pavement section.
2. Important criteria in monitoring pavement management system.
3. Study the condition of specific sites for research, and
4. Estimating vehicle operating cost.

There are several indices currently in use to quantify the road roughness. These indices are based either on pavement surface profile or response type road roughness measuring devices.

### Profilometric systems

System whose measurements based on the profiles of road are, generally termed as profilometric system. Continuous representation of road profile is used to local defects, road roughness, etc. It involves measuring the profile, filtering the profile and mathematically computing the relevant roughness index.

#### Straightedge

This is the simplest profiling system. It is made up of wood or metal having usual length of 3 meter. The surface undulation can be measured by measuring the distance of pavement surface from bottom side of the beam while keeping it on pavement surface. Straightedge had been modified and now it is called as TRRL Beam static profilometer. TRRL has tripod for levelling and wheel to measure the vertical displacement. Figure 2.1 shows 3-meter straightedge.

Pros:

1. It is very cheap
2. Simple
3. Reliable data collection

Cons:

1. It is very time consuming as it covers only 3 meter of pavement surface and requires human efforts to measure the distance of road surface from bottom edge.
2. Very careful readings are required.
3. Inefficient
4. Lower mechanization



Figure 2.1 Straightedge (source: google)

#### Rod and level

Short wave length roughness is normally caused by localized pavement distresses such as depressions and cracking. On the other hand, long wave length roughness is normally caused by environmental process in combination with pavement layer properties. Figure 2.2 shows rod and level surveying.

Pros:

1. Better that straightedge in case of time consumption.
2. Time stable.
3. It is very cheap.
4. Gives data to calibrate other high-speed instruments.

Cons:

1. It requires at most 250mm distance between two measuring stations that makes it very slow.
2. Require human efforts.
3. Inconvenient

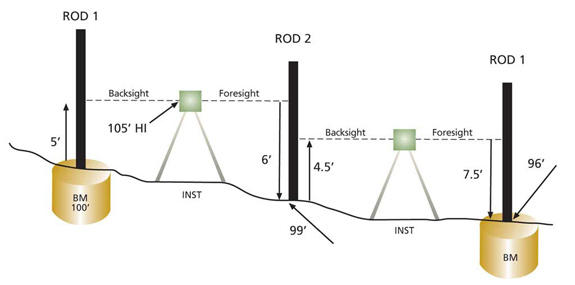


Figure 2.2 Rod and level surveying (source: google)

#### Dipstick

Dipstick contains a precision inclinometer which measure the difference in height between two supports. Dipstick has an accuracy of 0.15mm per reading. To get the profile device s walked along the line being profiled. Figure 2.3 shows a sketch of a dipstick profilometer.

Pros:

1. Better than straightedge and rod and level in case of time consumption.
2. Time stable.
3. Gives data to calibrate other high-speed instruments.

Cons:

1. Costly than rod and level surveying.
2. It covers distance with walking speed it makes it slower for longer pavements.

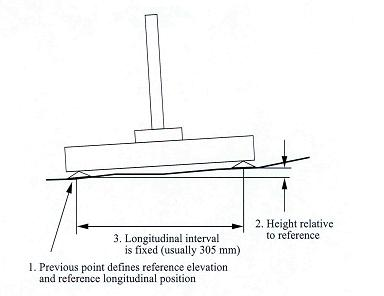


Figure 2.3 Dipstick (source: M. W. Sayers et al. 1998)

#### MERLIN

MERLIN stands for a Machine for Evaluating Roughness using low-cost instrumentation. The device can be used for calculating profile or calibrating response type devices. In Sri Lanka this device is used to calibrate the vehicle mounted bump integrator. The merlin was designed by Transport Research Laboratory (UK) for using developing countries. Merlin advantages are,

1. Robust – require so special care and handling
2. Easily built
3. Easily calibrated
4. Easily built
5. Easily used
6. Easily maintained
7. Direct reading of IRI is calculated without using QCS model.

To determine road roughness usually 200 measurements are made. The Merlin reading is converted to IRI scale using ‘Calibration scale’.

The sensitivity of the IRI scale varies with wavelength and IRI is the highest for waves of around to meter. The sensitivity of the Merlin is also high at these waves that’s why it is good estimates for IRI. (M.A.Cudil 1996).

When Merlin is used to take roughness measurements, following factors have to be taken into consideration;

1. Take 200 readings per chart.
2. Take measurements with the wheel in its normal position. These regular spaced measurements give the most representative result.
3. When the Merlin is used to measure the roughness of a test section for calibrating a vehicle – mounted bump integrator, it is important to ensure that both measuring devices are working in the same wheel tracks.

Figure 2.4 shows MERLIN device.

Cons:

1. Inconvenient
2. Inefficient



Figure 2.4 MERLIN device (Source: google)

#### Inertial Profiler

This is the most sophisticated road profiling measuring equipment. This has a sensor called accelerometer that measure acceleration. Data processing algorithms convert the vertical acceleration measure to an inertial reference that defines the height of the accelerometer. This height is measured with a non-contacting sensor. This method of measurements is more accurate and this eliminates many potential sources of human errors. Figure 2.5 shows inertial profiler.

Pros:

1. It is very straightforward.
2. It is high speed instruments that makes it efficient
3. Give direct value of IRI.

Cons:

1. These devices are mounted on a full-size van, automobile, or trailer, it is difficult to use them on the roadway for short periods of time.
2. High cost of operation and maintenance.

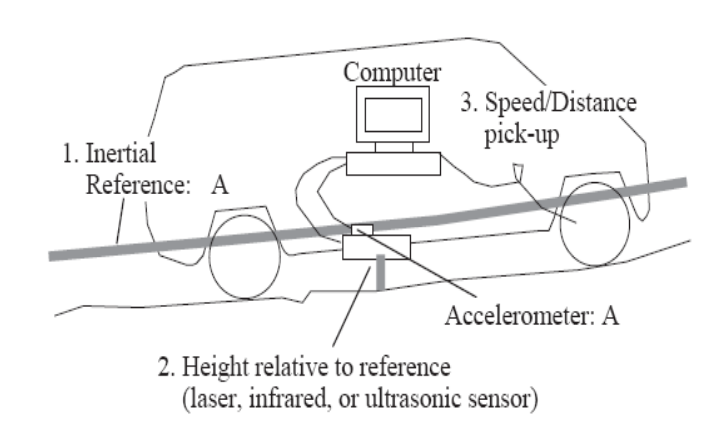


Figure 2.5 Inertial Profiler (source: M.W Sayers, 1998)

### Response Type Road Roughness Measuring System (RTRRMS)

Devices are installed in a car to record the suspension as a measure of road roughness. These are called road meters and several other names called Response-Type Road Roughness Measuring Systems (RTRRMS), response-type systems, and road meter systems. In these systems, the vehicle is a passenger car, a van, a light truck, or a special trailer. Nearly the entire road meter designs follow the concept of the Bureau of Public Roads (BPR) Rough meter, and accumulate deflections of the vehicle suspension as it travels down the road. The measure is usually reported with engineering units such as inches per mile (in/mi) or meter per kilometre (m/km).

#### Fifth Wheel Bump Integrator:

As shown in Figure 2.6 Fifth Wheel Bump Integrator is a response roughness measuring system. It consists of standard pneumatic wheel mounted on chassis with single spiring on either side of the wheel. Integrator makes cumulative measurements of the unidirectional vertical movements of the wheel relative to the chassis. The test is conducted at 32 km/hour keeping it steady and avoiding swerving. Roughness index is defined as the ratio of the cumulative vertical displacement to the distance travelled and denoted in mm/km unit. The readings of the revolution counter and integrating counters are noted automatically in the data sheet.

Pros:

1. Simple to use.
2. Very fast.
3. Can mount in any vehicle.

Cons:

1. It is not consistent.
2. Time-instable
3. Affected by vehicle vibrations and weight.
4. Performs at the same speed.
5. High cost for maintenance.

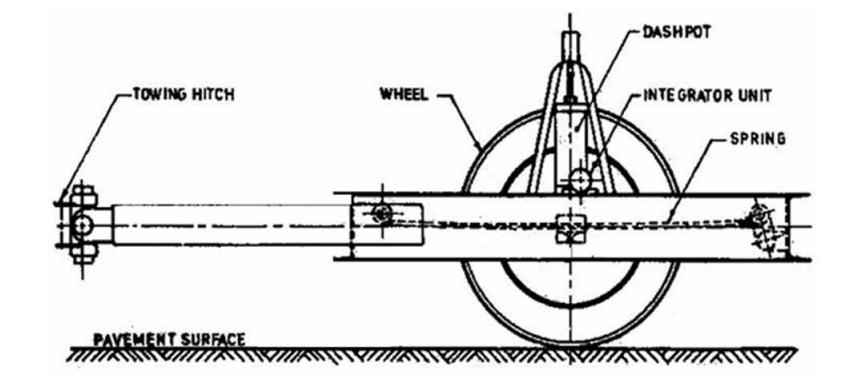


Figure 2.6 Sketch of fifth wheel bump integrator (source: IRC SP 16 2019)

#### Car Axle Mounted Bump Integrator:

The Car axle Mounted Integrator consists of bump integrator unit as provided in the fifth Bump Integrator as shown in Figure 2.7 The integrating end is fitted with the rear axle and placed in the rear portion of the car.

The difference of movement of body of the car and rear axle due to road unevenness is measured by the upward vertical motion of a wire which is transmitted into unidirectional rotator movement of the pulley of the integrator unit. Integrating unit convert rotational movement into electric pulses which is recorded into database. 1 count represents 1 cm relative movement between floor and axle in 1m length of distance travelled.

Road roughness is depending upon speed of the vehicle, vehicle loads and outer wheel path. This must be calibrated and validated with respect to class-1 equipment as per standard procedure.

Pros:

1. Simple to use.
2. Very fast.
3. Can mount in any vehicle.

Cons:

1. It is not consistent.
2. Time-instable
3. Affected by vehicle vibrations and weight.
4. Performs at the same speed.
5. High cost for maintenance.

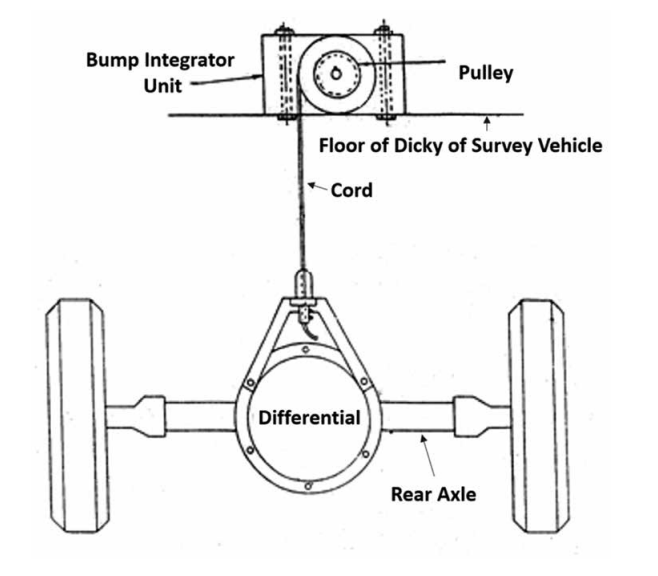


Figure 2.7 Car axle mounted bump integrator (source: IRC SP 16 2019)

### Accelerometer Based Equipment

These systems are based on the mechanism of measurement of vertical acceleration to calculate road roughness. This system may also be validated and calibrated against class- 1 equipment. Some portable type of roughness measuring equipment are available which consists of a small accelerometer (sensor) device (one or two) installed at the rear axle of the survey vehicle, a distance measuring instrument, interface module and a controller.

#### Roughometer

Roughometer is a high-speed device used for measuring pavement surface roughness. It is a portable type equipment and consists of a small accelerometer (sensor) device installed at the rear axle of survey vehicle, a distance measuring instrument, interface module and a controller. The pavement roughness measurements using this equipment are required to be done preferably at a speed in between 40 to 60 km/hr, in order to obtain most reliable and accurate data. The output is in the units of International Roughness Index (IRI). Figure 2.8 shows A Typical view of Roughometer Control Panel with GPS.

Pros:

1. Simple to use.
2. Very fast.
3. Can mount in any vehicle.

Cons:

1. It is not consistent.
2. Time-instable
3. Affected by vehicle vibrations and weight.
4. Performs at the same speed.
5. High cost for maintenance.
6. Require time to time calibration.

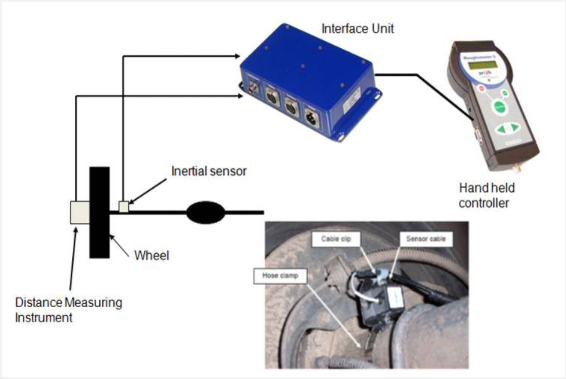


Figure 2.8 Typical view of a roughometer control panel (source: CSIR)

Another device in this category is measurement of IRI using mobile app-based application. This system uses inbuilt GPS and accelerometer to provide IRI of the pavement. Although these systems have self-calibration mechanism but it may be calibrated and validated against Class-1 instruments and also on different pavement types.

## Classification of Road Roughness Measuring System

Instruments used for the collection of roughness data are characterised into four classes.

### Class 1: precision profile

The instruments that provide the highest standard of accuracy for calculating IRI are called as Precision Profilers. This type of instruments provides series of accurately measured elevation points, closely spaced along the section not more than 250 mm with precision less than 0.5mm. for walking speed profilometer. But High speed profilometer have sampling interval is less than 25mm with precision less than 0.1mm.

### Class 2: Other profilometer Methods

An instrument which is not capable of giving accuracy as Class 1 or sampling intervals meet the criteria of class 2. The class 2 sampling intervals are set at a maximum of 500 mm with precision not less than 1mm for walking speed and interval of greater than 25 mm and less than 150 mm with precision not less than 0.2mm.

### Class 3: Response type Measurements:

All Response Type Road Roughness Measuring System (RTRRMS) belongs to this category of roughness measurement. RTRRMSs measure the dynamic response of vehicles to the road surface by using either mechanical or accelerometer devices. The estimation of roughness index for RTRRMS is made using correlation equation after calibration with Class-1 Road profiler.

### Class 4: Subjective Rating

In this class the evaluation of roughness investigated by driving the car on the road or making the visual survey.

## International Road Roughness:

International roughness index (IRI) is the accepted standard for measuring road surface’s roughness in worldwide. The IRI was obtained by the experiment led in Brazil. This experimental result helps in comparing directly data from different instruments and different countries that helps in enabling historical trend to be estimated with confidence. Without a common method for calculation, results from research could not be compared without the use of conversion factors from one unit to the next. IRI is reproducible, portable and stable with time. Accordingly, IRI is considered a geometric property of the road. Hence, it is a time-stable index, which generates the same values when applied to the same road (Sayers and Karamihas 1995)

The IRI was mainly developed to match the response of passenger car, but research has shown that IRI is also depending on other vehicles such as light trucks and heavy trucks. IRI is highly correlated to three vehicle response variables;

1. Road meter response
2. Vertical passenger acceleration, and
3. Tire load.

The IRI is a mathematical model applied to measure profile. This model simulates a quarter car system (QCS) traveling at a constant speed of 80Km/hr. The IRI is computed as the cumulative movement of the suspension of the QCS divided by the travelled distance, the unit of the index is m/km. Figure shows the QCS model.

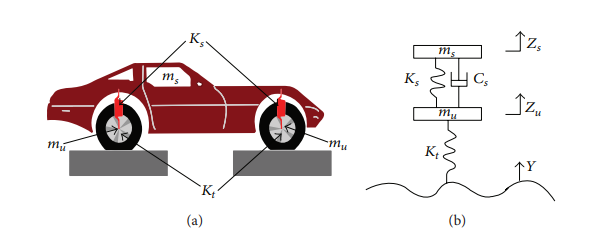


Figure 2.9 QCS model a) vehicle representation b) simplified representation (source: yuchuan du, 2014)

As stated by Sayers (1995):

1. From a solitary longitudinal profile might be processed. The specimen interim ought to be no bigger than 300 mm for exact figuring. The obliged determination is reliant on the roughness level and for smooth streets better determination is required.
2. It’s assumed that between sampled elevation point a constant slope persists. 3. By using the method of moving average the profile of base length 250mm.
3. After this by using quarter car simulation this smoothed profile is filtered, with Car at a simulated speed of 80km/hr (49.7 m/hr).
4. For finding out IRI direct amassing of mimicked suspension movement is partitioned by the profile length. Thus, IRI is measured with units in/mi or m/km

## Evaluating International roughness index.

International roughness index is very critical parameter for pavement management system. A high level of profile variation (i.e., roughness) can also increase vehicle operating cost by 4–5% (Islam and Buttlar 2012).

Class 1 and class 2 type instruments provide most accurate reading of the roughness but those are very time consuming and inefficient. In the 1920s, a vehicle’s vibrations caused by road surface irregularities became a major concern of highway engineers in identifying road roughness. This led to the development of response-type road roughness meters (RTRRMs). These devices measure vertical displacements in the rear axle of a vehicle. One of the major drawbacks of RTRRMs is that they are highly affected by the performance (particularly the suspension) of the vehicle that is used in the measuring process. These devices were not able to provide time-stable measurements. Hence, they were not comparable and not practical to be used for pavement management purposes (Gillespie 1992).

Nowadays consultants are using most modern roughness measurements devices which are noncontact profile measuring system (Islam et al. 2014). This devices measure deviation is longitudinal profile using acoustic and laser. Then these profiles are passed through software to calculate the IRI. Cost of operation of inertial profile varies from $1.4 - $6.2 per kilometre ((McGhee 2004) and in some cities like Wyoming, the cost of collecting roughness and video logs of pavement sections is around $31 per kilometre. However, many state department of transportations (DOTs) rely on IRI for their roadways’ maintenance and rehabilitation planning (Islam et al. 2014). Acceleration based instruments like roughometer have less maintenance and operation cost than inertial profiler but they are still high for developing countries and inconvenient because they need to perform at constant speed.

### Measuring Pavement roughness using Smartphone Application.

Modern smartphones are equipped with many useful sensors such as accelerometer, gyroscope, magnetometer and GPS. These sensors are usually used to identify the orientation of the smartphone screen and other functional activities (Douangphachanh and Oneyama 2013). A 3D accelerometer is a sensor that measures the changes in velocity among the x-, y-, and z-axes in the units of acceleration. Several studies were performed to use 3D accelerometers in identifying roadway conditions (Strazdins et al. 2011; Douangphachanh and Oneyama 2013; Jiménez and Matout 2014; Hanson et al. 2014; Islam et al. 2014, Waleed Aleaadelat 2018). In 2011, Strazdins performed research which states the use of android smartphones to detect potholes and bumps present in pavement. Even with the less accurate accelerometer and GPS they could detect potholes and bumps using simple algorithm.

In 2007 **A. Gonzalez** conducted study to use vehicle accelerometer’s acceleration data to estimates road roughness. They harnessed the data from vehicle accelerometer then PSD of the road profile was estimated from the PSD of the axle or body acceleration measurement. But this approach required prior knowledge of vehicle transformation function. Estimated profile then passed through QCS model to propose classification method to road roughness, speed, vehicle parameter and noise. However, this study did not give direct measure of IRI but it was able to output different level of roughness.

**Douangphachanh and Oneyama** conducted a study to estimate the IRI through smartphone accelerometer measurements (Douangphachanh and Oneyama 2013). They used two Android smartphones (Samsung Galaxy Note II and III) mounted on the dashboard of the test vehicle. Two vehicles, a Toyota VIGO 4WD pickup truck and a Toyota Camry were used in this experiment. The IRI was measured using Vehicle Intelligent Monitoring System (VIMS) for every 100 m (328.08 ft). A Fast Fourier Transform (FFT) was performed on the accelerometer data to obtain a frequency domain view of each signal. A linear relationship was established between the sum of magnitudes from FFT and the measured IRI. The resulting relationship was statistically significant when the speed was less than 60 km/h , with a partial dependence on the vehicle and smartphone type. After one year Jiménez and Matout (2014) used tablet’s accelerometer to evaluate pavement roughness. In there study they found that vertical acceleration normalized by the driving speed can give indication of the road roughness. However, the study did not develop direct relationship to find IRI but it was able to output different level of roughness.

In the same year, Islam et al. (2014) conducted a study at the University of Illinois to determine the IRI using a smartphones’ integrated accelerometers. Three test sites (each 3.22 km long) with various roughness conditions were selected. By using a double integration method on the vertical acceleration data obtained by the smartphones, a perceived road profile was formed. The perceived road profile was converted to IRI using ProVAL software. It was found that the calculated IRI values were consistent with the measured IRI values using a standard inertial profiler. However, calibration was required for rougher pavement sections to overcome the effect of suspension damping. Figure 2.10 shows the correlation between IRI by smartphone and reference IRI.

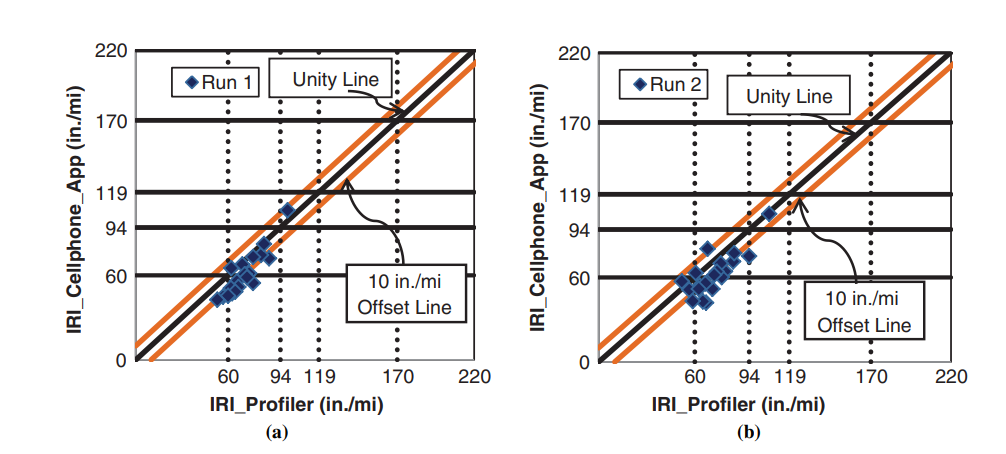


Figure 2.10 Correlation between measured IRI and actual IRI (source: Islam, 2014)

In 2018, **Waleed** conducted a study to calculate IRI on the basis of similar pavement condition may provide similar signal pattern (time acceleration series) using smartphone application. For this study two smartphones Samsung Galaxy SIII and Sony Xperia A were used to collect acceleration data. Phones were mounted on 2011 Ford Fusion sedan dashboard. Twenty random roadway segments were randomly selected from the Wyoming local county roads. Test vehicle is dived at the speed of 80km/h and 64km/hr and accelerometer data collected using AndroSensor application.

Acceleration signal data were pre-processed by applying both median filter with window size 5 and moving average filter with window size 10 to reduce noise in acceleration data. Different pattern recognition techniques like cross correlation and autocorrelation were applied to find similarities or key features between measured signals at each roughness category. Cross correlation shows the measured signals (time series acceleration data) using smartphones accelerometers are highly similar in shape. The actual IRI values do not affect the shape of the measured signals meaningfully. Correlation between variance of acceleration signal and reference IRI gave some promising results. However, results were not good for lower IRI values and higher IRI values as shown in Figure 2.11 and also significant difference were seen in calculated IRI values of both the smartphones. This study did not provide any reason on inconsistency of the data of two smartphones and vibrations due to car suspension was not normalized.

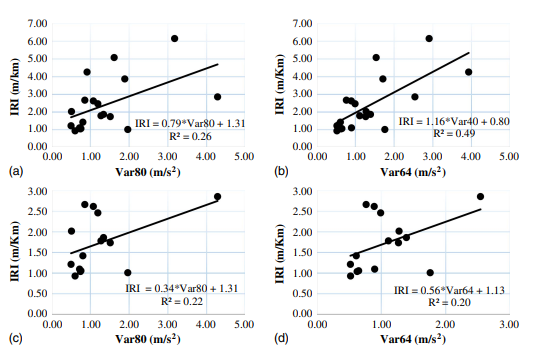


Figure 2.11 Correlation between IRI and variance a) Samsung mobile 80kmph b) Samsung mobile 64kmph c) Sony mobile 80kmph d) Sony mobile 64kmph. (Source: waleed et al. 2018)

In 2021, Hossain conducted a study to check consistency of Roadroid application data on different smartphones. Two smartphones were mounted on car dashboard and collected IRI data using Roadroid application. This study shows good consistency of IRI in between Samsung and Motorola with R^2 vale equal to 0.8. However, consistency of IRI with PCI value shows improper relationship. Figure 2.12 shows the consistency between measured IRI of Samsung J3 and Motorola G6.

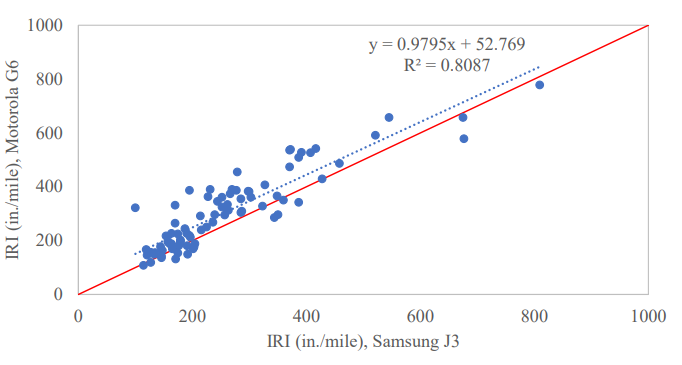


Figure 2.12 consistency between measured IRI of Samsung J3 and Motorola G6. (source: Hossain 2021)

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