CHAPTER 2: LITERATURE REVIEW

2.1 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;

a) construction techniques,
b) traffic loading. (For example repeated loads in a chanalized area may cause pavement distortion by plastic deformation),
c) environment effects,
d) construction material, and
e) 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. (M.W.Shahin, n.d., 5)

2.2 Roughness Measuring Systems.

Roughness measurements are used to

a) measure acceptability of newly constructed or repaired road section.

b) monitor the condition of a road net work for pavement management systems.

c) diagnose the condition of specific sites and determine appropriate remedies.

d) aid design engineers to determine the degree of success.

e) study the condition of specific sites for research, and

f) calculate vehicle operating cost.

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

2.2.1 Profiling Devices.

A profile – roughness measuring system involves measuring the profile, filtering the profile to remove the waves which have minimum effect and mathematically computing the relevant roughness index.

2.2.1.1 Straightedge.

This is the simplest profiling system. This is made of wood or metal to a length of usually three meter. After keeping the straight edge on the pavement surface the surface undulation can be measured by measuring the distance from the bottom of the straight edge and the road surface. Later, the straight edge is modified and called as TRRL Beam static profilometer. There is a tripod for leveling at each end of the aluminum beam and a wheel is mounted in between to record vertical displacement. Figure 2.1 shows a three meter straight edge.

Figure 2.1 Straightedge

2.2.1.2 Rod and Level.

This is a conventional surveying method using rod and level. Here it is essential to take elevation measures at close intervals of 300mm or less and the precision must be up to 0.5mm. ASTM standard E1364 provides guidelines for measuring profiles with a static method.

2.2.1.3 Dipstick

This contains a precision inclinometer which measures the difference in height between the two supports. The device is walked along the line being profiled. The Dipstick has an accuracy of 0.15mm per reading. Figure 2.2 shows a sketch of a Dipstick profilometer.

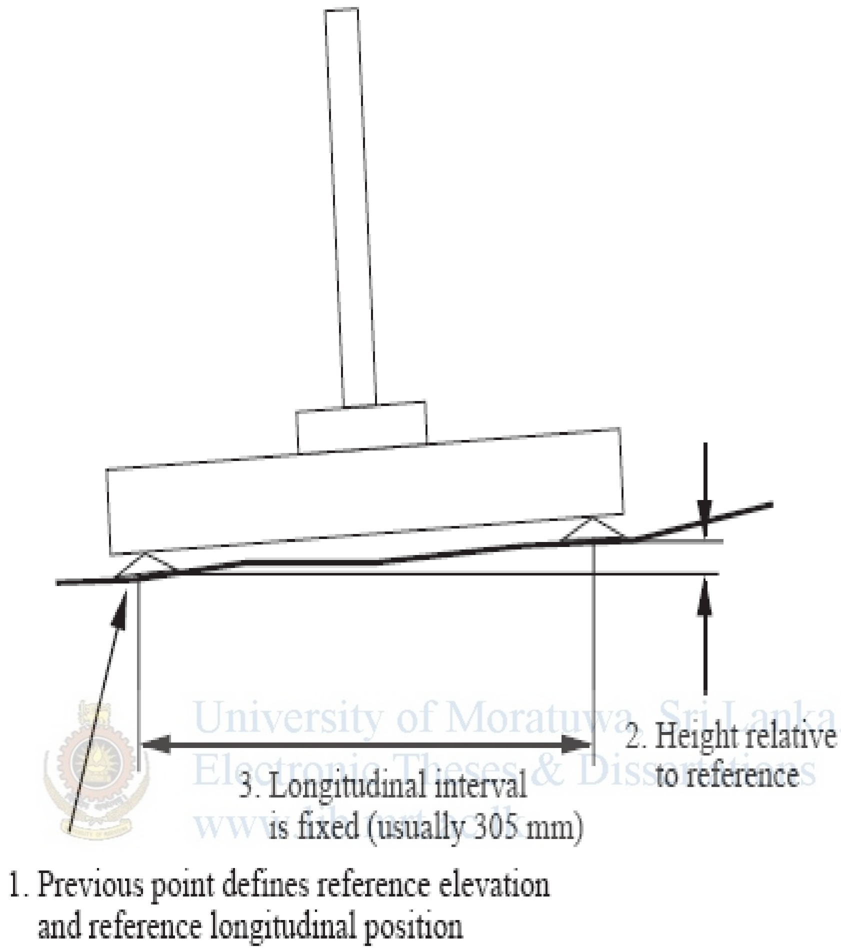

Figure 2.2 Dipstick
Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

2.2.1.4 MERLIN Road Roughness Machine

MERLIN stands for a Machine for Evaluating Roughness using Low cost Instrumentation. The device can be used either for direct profile measurement or for calibrating response type instruments. In Sri Lanka this machine is used to calibrate the vehicle mounted bump integrator. The methodology of calibration is given in chapter 3. Figure 2.3 shows the photograph of a Merlin machine.

Figure 2.3 MERLIN Machine
Source :(Herman de Solminihac T, Ricardo Salisill, Erwin Kohler ,Elva Bengoa. 2003)

The Merlin was designed by the Transport Research Laboratory (UK) for using developing countries. Its advantages are,

a) easily built,
b) robust – requires no special care and handling,
c) easily calibrated,
d) easily used – the measurement process is straightforward and an operator can be quickly trained, and
e) easily maintained.

The Merlin has two feet, 1.8m apart which rest on the road surface along the – wheel track whose roughness is to be measured.

A movable probe is placed on the road surface mid – way between the two feet and the Merlin measures the vertical distance, y, between the road surface under the probe and the centre point of an imaginary line joining the bottom of the two feet. There is a marker in the front wheel and when it touches the ground the Merlin is said to be in Normal position. When it is in normal position the reading is noted in the given chart which is kept in the Merlin machine. To determine the roughness usually 200 measurements are made. Then the Merlin reading is converted to IRI scales using ‘Calibration Scale’.

However, the undulations in surface of a road consist of as a mixture of surface waves of different Wave lengths. The sensitivity of the IRI scale varies with wavelength and it is the highest for waves of around two meters. The sensitivity of the Merlin is also high at these wave lengths and that is way it gives a good estimate of IRI. (M.A.Cundil 1996).

Merlin is used to calibrate Bump Integrator, Because of the different wave length sensitivities, it is important to calibrate the bump integrator on a range of test sections whose surfaces are typical of the surfaces which the bump integrator is going to measure.

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

a) Take about 200 readings per chart.

b) Take measurements with the wheel in its normal position. These regular spaced measurements give the most representative result.

c) 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.

2.2.1.5 Inertial Profiler

This is the most sophisticated road profiling measuring equipment. This has a sensor called accelerometer that measures 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 measurement is more accurate and this eliminates many potential sources of human errors. Figure 2.4 shows a sketch of an Inertial Profiler.

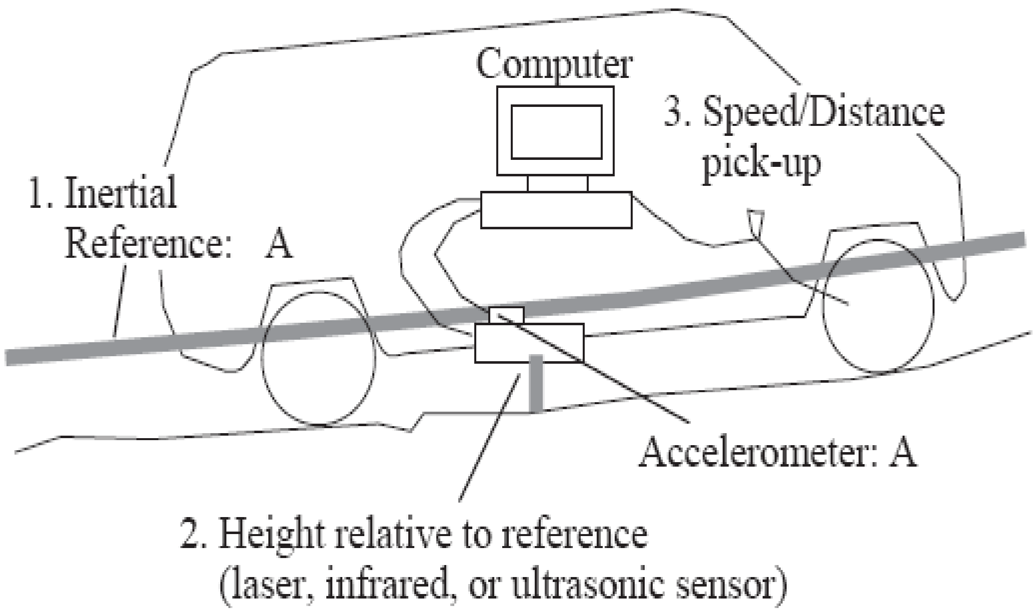

Figure 2.4 Inertial Profiler
Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

2.2.2 Response Type Devices.

Response Type Road Roughness Measurement (RTRRM) systems record the cumulative displacement of an axle relative to the body of the vehicle induced by the roughness of the road. The measure of vehicle response is very similar in its frequency content to the acceleration on the vehicle body, so it is highly correlated to ride vibration. This type of device sometimes called as road meters.

Vehicle vibration response could act as a better roughness index compared with the true profile because it directly relates to the discomfort a vehicle user is more concerned.

However, as this response – type system depends on the dynamics of the host vehicle, it has some unwanted effects: This measurement is not repeatable, even when the same vehicle is used due to change in characteristic over time. Also, roughness measurement is not transportable. Road meter measurements made by one system are seldom reproducible by another. So it is required a regular calibration.

2.2.2.1 T.R.R.L. Bump Integrator

The bump integrator (BI) unit is mounted on the vehicle floor at the centre line of the vehicle and the axle. The connection between the axle and the BI is by a wire cord which passes through a 25mm hole in the floor. It is important to position the cord such that it does not touch the hole edge otherwise the wire will fail and also distort results. The BI readings are recorded in a counter unit which is usually mounted onto the front facial of the vehicle. Figure 2.5 shows a sketch of a vehicle mounted Bump Integrator.

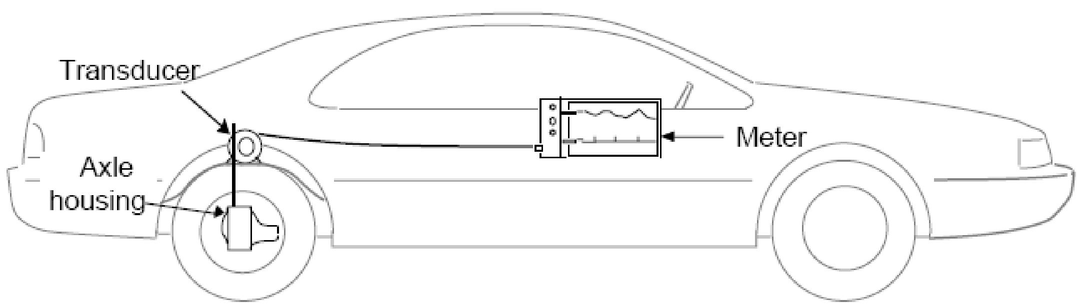

Figure 2.5 Vehicle Mounted Bump Integrator

Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

It is essential to follow the under mentioned procedures, otherwise the results that we get will not be accurate (Joseph Budras P.E., 2001)

a) The vehicle should be driven smoothly preferably at a speed of 32 km/h, on the test section without creating spurious input signals to the instrument through acceleration, deceleration and braking.

b) The weight of vehicle affects the roughness measure. Though some weight variation is unavoidable, such as weight due to fuel, other reasons, for instance having another passenger, shall be avoided.

c) Roughness measurements increase with tire pressure. Tires should be checked and maintained at a regular pressure, preferably recommended by the vehicle manufacturer.

d) Tire imbalance and out of roundness also cause to distort the roughness measurement.

e) Mechanical linkages, springs and shock absorbers are the main components which affect the response of RTRRMS. They should be regularly inspected and serviced.

The BI readings are finally converted to IRI values which are in m/km unit.

2.2.2.2 Other Response Type Roughness Meters

There are many popular brands of Response Type Roughness meters and those are Mays Ride Meter, the PCA meter, the Cox meter, and various home made models.

2.3 Pavement Roughness Indices.

Profile measurement is a series of numbers representing elevation relative to some reference. So, it has thousands of numbers for a particular road stretch. Using those values, it is essential to quantify the roughness. Roughness indices are used for that purpose.

2.3.1 International Roughness Index (IRI)

The International Road Roughness Measurement Experiment was held in Brazil in 1982, to develop an International roughness index (IRI) for exchanging data, and to publish guidelines for measuring roughness on a standard scale. IRI was the first widely used profile index where the analysis method is intended to work with different type of profiles. IRI is reproducible, portable and stable with time.

The IRI was mainly developed to match the response of passenger cars, but subsequent research has shown that IRI correlates well with 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 a measured profile. This model simulates a quarter car systems (QCS) traveling at a constant speed of 80 km/hr. The IRI is computed as the cumulative movement of the suspension of the QCS divided by the traveled distance, the unit of the index is m/km or inch/mile. Figure 2.6 shows the QCS model.

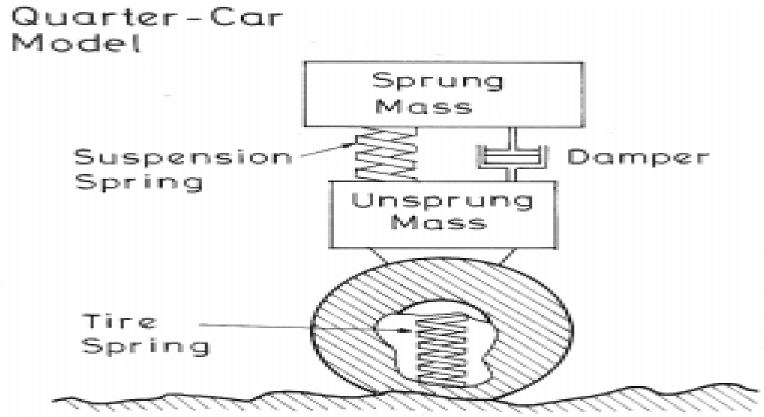

Figure 2.6 Quarter Car Model

Source: (M.W.Shahin, n.d)

The IRI summarizes the roughness qualities that impact vehicle response. IRI is influenced by wave lengths ranging from 1.2 to 30m (wavelength = 1/wavenumber). The amplitude of the output sinusoid is the amplitude of the input, multiplied by the gain shown as in the figure 2.7, which illustrates the sensitivity of IRI with wave number. The IRI has maximum sensitivity to wave numbers of between 0.04 and 0.7 cycles per meter, which corresponds to wave lengths of between 1.4 and 25 meter. The figure 2.8 describes the IRI roughness scale.

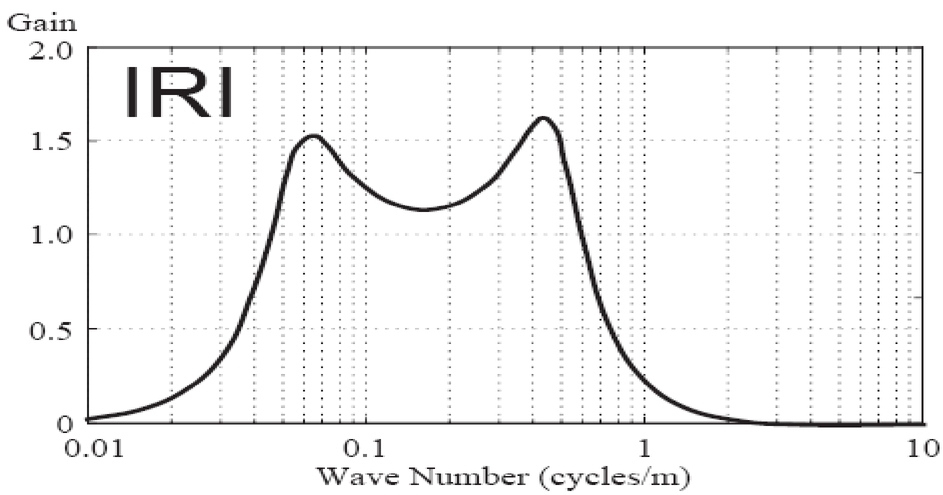

Figure 2.7 Sensitivity of IRI to Wave Numbers

Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

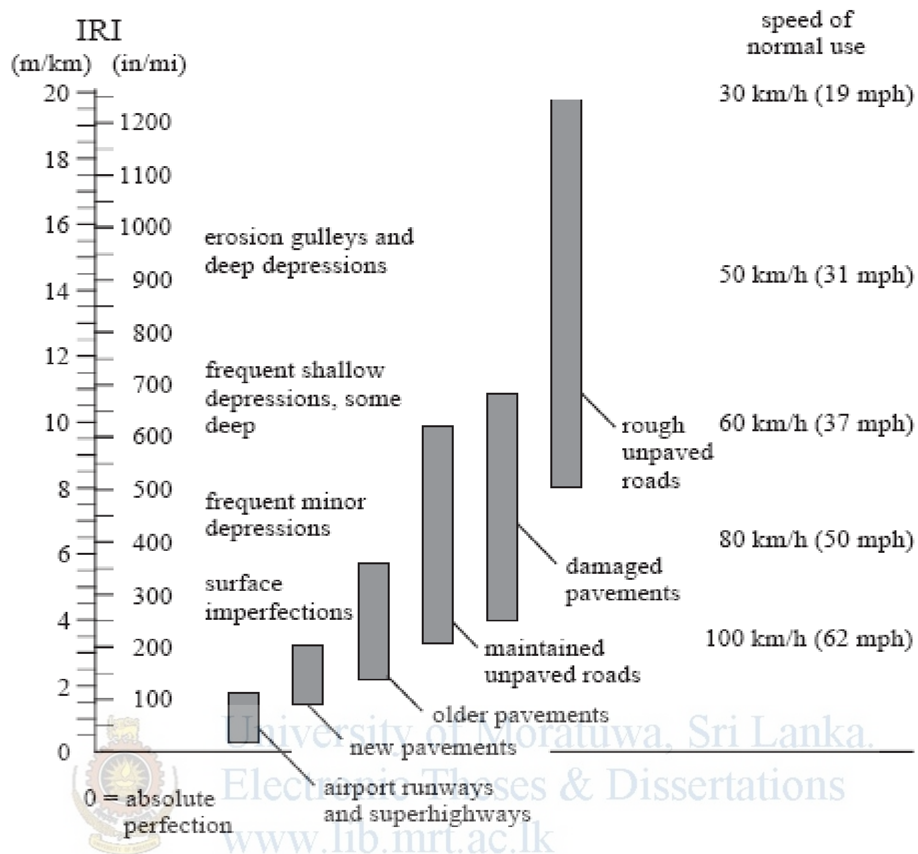

Figure 2.8 IRI Roughness scale

Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

2.3.2 Present Serviceability Rating (PSR), Present Serviceability Index (PSI) and Mean Panel Rating (MPR)

The AASHO 840 Road Test developed a definition of pavement serviceability, the present serviceability rating (PSR), which is based on individual observation and that is subjective. The PSR is defined as ‘The judgment of an observer as to the current ability of a pavement to serve the traffic it is meant to serve. The following figure shows a rating a person rates a road on a scale of 0 to 5. As PSR is based on passenger interpretations of ride quality, it generally reflects road roughness because roughness largely determines ride quality. Figure 2.9 illustrates Present Serviceability Rating scale.

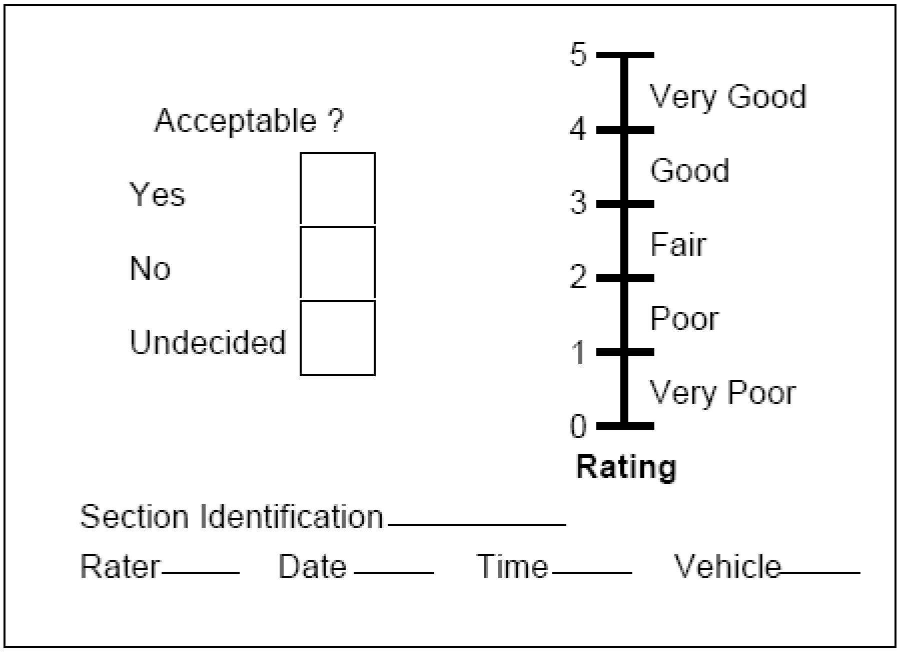

Figure 2.9 Present Serviceability Rating scale

Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

In additions to these rankings from individuals, several measurements can be obtained by using instruments. Using the measured data PSR can be estimated using an equation obtained from statistical analysis of the data. The estimate of the present serviceability rating (PSR) is called the Present Serviceability Index (PSI).

The opinion of a single person regarding the serviceability of the pavement is not so reliable. Then a group of ratings are taken together and after statistical processing, a rating for the panel is derived. This is called as Mean Panel Rating (MPR). However, panel ratings have some issues, such as

a) the rating scale is not a measure of road condition that is stable with time. For instance, roads considered “good” by a panel today might be considered something else by a panel 50 years from now.

b) it is expensive and not practical for large scale pavement networks.

Some road agencies calculate their own version of PSI that combines profile roughness index with other measures of distress such as rut, cracking etc.

However the recent advancement of profile measuring devices and responsive type devices in last decade have significantly reduced the use of subjective ratings for roughness evaluation.

2.3.4 Ride Number

Ride Number (RN) is a profile index intended to indicate reliability on a scale similar to PSI that is 0-5 scale. The RN uses same filtering method as IRI. However the sensitivity of RN to wavelengths is different to IRI. The figure 2.9 describes that. The maximum sensitivity is for a wave number of 0.164 cycle/m, which is a wavelength of about 6 meters. Although there is a correlation between IRI and RN, the content of road profile that affects RN is different than the content that affects IRI. Each provides unique information about the roughness of the road.

Figure 2.11 gives the correlation between IRI and PI which is a profile index used to define RN. PI generally ranges from “0”, a perfectly smooth profile, to positive values proportional to a type of roughness.

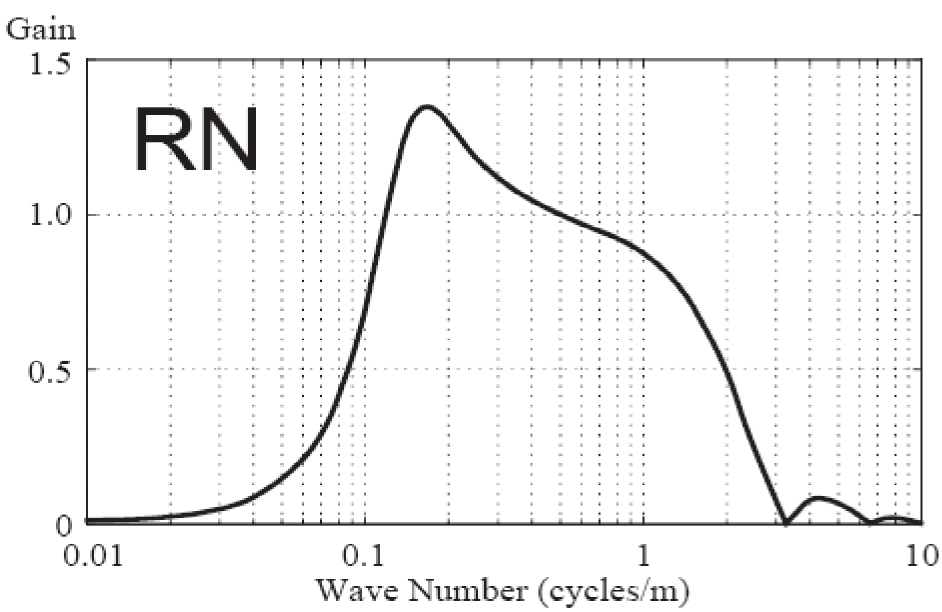

Figure 2.10 Sensitivity of RN to Wave numbers
Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

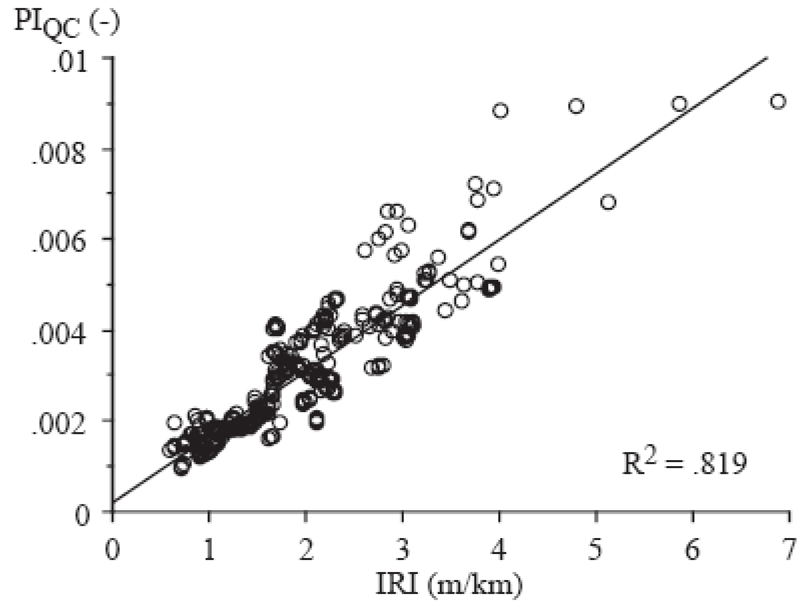

Figure 2.11 Correlation between PI (used to define RN) and IRI

Source :(M.W.Sayers ,Steven M. Karmihas, 1998)

2.3.5 Slope Variance

This is a roughness index based on the changes in the slope of a pavement profile. The following equation describes the Slope variance (SV).

$$SV = \sum (X_i - \bar{X})^2 / (n-1) \qquad [2.1]$$

Where

X_i = i^{th} slope measurement

n = number of slope measurements

$\bar{X}$ = mean of slope measurements

2.3.6 Other Roughness Indices

There are many indices related to roughness measurement such as Half – Car Roughness index (HRI), Road Mean Square Vertical Acceleration (RMSVA) and Wave Band indices.

2.4 Roughness Measurement – Current Practice in Sri Lanka.

2.4.1 Roughness Measuring Devices.

Vehicle mounted bump integrator is the equipment which is widely used in Sri Lanka. In regular intervals these bump integrators are calibrated using the profiler, MERLIN.

2.4.2 The Use Of Roughness Measurements

The planning division of Road Development Authority classifies the Core National roads based on ride quality which is measured in terms of IRI values as per the table 2.1 (network summary report). Annually, the core National Road Network is categorized to five parts in terms of roughness. An example for years 2007 and 2008 is given in the table 2.1 and figure 2.12 illustrates it for year 2008.

Table 2.1: Road Length Distribution by Roughness

Description	IRI Values (m/km)	Length (km)		Percentage	
		Year 2007	Year 2008	Year 2007	Year 2008
Excellent	< 3.0	508	636	7%	8%
Good	3.0 to 5.5	1819	1991	24%	25%
Fair	5.5 to 7.0	1599	1514	21%	19%
Poor	7.0 to 10.0	2996	2990	39%	38%
Bad	> 10	699	730	9%	9%

Further it is illustrated in provincial wise also. The Tables 2.2 and 2.3 and the Figures 2.12 and 2.13 describe it.

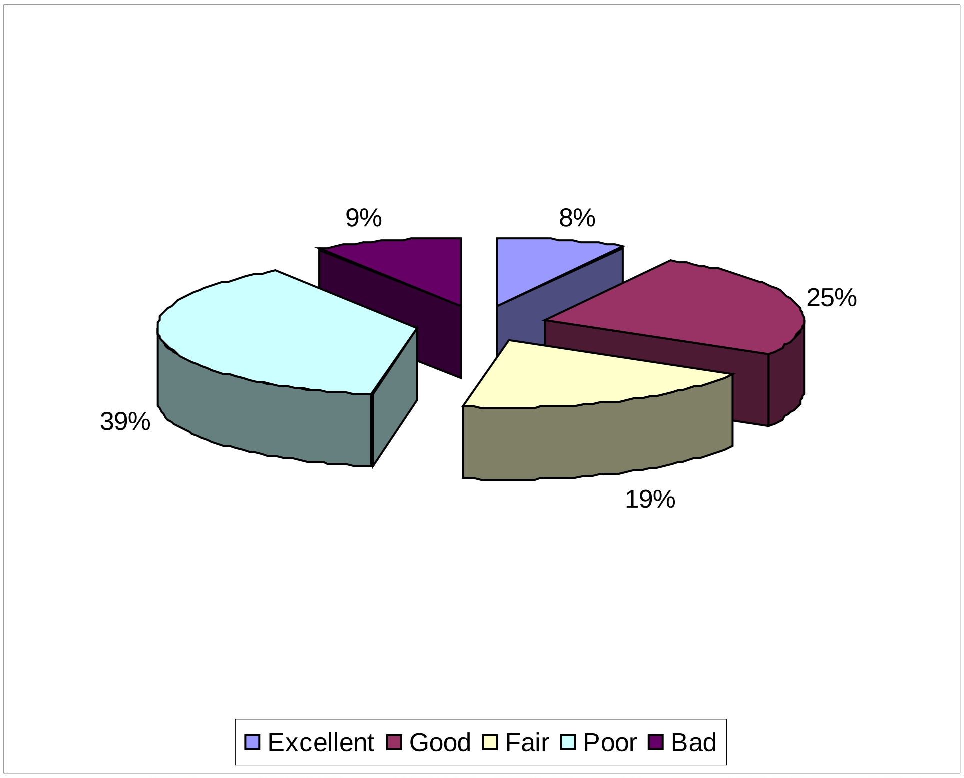

Figure 2.12: Road Length Distributions by Roughness in year 2008.

Source :(Planning Division RDA)

Table 2.2: Roughness Distribution by Province in 2007

Province Name	Excellent Length (m)	Excellent	Good Length (m)	Good	Fair Length (m)	Fair	Poor Length (m)	Poor	Bad Length (m)	Bad
Western	149	11%	315	24%	343	26%	480	36%	45	3%
Central	54	5%	274	23%	90	8%	576	48%	200	17%
Southern	134	12%	177	16%	174	16%	460	43%	130	12%
Nothern	1	1%	11	9%	27	21%	76	61%	10	8%
Eastern	31	10%	62	20%	51	17%	117	38%	43	14%
North Western	58	6%	243	25%	335	35%	314	33%	15	2%
North Central	26	3%	285	32%	197	22%	342	38%	41	5%
Uva	0	0%	248	29%	213	25%	282	33%	114	13%
Sabaragamuwa	54	6%	204	23%	169	19%	348	40%	102	12%

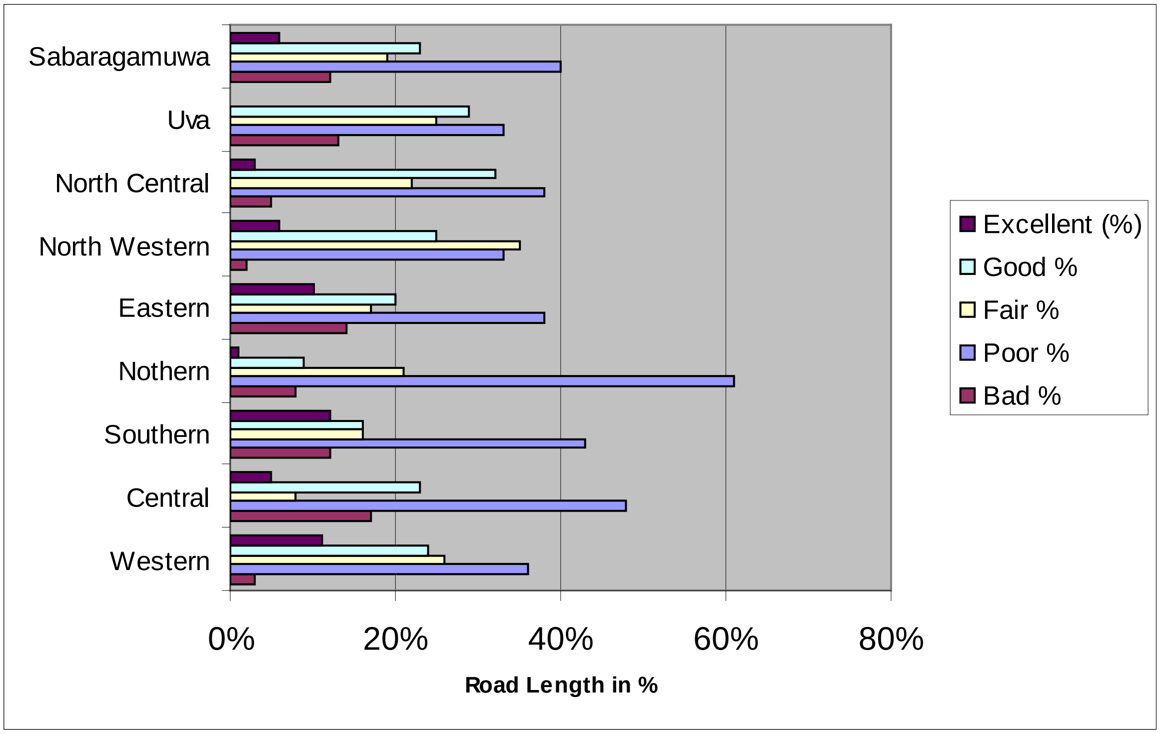

Figure 2.13 Roughness Distributions by Province in 2007

Source :(Planning Division RDA)

Table 2.3: Roughness Distribution by Province in 2008

Province Name	Excellent Length (m)	Excellent	Good Length	Good	Fair Length	Fair	Poor Length (m)	Poor	Bad Length (m)	Bad
Western	168	13%	371	28%	289	22%	468	36%	18	1%
Central	104	8%	212	16%	83	6%	529	40%	288	22%
Southern	163	12%	259	20%	193	15%	399	30%	112	8%
Nothern	0	0%	0	0%	0	0%	8	1%	3	0%
Eastern	0	0%	78	6%	98	7%	242	18%	44	3%
North Western	100	8%	337	26%	328	25%	258	20%	10	1%
North Central	10	1%	327	25%	208	16%	367	28%	44	3%
Uva	6	0%	177	13%	214	16%	428	33%	113	9%
Sabaragamuwa	85	6%	229	17%	102	8%	292	22%	98	7%

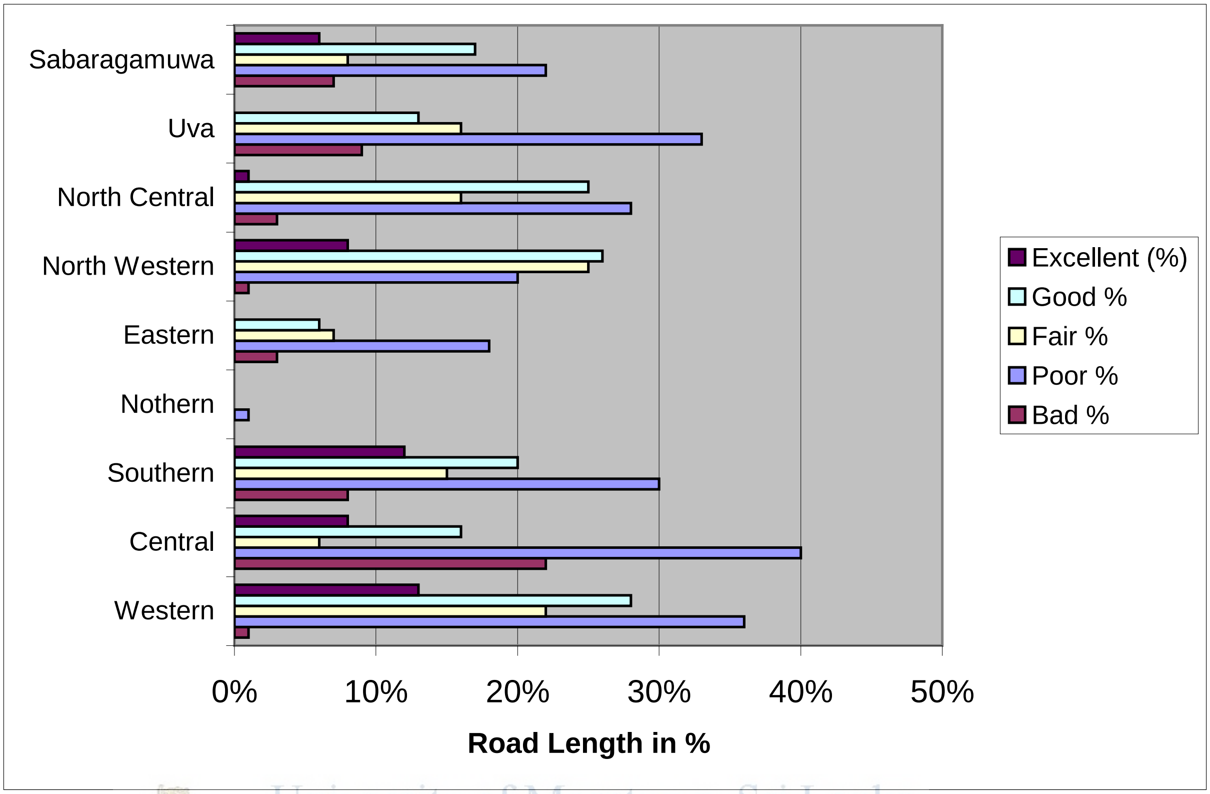

Figure 2.14 Roughness Distributions by Province in 2008

Source :(Planning Division RDA)

The data for 2007 and 2008 reveal that;

a) the category of excellent and good condition of Core National Road network in terms of Roughness is in increasing trend. In year 2007, it is about 31% while in 2008 it is about 33%,

b) Western, Central and Southern provinces contribute more for the above improvement, and

c) the category of bad percentage is in decreasing trend in all the Provinces except in Central Province.

IRI is also used as one of the input parameters for Highway Development and Management (HDM) software which is used for Pavement Management System (PMS) in Sri Lanka. In addition to roughness indices, structural number, cracking area, raveled area, potholes, edge break area and skid resistance are also used for inputs for HDM package.

Further, usually IRI is measured in a road just before it is overlaid with asphalt and just after overlaying in order to calculate the savings of Vehicle Operating Cost (VOC). Then the saving is used for economic analysis of road project to derive Net Present Value (NPV) and Benefit Cost Ratio (BCR) etc.

2.5 Pavement Smoothness Specifications.

A study in Canada in 1966 showed that 95% of the information defining the serviceability of a pavement is by the roughness of the surface profile. (Canada 1999). So, the specification, measurement and monitoring of roughness are critical to have roads of adequate ride quality. Initial pavement smoothness is important as it has a direct relationship between smoothness, serviceability and cost. Several investigations have clearly shown that even small improvement in initial smoothness provides significant increases in the long-term performance of the pavement surface with respect to roughness progression and long term cracking. As a result of the reduction in progression and severity of roughness, maintenance and life cycle cost of roads are significantly reduced. Therefore, road agencies in many countries specify initial smoothness requirements. Some countries have introduced incentives to contractors to produce smoother pavements and they are confident that the extra investment made at the beginning of the project may be returned many times over with the associated increase in long-term performance. On the other hand, some agencies have imposed penalties for poor initial smoothness.

The specifications and bonus and penalty systems vary both within individual countries as well as between different countries. Some specifications have exclusions. Exclusions generally include approach sections, acceleration and deceleration lanes, tight curves, detours, areas rehabilitated with hot-in- place or cold in place recycling and sections with obstructions such as utility access points (Canada 1999). However some specifications, for example western provinces in Canada, do not exclude such sections but rather use lower requirement for smoothness. (Canada 1999)

The Table 2.4 describes the Summary of Acceptance Requirements for Pay Adjustment in Canada and Comparisons of Smoothness Specifications from selected European countries and some States in Canada are given in Table 2.5(Canada 1999). Countries use various kinds of Roughness Indices. The Profile Index (PI) is determined by averaging the Rate of Smoothness of both wheel paths for given test section. The Rate of Smoothness is calculated by adding the heights of all bumps and depressions out side of datum line called the “blanking band” and dividing by the length of the test section. Total Cumulative Roughness (TCR) is a summation of all roughness including roughness within the blanking band. Coefficient of Unevenness (CP) is another index to measure roughness. CAPL25 is another one which is used when APL trailer, one profile meter, is used for measuring roughness. CAPL25 is calculated for each 25m of wheel track tested.

Standard Specifications for Construction and Maintenance published by Ministry of Highways Sri Lanka in 1989, specifies the tolerance of surface regularity in Table 1601. This is given in Table 2.6. ICTAD specification is given in Table 2.7.

Table 2.4: Summary of Acceptance Requirements and Pay Adjustments in Canada

Province	**Requirements for Acceptance/Rejection**	**Pay Adjustments**		
		Full Contract	**Bonus**	**Penalty**
Manitoba	• Correction: • No corrective measures for AC pavements (Penalty only)	6 < PI < 11 mm/100m Bumps <8mm	PI < 6 mm/100m (AC) • Bonus of $59 (AC) TCR < 70mm/100 (AC) • Bonus of $5 to $59 per 100m	PI > 11 mm/100m (AC) • Penalty of $118 (AC)

Source: (Canada 1999)

Table 2.4: Summary of Acceptance Requirements and Pay Adjustments in Canada (Ctd)

Province	**Requirements for Acceptance/Rejection**	**Pay Adjustments**		
		Full Contract	**Bonus**	**Penalty**
British Columbia	•Correction Bumps>12mm Bumps between 8-12mm At discretion of Engineer •Rejection PI>24mm/100m (multi lift) PI>24mm/100m (Single lift) PI > 30mm/100m (Curb Gutter)	0<PI<10 mm/100m (Multi lift) 0<PI<15 mm/100m (Single lift) 0<PI<22 mm/100m (Curb gutter) Bumps/Dips <8mm	PI=0mm/100m (all lift/ section types) Bonus of $ 100 per 100m PI = 0mm/100m (all lift/section types) Bonus of $ 25 per 100m	10 < PI < 24mm /100m (Multi lift) • Penalty of $40 to $340 per 100m 15 < PI < 24mm /100m (Single lift) • Penalty of $40 to $320 per 100m 22 < PI < 30mm /100m (Curb gutter) • Penalty of $40 to $320 per 100m Bumps/Dips>8mm • Penalty of $100 per bump/dip
Saskatchewan	• Correction: • No corrective measures (Penalty only) unless bumps >12mm • Rejection: • Sections rejected/replaced if: • PI > 23 mm/100m (Tangents and Curves > 600m) • PI > 28 mm/100m (Other) • Bumps > 12 mm	PI < 15 mm/100m (Tangents and Curves > 600m) PI < 20mm/100m Curves<600m , Sublots within 50m of bridge or RR crossing or end sublot	No bonus offered (Penalty only)	16 < PI < 23 mm/100m (Tangents and Curves > 600m) 21 < PI < 28 mm/100m (Curves < 600m, Sublots within 50m of bridge or RR crossing or end sublot) • Penalty of $40 to $600 per 100m 8 < Bumps < 12 mm • Penalty of $100 to $400 per bump

Source :(Canada 1999)

Table 2.5: Comparison of Smoothness Specifications from Selected European Countries

Country	Smoothness Indicator and Equipment	Specifications	Acceptance, Penalty or Rejection
Belgium	mm^2/km • Analyseur de profil enlong (APL)	• 25m section (urban) Speed = 21.6 km/h CP2.5 ≤ 35 • 100m section (rural) Speed = 54 km/h CP10 ≤ 70	• Penalty 35 < CP2.5 ≤ 50 • Rejection CP2.5 > 50
Denmark	IRI • Viagraphe (Danish Highspeed profilograph) • 100m sections	• No. of Irregularities allowed: 0 ≥ 7.5mm 2 ≥ 6mm 3 ≥ 5mm Max 9 ≥ 3mm	• No penalties but contractor provides 5 year warranty
Spain	IRI • Laser Profilometer, APL and Dipstick • 100m sections	• New Construction IRI ≤ 2.0 m/km • High Traffic Areas IRI ≤ 2.5 m/km • Low Traffic Areas IRI ≤ 3.0 m/km	• Acceptance 20% of job + 0.5 m/km 20% of job - 0.5 m/km
Hungary	cm/100m • UT-02 (Hungarian)	• New specifications under development	• Penalty 5 < UT-02 (National Roads) 10 < UT-02 (Other Roads)
Italy	IRI, RCI, CAPL25 • ARAN, Automatic Road Analyzer, APL	• Specifications are project specific	• Penalty (20% price reduction) Spec. < IRI < 4.5 m/km • Rejection IRI > 4.5 m/km
Sweden	IRI • RST Laser, Static Beam (3m)	• 20m section IRI ≤ 1.4 m/km • 200m section IRI ≤ 2.4 m/km	• Penalty imposed after case study • Penalty and repairs may be cumulative

Source :(Canada 1999)

Table 2.6 Tolerance of surface regularity in Sri Lanka - SSCM 1986

Type of construction	Maximum Permissible undulation with 3m Straightedge	
	Longitudinally	Transversely
Asphalt Concrete Surfacing	6	4

Table 2.7 Tolerance of surface regularity in Sri Lanka - ICTAD Specification

Type of construction	Longitudinal Profile with 3m Straightedge		Transverse Profile
	Maximum Permitted undulation template	Maximum number of undulations permitted in any 300 meter length Exceeding 5mm	Maximum permissible variation from specified profile under camber
Asphalt Surfacing	8 mm	30	6