LONGITUDINAL IRREGULARITY OF ROAD SURFACES: DEPTHS UNDER ROLLING STRAIGHT-EDGE VERSUS INTERNATIONAL ROUGHNESS INDEX

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ABSTRACT

Undulating surface on newly constructed or rehabilitated roads is not unusual in Malaysia. Presently, the occurrence of irregularity on the road surface in the longitudinal direction is restricted by the permissible number of depths as measured by an instrument called the rolling straight-edge as stipulated in the Standard Specification for Road Works of Public Works Department, Malaysia (JKR). This test method is widely used in developing countries including Malaysia as it is practical and relatively cheap. However, recent developments have seen an increasing usage of more modern and sophisticated equipment for measuring road surface irregularity in this country. In the new Standard Specification for Road Works of JKR, the usage of rolling straight-edge has been replaced with the ARRB Walking Profiler or equivalent equipment. However, these relatively new instruments yield a surface irregularity parameter which is different from the normal depths measured under the rolling straight-edge. This parameter is known as the International Roughness Index (IRI). Furthermore, the Walking Profiler is more expensive than the rolling straight-edge. In addition, there is no existing correlation between the permissible number of depths under the rolling straight-edge and the IRI. As such, the main objective of this paper is to establish a correlation between the IRI as measured by the Walking Profiler or equivalent equipment, and the normal depths as measured under the rolling straight-edge in measuring longitudinal irregularity on road surfaces. Measurements of longitudinal irregularity using both methods were carried out on a number of existing road surfaces which were prominently undulating as well as on the surface of selected newly rehabilitated roads.

1. INTRODUCTION

The occurrence of undulating surface on a newly constructed or rehabilitated road is not unusual in this country. For examples, during the construction of the KL International Airport (KLIA), it has been observed on the runways and taxiways, as well as on Route B20 Nilai - KLIA. It was noticeable on Route 29 Putrajaya – Dengkil[1] which required to be resurfaced not long after the construction of the new road was completed. It was prominent on Route 54 Assam Jawa – Sg. Buluh and Route 5 Sepang – Banting even after resurfacing. This phenomena eventually came under the limelight when a typical form of such defect was observed on the newly completed Route 8, Lencongan Teranum, Bentong[2] and was repeatedly highlighted by the Director General of Public Works Department, Malaysia (JKR). Such incident should not have happened in the first place had the supervising officers diligently overseen the construction works and fully understood the relevant requirements in the Standard Specification for Road Works of JKR[3] (hereafter referred to as JKR/SPJ).

2. OBJECTIVE

Presently, the occurrence of irregularity on the road surface in the longitudinal direction is restricted by the permissible number of depths as measured by an instrument called the rolling straight-edge as stipulated in Sub-Section 4.4.3 of JKR/SPJ. However, recent developments have seen an increasing usage of more modern and sophisticated measuring instruments for measuring road surface irregularity in this country. These instruments are the Australian Road Research Board (ARRB) Walking Profiler and the ARRB-developed IKRAM Road Scanner. However, these relatively new instruments yield a surface irregularity parameter which is different from the normal depths measured under the rolling straight-edge. This parameter is known as the International Roughness Index (IRI). As such, the main objective of this study is to establish a correlation between three different standard methods of measuring longitudinal irregularity on road surfaces which are commonly used in this country namely the ARRB Walking Profiler, IKRAM Road Scanner and rolling straight-edge. There is a need to establish the correlation for use in this country as there are enquiries whether the use of the Walking Profiler as specified in the existing contract, for example, can be replaced with the rolling straight-edge if the former is not available. If allowed so, is Class of Surface Regularity SR1, for example, similar to IRI less than 2.0 m/km? If not, what limiting value of IRI is more appropriate?

For the purpose of this study, measurements of longitudinal irregularity were carried out on a number of existing road surfaces which were prominently undulating as well as on the surface of newly rehabilitated roads.

As some of the test sections selected were then recently resurfaced prior to the measurements and were reportedly undulating prior to the resurfacing work, the study would also be able to determine the effectiveness of road resurfacing in rectifying undulating surfaces.

3. BACKGROUND

Road pavement structures comprise various combinations of layers between the surface of the road and the ground over which the road is constructed. Its primary objective is to support the loading from passing traffics and distribute them to the underlying subgrade. Each layer has a specific role in resisting the loading so that the stresses and strains developed in all the layers and the subgrade do not exceed the capability of the materials in respective layers.

From the perspective of road users, the road feature which would readily capture their attention is arguably the surface of the road itself. Though being ignorant to the existence and functions of the various layers underneath, they would at least expect the road surface to have a smooth and comfortable riding quality.

3.1. Surface Regularity

In general, the riding quality is affected by the ‘surface regularity’, the term used in JKR/SPJ. The road surface may vary from a plane surface both in the transverse and longitudinal directions

3.1.1 *Transverse Irregularity*

Transverse irregularity is normally caused by permanent deformation along the wheelpaths, commonly known as rutting. It could be attributed to unstable bituminous mixtures due to improper design and lack of quality control during production and laying of the mixtures, visco-elastic behaviour of bitumen and secondary compaction due to insufficient density achieved during paving.

3.1.2 *Longitudinal Irregularity*

Sub-Section 4.4.3 of JKR/SPJ defines longitudinal irregularity as a variation in profile of the road surface as measured by a rolling straight-edge or a straight-edge device and wedge. In general, it can be categorized into three types namely short waves, long waves and washboard effect[4].

i. Short waves
   Short waves are generally 0.5 to 3.0 metres apart, usually caused by improper operation of the paver likes fluctuating head of material in front of paver screed, frequent changes in paver speed, poor mechanical condition of screed and improper mounting or use of automatic leveling control devices.

ii. Long waves
   Long waves are considerably further apart, usually greater than 3.0 metres, and are frequently associated with a lack of bearing capacity of the subgrade or a change in bituminous mixture composition and temperature between tip-truck loads during paving.

iii. Washboard effect
   Washboard effect is typically caused by improper operation of vibrating roller such as over-rolling, rolling when mixture is too hot or roller traveling too fast. The distance between waves is relatively small, generally less than 0.5 metre.

3.2. Surface Regularity Measuring Instrument

There are various types of instrument that can be used to measure surface regularity. It can be generally categorized as follows;

3.2.1 *Absolute Profile Instrument*

The instrument measures profile elevation relative to a true horizontal datum e.g. rod and level survey.

3.2.2 *Moving Datum Instrument*

The instrument measures deviations of profile relative to a datum moved along the road e.g. rolling straight-edge, profilograph.

3.2.3 *Vehicle Motion Instrument*

One version of the instrument measures relative displacement between axle and body of vehicle, summing upward and downward movements with read out at regular distances to give cumulative ‘bumps’ per unit distance (m/km etc) e.g. Bump Integrator (trailer or car mounted).

The other version measures acceleration of axle or body by accelerometer e.g. ARAN (Automatic Road Analyser).

3.2.4 *Dynamic Profile Instrument*

The instrument measures profile elevation electronically relative to an artificial horizontal datum. The early version like General Motor Research (GMR) profilometer uses direct contact through a following wheel on the road surfacing while the more recent version like the British High Speed Road Monitor (HRM) uses indirect or non-contact method such as visible light lasers, infrared light sensors and ultrasonic sensors. This method is capable of measuring very short wavelengths generated by surface texture, cracks etc which need to be filtered to suppress these effects.

3.3. International Roughness Index

The International Roughness Index (IRI) is a mathematically-defined summary statistic of the longitudinal profile in the wheelpath of a traveled road surface. The index is an average rectified (both upward and downward movements are counted) slope statistic computed from the absolute profile elevations. It is representative of the vertical motions induced in moving vehicles for the frequency bandwidth which affects both the response of the vehicle and the comfort perceived by the occupants[5].

The IRI is defined by a mathematical simulation of a quarter-car (i.e. one wheel with the associated dynamic characteristic of the suspension and sprung mass of a typical passenger car), traveling at 80 km/h which produces the range of frequencies most affecting the users' perception of comfort and the impact on moving vehicles. The IRI describes a scale of roughness which is zero for a true planar surface, increasing to about 6 m/km for moderately rough paved roads, 12 m/km for extremely rough paved roads with potholes and patches, and up to about 20 m/km for extremely rough unpaved roads.

Incidentally, the trigger value of IRI for maintenance purposes as being presently used by JKR is 3.5 m/km. In the latest JKR/SPJ, IRI of not more than 2.0 m/km is specified for newly constructed roads.

3.4. Methods of Measuring Surface Regularity in Malaysia

As mentioned earlier, there are three common methods of measuring surface regularity in this country, but at present only one is being specified in JKR/SPJ namely the rolling straight-edge[3,6,7].

3.2.5 *Rolling Straight-Edge*

The rolling straight-edge is a relatively simple device to measure surface regularity. It has wheels at both ends, supporting a frame that acts as a straight-edge with a measuring wheel in the middle. It is hand-pushed manually along the road and irregularities in the forms of bump and dip on the road surface are either recorded automatically on a profile paper or manually. This equipment measures surface deviation relative to a moving datum. The wavelengths measurable are limited by the base length of the datum viz. the length of the straight-edge which is normally three metres.

Figure 1 - Rolling Straight-Edge

3.2.6 *ARRB Walking Profiler*

The Australian Road Research Board (ARRB) Walking Profiler is a precision, compact and easy to use instrument designed to facilitate efficient collection and presentation of continuous road or runway profiles. It also enables accurate measurements of IRI, complying with the World Bank Class 1 profilometer requirements[8]. This compact device is pushed over the surface to be surveyed and the on-board computer calculates and displays results in graph and table formats.

Figure 2 – ARRB Walking Profiler

3.2.7 *IKRAM Road Scanner*

The IKRAM Road Scanner (IRS) is one of the survey vehicles developed by ARRB to capture pavement condition data, survey mapping information and roadside asset details while traveling at high speeds. It is capable of capturing elements for road roughness, rutting, texture and surface conditions. The IRS consists of four main systems namely the Multi Laser Profiler (MLP), Gipsi-Trac, Global Positioning System and digital imaging system. The MLP is used to calculate the IRI value.

The MLP uses 13 laser height transducers mounted in a beam in front of the vehicle. These transducers measure the distance from the beam to the pavement surface. Accelerometers located in each wheelpath are used to measure vehicle bounce and vertical movement of the beam and compensate any interference accordingly. Outputs from the accelerometers and lasers are then combined mathematically to produce a longitudinal elevation profile of the pavement surface.

Figure 3 – IKRAM Road Scanner

4. SPECIFICATION ON SURFACE REGULARITY IN JKR/SPJ

The specifications on surface regularity are stipulated in Sub-Section 4.4.3 of JKR/SPJ. The regularity of the surfaces, in either longitudinal or transverse direction, is limited by the figures as given in Table 4.14 in JKR/SPJ[3,9] (refer to Table 1 below).

4.1. Transverse Irregularity

Sub-Section 4.4.3 of JKR/SPJ specifies that the maximum permissible depth of transverse irregularities under a 3-metre straight-edge, as given in Table 4.14 in JKR/SPJ, shall be 4 mm, 8 mm and 12 mm for Surface Regularity Class SR1, SR2 and SR3 respectively.

4.2. Longitudinal Irregularity

Sub-Section 4.4.3 of JKR/SPJ specifies that the maximum permissible number of longitudinal irregularities in terms of depth exceeding 4 mm under a rolling straight-edge over a traverse length of 300 metres, as given in Table 4.14 in JKR/SPJ, shall not exceed 20 for Surface Regularity Class SR1, 40 for Class SR2 and 60 for Class SR3. For depth exceeding 7 mm, the maximum permissible numbers are 2, 4 and 6 for Class SR1, SR2 and SR3 respectively. In any case, no longitudinal irregularity exceeding 10 mm is permitted for Class SR1 whereas for Class SR2 and Class SR3, longitudinal irregularity exceeding 15 mm is not permitted.

Where the continuous length of the completed pavement is less than 300 metres, the measurements shall be taken over a traverse length of 75 metres. The corresponding maximum permissible number of surface irregularities for depths exceeding 4 mm and 7 mm are given in Table 4.14 in JKR/SPJ.

Table 1 - Table 4.14 in JKR/SPJ-Tolerances for surface irregularities

<table>
<tr><th rowspan="4">Class of Surface Regularity</th><th colspan="4">Longitudinal Direction</th><th>Transverse Direction</th></tr>
<tr><th colspan="4">Maximum Permissible Number of Surface Irregularities</th><th rowspan="3">Maximum Permissible Depth Of Transverse Irregularities</th></tr>
<tr><th colspan="2">Depth Exceeding 4 mm</th><th colspan="2">Depth Exceeding 7 mm</th></tr>
<tr><th>Over traverse length of 300 m</th><th>Over traverse length of 75 m</th><th>Over traverse length of 300 m</th><th>Over traverse length of 75 m</th></tr>
<tr><td>Class SR1</td><td>20</td><td>9</td><td>2</td><td>1</td><td>4 mm</td></tr>
<tr><td>Class SR2</td><td>40</td><td>18</td><td>4</td><td>2</td><td>8 mm</td></tr>
<tr><td>Class SR3</td><td>60</td><td>27</td><td>6</td><td>3</td><td>12 mm</td></tr>
<tr><td colspan="6">No longitudinal irregularity exceeding 10 mm shall be permitted for Class SR1 Surface Regularity and no longitudinal irregularity exceeding 15 mm shall be permitted for Class SR2 and Class SR3 Surface Regularities.</td></tr>
<tr><td colspan="6">The class of surface regularity for each portion of the Works shall be as stated on the Drawings or in the Bills of Quantities.</td></tr>
</table>

5. SITE MEASUREMENTS

The location of the sites and measurements carried out at respective sites are as described below.

5.1. Route 5 Sepang - Banting

Some sections of this route have been recently resurfaced after they were being triggered for maintenance in the Pavement Management System, by IRI exceeding 3.5 m/km. The IRI was obtained from the routine run of the IKRAM Road Scanner on the Federal Road network. Test sites between Sections 357 – 364 and 377 – 380 were selected as the new surfacing at these locations were prominently undulating.

The following measurements were carried out at the sites approximately 10 months after resurfacing;

i. IRI using IKRAM Road Scanner, traversing three times at a steady speed of 90 km/hr on the Banting-bound lane.
ii. IRI using ARRB Walking Profiler pushed along the vergeside wheelpath on the Banting-bound lane.
iii. Depths under rolling straight-edge pushed along the vergeside wheelpath on the Banting-bound lane.

The results are shown in Table 2.

The results indicate that out of 9.9 km that were recently resurfaced and re-measured for surface regularity, 3.3 km was still undulating with IRI values exceeding 3.5 m/km, the trigger value for maintenance. However, based on depth figures under the rolling straight-edge, 6.0 km of the road did not comply with the JKR/SPJ requirements if the route was designated as Class SR1 Surface Regularity while 3.9 km did not comply if the route was designated as Class SR2 Surface Regularity. This appears to indicate that barring differential settlements that could have taken place during the 10-month period, the resurfacing exercise on the above stretch was not completely effective in rectifying the undulating surface.

Table 2 – Route 5 Sepang – Banting: Surface regularity test results

Item	Sections	No. of depth, ***d*** mm, under Rolling Straight-Edge					IRI (IRS)	IRI (WP)
		4 < ***d*** ≤ 7	7 < ***d*** ≤ 10	***d*** >10	7 < ***d*** ≤ 15	***d*** >15		
1	357.00 - 357.30	17	0	1	1	0	2.56	2.41
2	357.30 - 357.60	9	0	0	0	0	2.25	2.32
3	357.60 - 357.90	9	2	0	2	0	1.47	2.88
4	358.00 - 358.30	13	5	0	5	0	2.90	3.32
5	358.30 - 358.60	12	1	0	1	0	2.63	2.71
6	358.60 - 358.90	5	0	0	0	0	1.90	2.57
7	359.00 - 359.30	8	1	0	1	0	2.41	2.43
8	359.30 - 359.60	9	1	0	1	0	3.16	3.13
9	359.60 - 359.90	15	1	2	1	2	3.35	3.32
10	360.00 –360.30	39	2	0	2	0	3.14	3.14
11	360.30 –360.60	33	2	0	2	0	2.56	2.58
12	360.60 –360.90	37	7	0	7	0	3.24	3.15
13	361.00 –361.30	30	6	0	6	0	2.69	2.65
14	361.30 –361.60	25	3	4	4	3	3.28	3.28
15	361.60 –361.90	30	7	0	7	0	3.78	3.72
16	362.00 –362.30	30	8	0	8	0	3.99	3.95
17	362.30 –362.60	28	1	1	2	0	3.99	4.00
18	362.60 –362.90	28	3	0	3	0	4.32	4.39
19	363.00 - 363.30	17	1	0	1	0	4.30	2.48
20	363.30 - 363.60	15	1	0	1	0	3.04	2.11
21	363.60 - 363.90	19	0	0	0	0	3.39	1.91
1	377.00 - 377.30	18	0	0	0	0	3.56	3.34
2	377.30 - 377.60	27	2	0	1	1	3.49	3.92
3	377.60 - 377.90	13	3	0	3	0	3.19	4.30
4	378.00 - 378.30	30	8	0	8	0	4.19	4.73
5	378.30 - 378.60	20	10	0	7	3	3.82	4.59
6	378.60 - 378.90	13	9	1	8	2	3.99	5.30
7	379.00 - 379.30	18	9	1	6	4	3.99	4.62
8	379.30 - 379.60	23	12	1	11	2	3.77	4.95
9	379.60 - 379.90	19	5	0	5	0	3.40	4.19

Notes: IRS – IKRAM Road Scanner, WP – ARRB Walking Profiler

5.2. Route 5, Kuala Selangor – Tanjung Karang

Some sections of this route have been recently resurfaced after they were being triggered for maintenance in the Pavement Management System, by IRI exceeding 3.5 m/km. The IRI was obtained from the routine run of the IKRAM Road Scanner on the Federal Road network. Test sites between Sections 357 – 364 and 377 – 380 were selected as the new surfacing at these locations were prominently undulating.

Two sections of this on-going rehabilitated road were selected for surface regularity measurements by using rolling straight-edge and IKRAM Road Scanner on the newly laid wearing course. The rolling straight-edge was pushed manually along the vergeside wheelpath on the fast lane in the direction towards Tanjung Karang at Chainages 1800 – 3900 and Chainages 6350 - 7550 whereas the IKRAM Road Scanner was run three passes on the fast lane between the same chainages. The results are shown in Table 3.

The results indicate that there were a number of 300-meter long sections which did not comply with Class SR1 and/or Class SR2 Surface Regularity requirements which needed to be rectified by the contractor.

Table 3 - Route 5, Kuala Selangor – Tanjung Karang: Surface regularity test results

Chainages	No. of depth, ***d*** mm, under Rolling Straight-Edge					IRI (IRS)
	4 < ***d*** ≤ 7	7 < ***d*** ≤ 10	***d*** >10	7 < ***d*** ≤ 15	***d*** >15	
3900 – 3600	14	0	0	0	0	2.52
3600 – 3300	13	0	0	0	0	2.66
3300 – 3000	11	4	1	4	1	2.84
3000 – 2700	20	2	0	2	0	3.09
2700 – 2400	15	0	0	0	0	2.58
2400 – 2100	10	0	0	0	0	2.30
2100 – 1800	5	0	0	0	0	2.32
7550 – 7250	27	6	0	6	0	3.62
7250 – 6950	11	28	0	28	0	4.53
6950 – 6650	11	4	0	4	0	2.68
6650 – 6350	12	1	0	1	0	2.13

However, it should be noted that this stretch was a newly rehabilitated pavement and if the suggestion of imposing IRI value not exceeding 2.0 m/km for a new surfacing was to go by, then the whole sections under study would have been considered not satisfactory.

6. DATA ANALYSIS

6.1. Consistency of IRI Computed From Replica Runs of IKRAM Road Scanner (IRS)

As described earlier, the IRS made three replica runs at highway speeds at all the sites selected without the road being closed to the publics. Under such circumstances, the IRS was more likely not to be traversing through an exactly similar path and at an exactly similar speed throughout each run due to close proximity to other vehicles. The IRI computed for each run was then compared with each other to verify the consistency of the values.

Table 4 indicates in general that the variation between the runs is small. Thus it can be concluded that the IRI values are not significantly affected by variation in speed and path taken within the lane being measured. Previous study carried out on the North – South Expressway has shown that there was little or no variation in the roughness measurements made by the IRS between the 30 km/h to 90 km/h speed range.

Table 4 - A comparison of replica IRS runs at similar sites.

Route B20 Nilai – KLIA	**KLIA-bound**			**Nilai-bound**		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Minimum	1.58	1.67	1.75	1.57	1.53	1.53
Maximum	4.75	4.57	4.55	3.19	3.34	3.21
Average	2.61	2.60	2.65	2.28	2.27	2.27
Standard Deviation	0.95	0.90	0.98	0.47	0.53	0.48
Route 5 Sepang - Banting	**Sepang-bound**			**Banting-bound**		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Minimum	1.92	1.56	1.74	1.91	1.78	1.72
Maximum	4.81	5.01	4.83	6.01	5.98	5.99
Average	3.02	3.02	2.99	3.54	3.52	3.59
Standard Deviation	0.69	0.71	0.69	0.93	0.93	0.93
Route 54 Asam Jawa - Sg. Buluh	**Asam Jawa-bound**			**Sg. Buluh-bound**		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Minimum	1.40	1.84	1.89	1.88	1.95	2.00
Maximum	3.99	4.14	4.26	3.46	3.49	3.74
Average	2.66	2.70	2.66	2.72	2.68	2.70
Standard Deviation	0.50	0.54	0.54	0.45	0.44	0.47
Route 5 K. Selangor - Tg. Karang	**K.Selangor-bound**			**Tg. Karang -bound**		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Minimum	1.34	1.40	1.36	1.84	1.69	1.82
Maximum	4.94	5.03	5.20	3.63	3.57	3.49
Average	2.42	2.41	2.48	2.62	2.62	2.59
Standard Deviation	0.98	0.98	1.04	0.51	0.52	0.50
Route 29 Putrajaya – Dengkil	**Putrajaya-bound**					
	Run 1	Run 2	Run 3			
Minimum	1.32	1.31	1.30			
Maximum	3.93	4.07	3.96			
Average	2.30	2.31	2.30			
Standard Deviation	0.63	0.63	0.62			

6.2. Relationship Between IKRAM Road Scanner's and ARRB Walking Profiler's IRI

Figures 4 and 5 are direct comparison between the IRI results acquired from the IRS and the Walking Profiler at two different locations namely Route 5 Sepang – Banting, Sections 377.0 - 379.9, and Route 5 Sepang – Banting, Sections 357.0 - 364.0 respectively. Figure 4 gives a linear equation $y = 0.57x + 1.13$ with $r^2 = 0.66$ whereas Figure 5 yields a linear equation $y = 1.06x$ with $r^2 = 0.63$, which consistently indicate a good correlation between the two equipments.

A higher degree of correlation could be achieved if this comparison exercise was done in a controlled environment as was done in a previous study on the North – South Expressway. In the controlled environment test run, a 500-meter stretch of the expressway was closed to traffic. The IRS and Walking Profiler were then run on exactly similar wheelpaths. The coefficient of variation obtained for that exercise was 0.96.

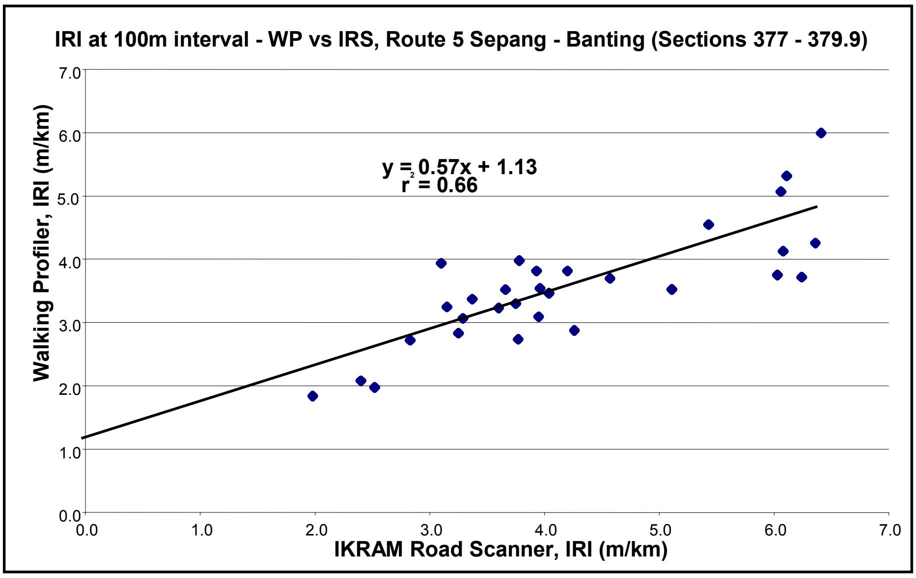

Figure 4 – Correlation between IKRAM Road Scanner and ARRB Walking Profiler, Route 5 Sepang - Banting, Sections 377.0 - 379.9.

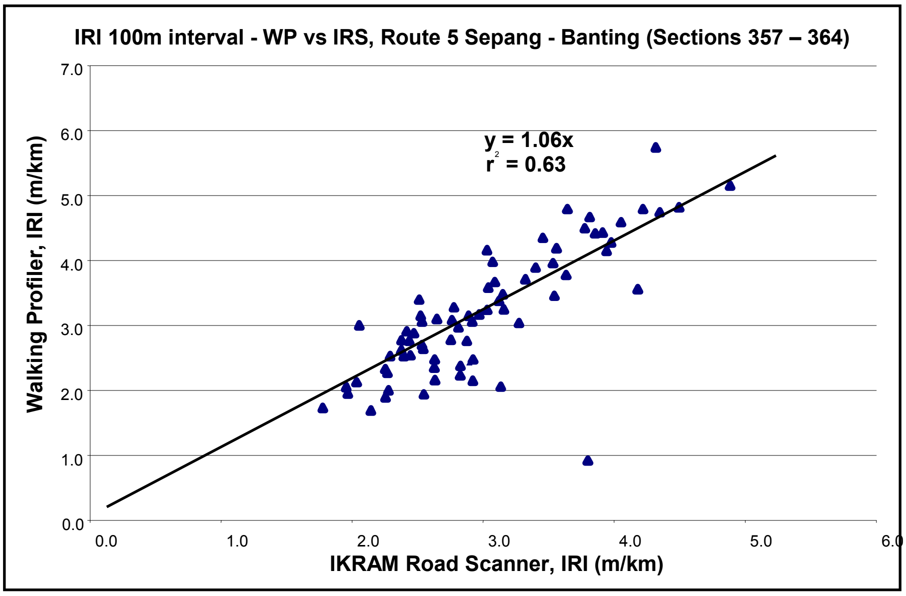

Figure 5 – Correlation between IKRAM Road Scanner and ARRB Walking Profiler, Route 5 Sepang – Banting, Sections 357.0 – 364.0.

6.3. Relationship Between Depths Under Rolling Straight-Edge and IRI Computed from ARRB Walking Profiler or IKRAM Road Scanner

Figure 6 is a plot of depths under the rolling straight-edge and average IRI values computed from the Walking Profiler against the same chainages at location Route 5 Sepang – Banting, Sections 377.0 – 379.9 whereas Figure 7 is a similar plot but for location Route 5 Sepang – Banting, Sections 357.0 – 364.0. It is apparent that the profile of depths under rolling straight-edge across the chainages does mirror the IRI. Even though the rolling straight-edge is not a precision equipment of Class 1 World Bank profilometer as the IRS and Walking Profiler, it would be immensely useful to be able to correlate the readings from these three equipments as this would allow the use of the cheaper rolling straight-edge to predict the IRI instead of the more expensive IRS or Walking Profiler especially over a relatively short length of road.

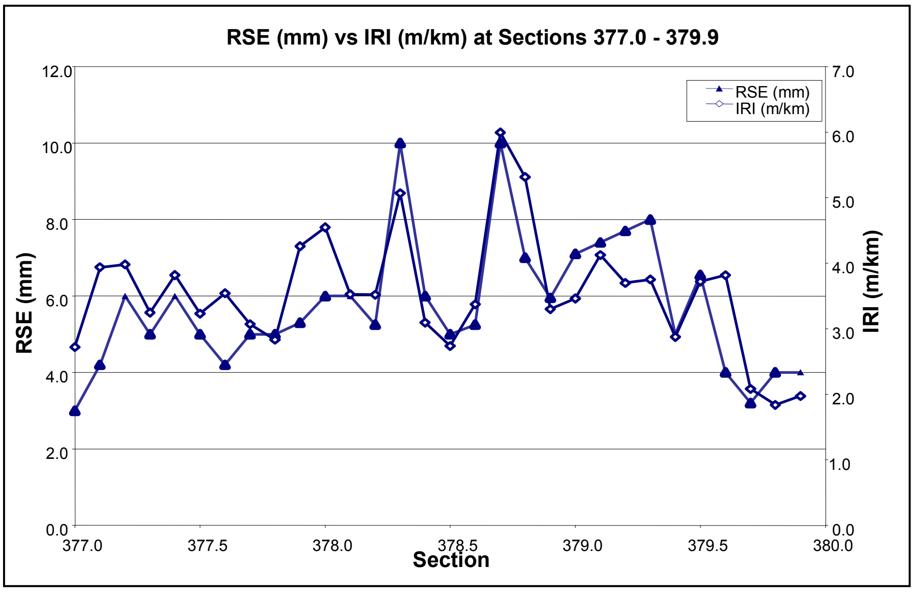

Figure 6 – Comparison of depths under rolling straight-edge and IRI from Walking Profiler at Route 5, Sections 377.0 - 379.9.

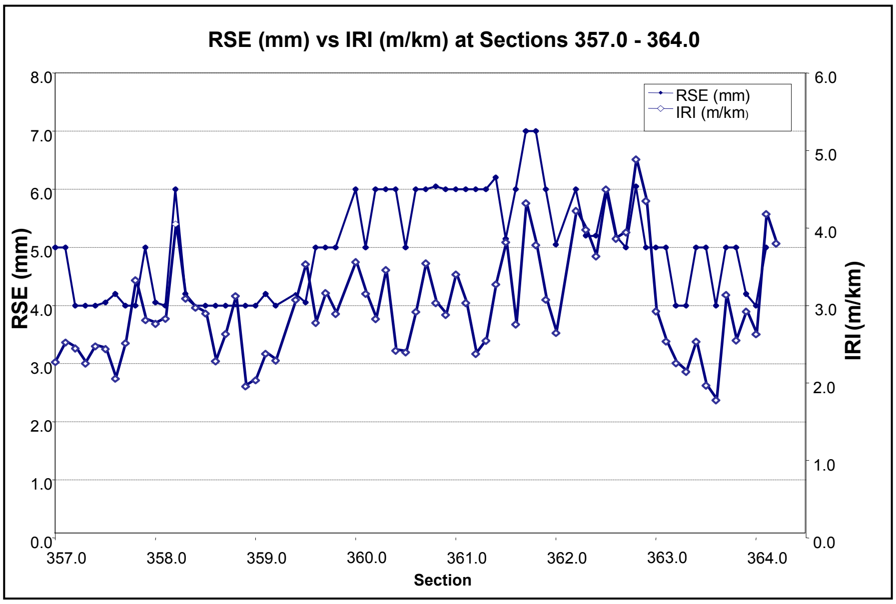

Figure 7 – Comparison of depths under rolling straight-edge and IRI from Walking Profiler at Route 5, Sections 357.0 - 364.0.

Figures 8 and 9 are a plot of average depth under the rolling straight-edge against average IRI (acquired by the IKRAM Road Scanner) over 100-meter length traversed at the same chainages along Route 5, Sections 357.0 – 364.0 and Sections 377.0 – 379.9 respectively.

Figure 8 yields a linear equation y = 0.66x + 3.03 with r^2 = 0.27 whereas Figure 9 exhibits a linear equation y = 1.39x + 0.80 with r^2 = 0.56, where y = average absolute depth > 4mm under rolling straight-edge in mm, and x = IRI in m/km.

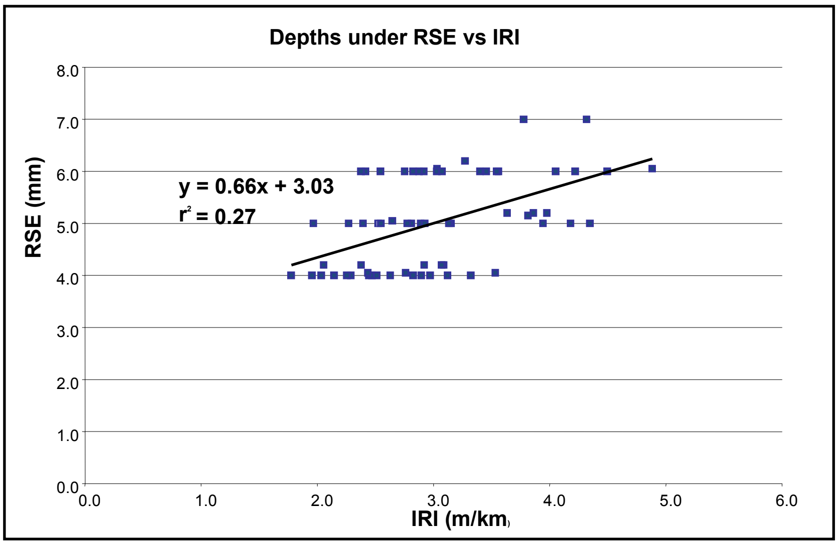

Figure 8 – Depths under RSE vs IRI at Route 5, Sections 357.0 - 364.0.

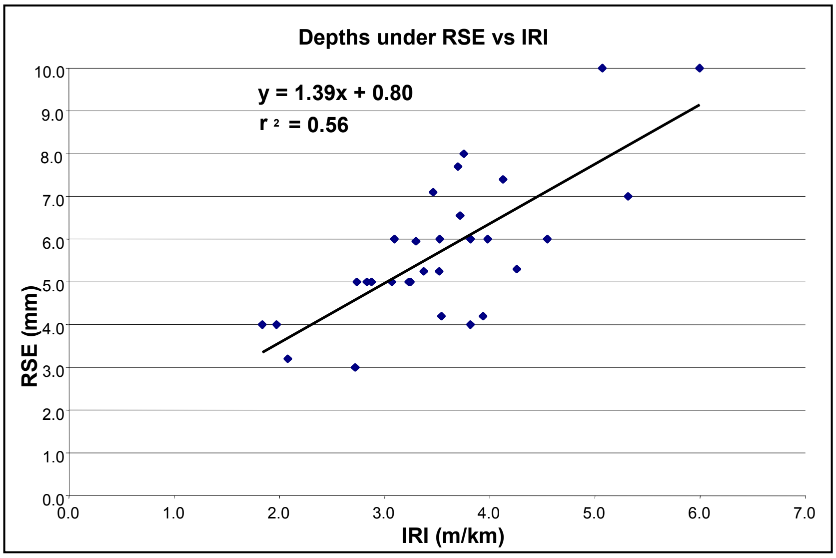

Figure 9 – Depths under RSE vs IRI at Route 5, Sections 377.0 - 379.9.

A similar exercise was repeated at another site which was a totally new road namely the Padang Terap road. The analysis was carried out for every 3 km stretch between Section 3.0 and Section 18.0. The resulted linear equations and r^2 values are as shown in Table 5, where y = average absolute depth > 4mm depth under rolling straight-edge in mm, and x = IRI in m/km.

Table 5 – Linear equations relating depths under rolling straight-edge and IRI

Sections	Equation	r^2
3.0 – 6.0	y = 0.51x + 4.27	0.31
6.0 – 9.0	y = 0.73x + 3.91	0.35
9.0 – 12.0	y = 0.36x + 5.57	0.21
12.0 – 15.0	y = 0.65x + 4.26	0.43
15.0 – 18.0	y = 0.84x + 3.51	0.39

There exists a similar linear trend between 'y' and 'x'. Averaging the 'm' and 'c' values in the linear equations results in an equation y = 0.62x + 4.3, with r^2 = 0.34.

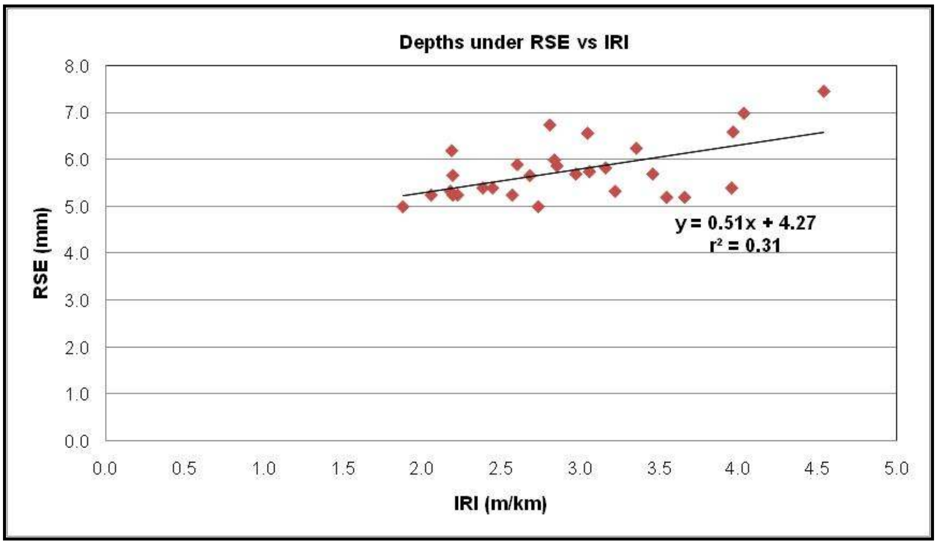

Figure 10 – Depths under RSE vs IRI at Padang Terap, Sections 3.0–6.0.

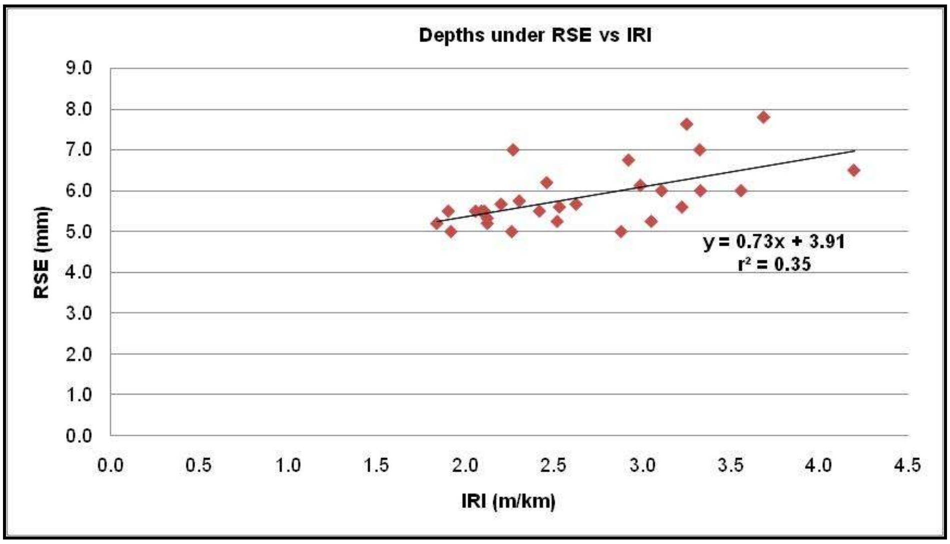

Figure 11 – Depths under RSE vs IRI at Padang Terap, Sections 6.0–9.0.

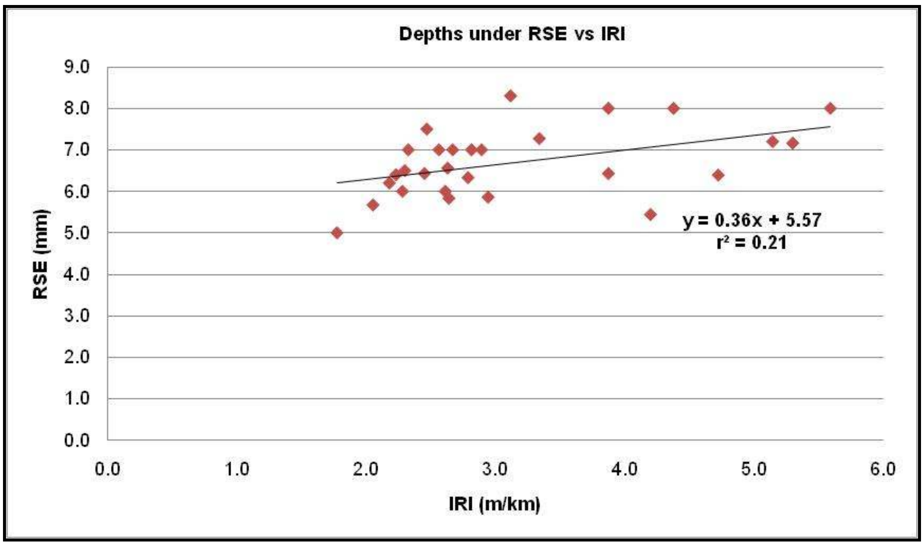

Figure 12 – Depths under RSE vs IRI at Padang Terap, Sections 9.0–12.0.

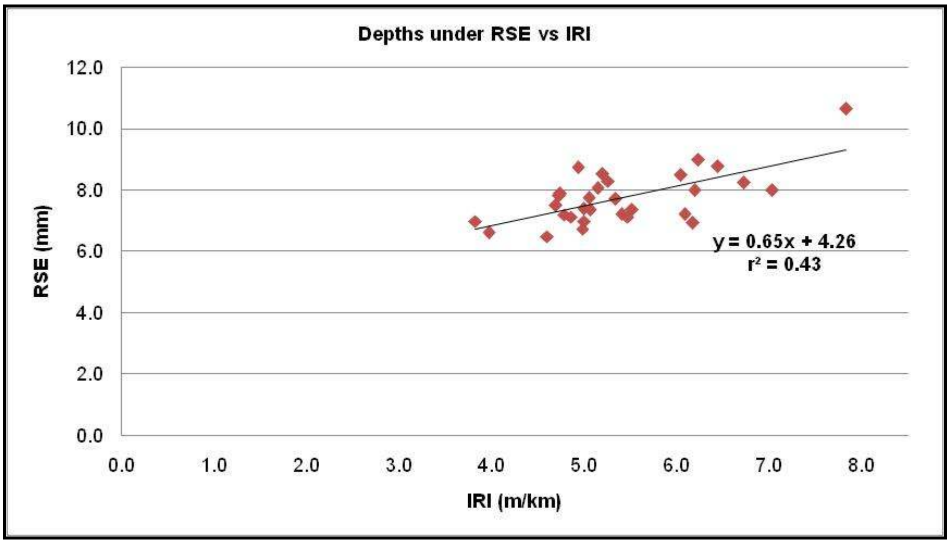

Figure 13 – Depths under RSE vs IRI at Padang Terap, Sections 12.0–15.0.

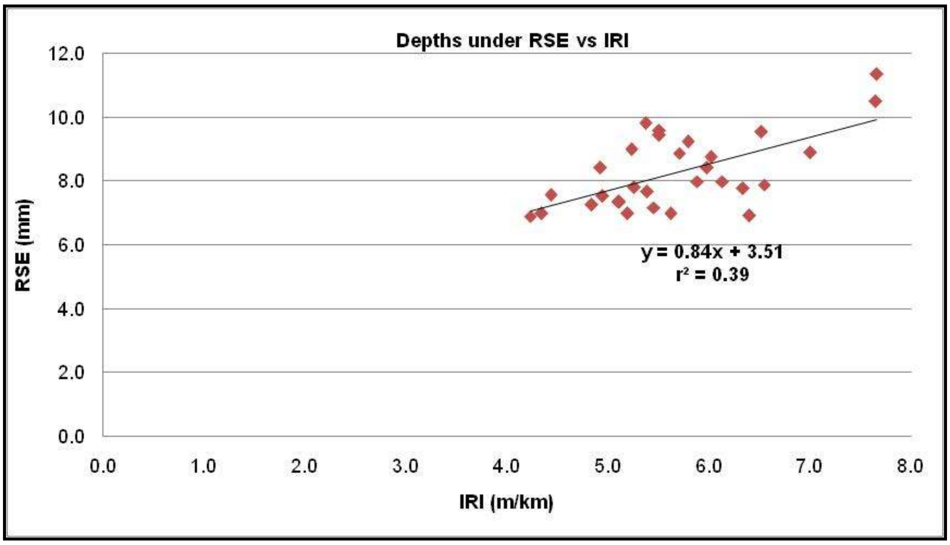

Figure 14 – Depths under RSE vs IRI at Padang Terap, Sections 15.0–18.0.

6.4. Comparison between Class of Surface Regularity and IRI

Using the equation y = 1.39x + 0.8, where y = average absolute depth > 4mm under rolling straight-edge and x = IRI in m/km and taking the average number of readings equal to and greater than 4 mm and the average absolute depth over 100-meter length traversed as 14 and 5.5 mm respectively (Table 2, including readings equal to 4 mm), the comparison of classes of surface regularity between two standards is shown in Table 6 below.

Table 6 – Comparison between Class SR and IRI

IRI m/km	No. of depth > 4 mm under RSE	Class of Surface Regularity*
2.0	9.11	SR1
2.5	10.9	SR1
2.8	11.9	SR1
2.9	12.3	SR2
6.0	23.3	SR2
6.2	23.9	SR2
6.3	24.3	SR3

*By linear extrapolation of figures in Table 1, the maximum permissible number of depth exceeding 4 mm over traverse length of 100m are 12 and 24 for Class SR1 and Class SR2 respectively.

7. CONCLUSIONS AND RECOMMENDATIONS

1. The variation between replica runs of a high-speed survey vehicle (the ARRB - developed IKRAM Road Scanner) are small. Thus, it can be concluded that the IRI values are not significantly affected by the variation in speed and path taken within the lane being measured.

2. Direct comparisons between IRI acquired from a high speed survey vehicle (the ARRB - developed IKRAM Road Scanner) and the ARRB Walking Profiler consistently indicate a good correlation between the two equipments.

3. Resurfacing exercise on existing undulating road surfaces was not effective in rectifying the surface defect.

4. The profile of depths under the rolling straight-edge across the chainages does mirror the IRI. Even though the rolling straight-edge is not a precision equipment of Class 1 World Bank profilometer, it would be immensely useful to correlate with IRI as this would allow the use of the cheaper rolling straight-edge to predict IRI.

5. While IRI should be introduced in the standard specification, the rolling straight-edge requirements should be retained as the advantages of using the device are apparent in its lightweight and cost, especially when there is a need to measure surface regularity over a relatively short length.

6. Comparison between average depth under the rolling straight-edge and average IRI over 100-meter length traversed yields a moderate correlation with varying linear equations and r^2 ranging from 0.21 to 0.56. The best equation is $y = 1.39x + 0.80$ with $r^2 = 0.56$, where y = average absolute depth > 4 mm under rolling straight-edge in mm, and x = IRI in m/km.

7. The correlation could be improved further had the comparison exercise been done in a controlled environment which would ensure similar wheelpaths for both equipments viz. rolling straight-edge and IKRAM Road Scanner.

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