Roughness of Runways and Significance of Appropriate Specifications and Measurement

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Abstract— Most airport runways in southern Africa and Australia are surfaced with asphalt. Many of the runway surfacing specifications have been adapted from relevant road specifications. However roughness is one parameter where airport and road specifications differ. The International Roughness Index (IRI) is a measure of riding comfort commonly used and specified for roads. IRI is fundamentally related to riding comfort experienced by the motor vehicle passenger. In contrast, runway roughness is defined in terms of fatigue on aircraft components and other factors such as cockpit vibrations and excessive g-forces. As a control measure of roughness, IRI has been specified on some airport projects which has the disadvantage in that it is not measuring the elements important on runway pavements. The paper introduces straight-edge, Boeing Bump Index (BBI), aircraft simulation and their use on various runways in southern Africa and Australia. Emphasis is placed on the interpretation and implementation of the latest roughness criteria for runways included in ICAO Annexure 14. The objectives of this paper are to emphasise the significance of appropriate roughness specifications on runways and to share experiences with the implementation of more relevant specifications, including aspects of roughness measurement and interpretation.

Keywords—airport, roughness, ICAO, IRI, Boeing Bump Index

I. INTRODUCTION

On roads, smoothness/roughness has been defined in terms of the ride quality experienced by a passenger in a car. Typically this involves smoothness or riding quality that is measured with various devices such as non-contact laser profilometers and the values expressed as International Roughness Index (IRI) units.

On airports, smoothness/roughness has been defined as being free of bumps and irregularities that can impair safe operations, cause damage, or increase structural fatigue to an aircraft. There is a difference between cars and aircraft. The primary purpose of an aircraft suspension system is to absorb energy expended during landing. Aircraft suspension systems have less capacity to dampen the impact of surface irregularities due to the magnitude of the energy that must be addressed during landing. Runway roughness becomes defined in terms of fatigue on aircraft components (increased stresses and wear) and/ or other factors which may impair the safe operation of the aircraft (cockpit vibrations, excessive g-forces, etc.). There are so many differences between aircraft and vehicles that airport and highway pavement roughness studies should be treated as different issues [4].

A. Road roughness

Road roughness was initially measured as Present Serviceability Rating (PSR), using a panel of road users who subjectively rated the serviceability of various roads. Present Serviceability Index (PSI) was then introduced and by the 1960s, vehicle measuring devices such as the Mays Meter and PCA Meter were in use [8].

Routine road roughness measurements have been taken in South Africa since the early 1970s, initially with the PCA Roadmeter. The Linear Displacement Integrator (LDI) was developed at the CSIR in the late 1970s. This instrument sums the linear movement between vehicle body and the rear axle, much the same as the Mays Meter. The output was converted to the PSI scale through a regression equation. The Quarter-car Index (QI) scale was introduced to South Africa in the early 1980s, then by the middle 1990s conversion to the IRI scale for road roughness commenced in South Africa [16].

IRI is expressed as the average longitudinal road profile that represents the vertical response of a hypothetical quarter-car traveling at 80 km/h to the measured longitudinal road profile.

B. Runway roughness

Runway roughness is not defined by perceived ride quality or passenger discomfort. Although important, passenger discomfort due to runway surface irregularities is often not a significant issue since the degree of discomfort is small and the time of exposure is limited to a few seconds. Further, passenger discomfort often occurs during take-off and landing operations when engine noise, aerodynamic noise, and/or horizontal acceleration or deceleration otherwise distract the passengers.

Runway roughness can induce stress on aircraft components which increases the risk of premature failure due
to fatigue. It can cause enough vibrations in the cockpit that pilots cannot focus on critical instrumentation or could have difficulty manipulating the controls during take-off or landing. Aircraft response to surface irregularities can even reduce braking capacity as the aircraft responds to vertical acceleration. These factors can occur individually or in combination, depending on aircraft response.

Runway roughness is therefore often defined in terms of fatigue on aircraft components (increased stress and wear) and/or other factors which may impair the safe operation of the aircraft (cockpit vibrations, excessive g-forces, etc.), and not in terms of driver and passenger comfort.

The FAA has defined two categories of roughness based on the dimensions and frequency of surface deviations [6].

Single Event Bump. Single event bumps are isolated events where changes in runway elevation occur over a relatively short distance of 100 metres or less. This may occur as an abrupt vertical lip or as a more gradual deviation from a planned runway profile. Depending on the operational speed and bump length, an aircraft suspension system may not be able to fully absorb the energy produced when it encounters a bump. Aircraft components and occupants feel the impact as a shock or sudden jolt. Discrete bumps create impact loading that can accelerate fatigue damage, as well as rattle equipment, crew, and passengers. Basic “straight-edge” analysis can easily identify single event bumps. Riding the runway in a passenger vehicle might reveal shorter length bumps, but finding longer length bumps might require a thorough analysis of the runway profile.

Profile Roughness. Profile roughness is surface profile deviations present over a portion of the runway that cause aircraft to respond in ways that can increase fatigue on aircraft components, reduce braking action, impair cockpit operations, and/or cause discomfort to passengers. Response depends on aircraft size, weight, and operation speed. Repeated large wavelength bumps can induce harmonics and can accelerate fatigue damage to both the aircraft and the pavement. Repeated short wavelength bumps can cause heat build-up in struts/suspension. Even when roughness does not cause discomfort to passengers, it may still affect the fatigue life of aircraft components or decrease operational safety of the aircraft. Depending upon aircraft characteristics and operating speed, an aircraft may be excited into harmonic resonance due to profile roughness which can increase inertial forces or vibrations within the aircraft structure. One example is resonant response in a dual tandem 4-wheel gear, such as the Airbus A330 gear, where the pitch mode increases friction in the pivot joint.

C. Role of pilot feedback

Pilot observations and complaints are one of the more important factors in determining runway roughness. Although pilot observations do not directly indicate that structural fatigue of aircraft components is occurring, they are often the first sign that something is wrong with the runway profile. The magnitude of observation and discomfort is a different order in aircraft compared to cars. Pilot discomfort is vertical acceleration so severe that the instruments are blurred or the pilot could have difficulty manipulating the controls. The authors have heard it expressed in phrases like “couldn’t see the instruments” or “the stick was shaking so badly that it was hard to hold”.

D. Aircraft simulation

Airport pavement roughness can be assessed by simulating the movement of aircraft along the runway or taxiway. The history of aircraft simulation was summarised by Chen and Chou [4] who reported that “In 1967, the National Aeronautics and Space Administration (NASA) established an airport pavement roughness evaluation procedure using an aircraft’s vertical acceleration at the cockpit, setting the maximum acceptable acceleration to be 0.4 g.” Gerardi [7] “conducted a series of studies to develop a rigid-body aircraft model to simulate the vertical acceleration at the pilot’s station and at the centre of gravity of aircraft, as well as pavement loading at main and nose gears. That model has degrees of freedom on pitch, roll, vertical and horizontal translation and it was verified with the field data gathered from KC-135, B-52, F-4C, and C-141. The model was further implemented to become the commercialized software, APRas (Airport Pavement Roughness assessment software)”. Elements of APRas have been incorporated in the ProFAA software, where aircraft response can be simulated for a library of representative commercial aircraft [5].

E. Regulatory control of runway roughness

Historically runway roughness has been dealt with by fairly simple regulations, such as earlier editions of International Civil Aviation Organisation Annex 14 [11]. Their only mandatory requirement in earlier editions was that:

3.1.22 The surface of a runway shall be constructed without irregularities that would result in loss in friction characteristics or otherwise adversely affect the take-off or landing of an aeroplane. Note 1. Surface irregularities may adversely affect the take-off or landing of an aeroplane by causing excessive bouncing, pitching, vibration, or other difficulties in the control of an aeroplane.

The earlier Annex 14 editions up to and including the 4th edition (ICAO, 2004) had two suggested roughness measurements in Attachment A-6 to the Annex:

5.1 In adopting tolerances for runway surface irregularities, the following standard of construction is achievable for short distances of 3 m and conforms to good engineering practice: Except across the crown of a camber or across drainage channels, the finished surface of the wearing course is to be of such regularity that, when tested with a 3 m straight-edge placed anywhere in any direction on the surface, there is no deviation greater than 3 mm between the bottom of the straight-edge and the surface of the pavement anywhere along the straight-edge.

5.3 The operation of aircraft and differential settlement of surface foundations will eventually lead to increases in surface irregularities. . . . In general, isolated irregularities of the order of 2.5 cm to 3 cm over a 45 m distance are tolerable . . . [there are also maximum limits of 80mm over 45m and temporarily acceptable limits of 130mm over 45m] . . . . If the maximum limits are exceeded, corrective action should
be undertaken as soon as reasonably practicable to improve the ride quality. If the temporarily acceptable limits are exceeded, the portions of the runway that exhibit such roughness should have corrective measures taken immediately if aircraft operations are to be continued.

The Annex 14 5th edition [12] continued with these and introduced Boeing Bump Index at its Fig. A-3 which compared ICAO and FAA standards against a background of the Boeing Bump Index; this is not a standard nor is it mandatory. It is the same as the latest Annex 14 (6th edition) [13].

II. ROUGHNESS MEASURING

A. Road profile measurement

The roughness measurement equipment in most common use today on roads is the laser (non-contact) profiler, in which a vehicle is fitted with a laser-based measurement system consisting of lasers and accelerometers that measure and record the road profile. In South Africa, the laser profilometer is validated on validation sections and calibrated by the manufacturer. Response type devices are calibrated on calibration sections, measured with rod-and level and against a contact profiler such as the Dipstick profilometer. Laser profilometers, such as the Dynatest RSP or Hawkeye 1000 profilometers, measure at speed and are used on roads. They have had limited use on runways in some countries, although this has sometimes proved unsatisfactory because road measurements do not necessarily translate to runway requirements.

B. Runway profile measurement

Runway profile measurement is often done using elevation surveys. At its simplest, a profile elevation survey over the runway using a rod and level survey is a quick and valid method. The profile survey should be conducted along the centreline of the runway over the reported rough areas as a minimum, but it is preferable to survey the entire runway length. Survey lines along the track where the main gear would normally be, are very helpful in determining the full extent of the roughness and airplane response. The main gear tracks are normally about 3 metres either side of the centreline for narrow body passenger aircraft such as the Boeing 737. An additional survey track for wide body aircraft such as the Airbus A330 at the 6 metre offset may be necessary. It is recommended that the longitudinal survey interval be on a maximum of 3 metre stations. It can be performed with an ordinary surveyor’s level and rod or by the use of a laser instrument and a rod that detects the laser beams. A runway can be surveyed in a few hours.

The self-contained profile measuring devices are also proficient in measuring the runway profile quickly. These include the contact profilers such as the Dipstick and SurPRO. These are typically used to survey a full runway at 3m, 6m, 10m and 20m offsets from the centreline.

Laser profilometers can be used on runways provided they are able to output a longitudinal profile in a form that can be used by runway roughness software such as ProFAA. ProFAA has very specific requirements for input data and it is not normally possible to read directly from the profilometer software. Instead profilometer machine files, such as the Dynatest .RSP files, are converted to a .TXT file using ProVAL, which is then converted by the ConvertProfileFormat software to the ProFAA format which is a .PRO file.

<table>
<thead>
<tr>
<th>Limit Value (Average 100 m IRI)</th>
<th>Maximum (% of 1 km Segment with Roughness Worse Than Limit Value)</th>
</tr>
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<tbody>
<tr>
<td>1.40</td>
<td>20%</td>
</tr>
<tr>
<td>1.60</td>
<td>5%</td>
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<tr>
<td>2.00</td>
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Isolation of runway roughness can only be really understood by a surface profile survey. A high-speed run over the runway in a vehicle is less than an ideal indicator because of the differences in wheel base, mass, speed, and suspension between the car and the airplane. Visual observance will normally not reveal a runway roughness problem either, because the bumps are often too long in length or shallow in depth to appear to the eye.

C. Application of road profile measurements to runways

The IRI is not part of the ICAO regulations, but roughness equipment used to measure it on roads is readily available. This makes the application of IRI to runways tempting, even as an indirect value to quantify smoothness, even if it is not recommended. A recent specification for an airport runway in southern Africa is shown in Table 1 to illustrate such an application. The average 100 m IRI for a “survey lane” was calculated by averaging the 100 m IRI left and right wheel path values as specified and the measurements had to be taken immediately after completion of the runway construction [10].

III. AIRPORT ROUGHNESS MEASUREMENTS

A. Roughness software

ProFAA is the Federal Aviation Administration’s software for computing airport pavement elevation profile roughness indexes [5]. Data analysis performed by the program includes the calculation of the indices for Straight-edge (SSI), Boeing Bump Index (BBI) and International Roughness Index (IRI). It also does the simulation of aircraft response in a similar process as the APRas software.

The ProVAL software allows one to view and analyze longitudinal pavement profiles in many different ways, including the common road measurements such as IRI, profilograph and rolling straight-edge. It takes machine data files from several profilometers, such as the Dynatest .RSP files. ProVAL [15] is a US FHWA/LTPP product, and was originally released in 2001; the current version is 3.5.

The commercial software APRas can simulate 15 different types of commercial aircraft ranging from the Boeing 737-800 up to the Boeing 747-400 aircraft as well as a select variety of military aircraft. Simulations include take-off, landing, constant speed taxi and aborted take-off scenarios [1].
B. Airports analysed

Roughness measurements at two airports were analysed for this paper. Airport M had a new asphalt surfaced runway 2720 x 45 metres; it was designed to ICAO 4E geometric standards. The forecast traffic was very light, with less than 100 wide-body departures forecast for the 20 year design life. The surfacing construction quality was hindered by asphalt plant supply problems and paving issues, and it was done by asphalt paving to a roads standard without the use of a shuttle buggy. Airport B had an existing 2500 x 45 metre runway which was designed to ICAO 4C geometric standards. The pavement had been overloaded for many years by Boeing 737 traffic and the runway was significantly deformed and rough. The runway was the subject of some pilot complaints about roughness. Airport B runway was then rehabilitated and reshaped by a major asphalt overlay involving multiple layers of asphalt. The construction quality of the surfacing was to a high standard, and smooth construction was assisted by the use of a shuttle buggy (materials transfer vehicle).

C. Straight-Edge Measurement

Roughness for acceptability of new construction in the ICAO system is typically measured with a straight-edge. This detects adjoining asphalt paver runs or concrete slabs that are mismatched in elevation. It also detects light fittings or drain grates that may be set too low or protrude too high. The ICAO standard is 3mm under a 3m straight-edge at construction.

The ProFAA software calculates a Straightedge Smoothness Index (SSI), which uses data from any profiling device and finds the maximum deviation anywhere along that straightedge and plots the absolute value [14]. This is different to the rolling straightedge software where, for example, ProVAL simply determines the vertical deviation between the centre of the straightedge and the profile. Experience shows that undulations can have both an upward and downward component and Straightedge Smoothness Index better captures the bump from both.

1) Airport M

At Airport M, for the left and right wheel tracks (3m each side of centreline), the 3m straight-edge was applied along the runway using the ProFAA software. The graph of 3m north of centreline is shown in Fig. 1 (3m S CL is similar and is omitted for reasons of space); the Y axis ranges from 0mm to 9.1032mm. Clearly the limit of 3mm is exceeded at a number of localised points along the runway, which is unacceptable.

Roughness of existing runways in the ICAO system is also measured with a straight-edge. This detects surface irregularities resulting from the operation of aircraft and differential settlement of surface foundations. ICAO Annex 14 suggests that isolated irregularities of the order of 25 to 30mm over a 45 m distance (under a 45m straight-edge) are tolerable, with the maximum surface irregularity height (or depth) of 80 mm over 45m. If the maximum limits are exceeded, corrective action needs to be undertaken as soon as reasonably practicable to improve the ride quality.

At Airport M, for the left and right wheel tracks (3m each side of centreline), the 45m straight-edge was applied along the runway using the ProFAA software, even though this runway was newly constructed. The graph of 3m north of centreline is shown in Fig. 2 (3m S CL is similar and is omitted for reasons of space); the Y axis ranges from 0mm to 42.491mm. Clearly the 25-30mm tolerable limit is exceeded at a few localised points along the runway, which is unacceptable for new construction. It would however be acceptable for an existing runway which had been trafficked for a number of years.

2) Airport B

Here, for the left and right wheel tracks (3m each side of centreline), the 3m straight-edge was applied along the runway using the ProFAA software. The graph of 3m north of centreline is shown in Fig. 3 (3m S CL is similar and is omitted for reasons of space); the upper graph is the rough runway before rehabilitation (Y axis ranges from 0mm to 1.9186mm) and the lower graph is the smooth runway after rehabilitation (Y axis ranges from 0mm to 0.8379mm). In neither case was the limit of 3mm exceeded, which is acceptable. It does show the limitation of the 3m straight-edge in not detecting runways which have become rough over time due to aircraft traffic generating long wavelength roughness. During the rehabilitation at Airport B, a 3m rolling straight-edge was used on the asphalt surfacing layer, run longitudinally along every paver lane, and no occurrences of 3mm or more were recorded. This provided a check of SSI against the manual rolling straight edge.

Fig. 1. Airport M - 3m N CL - 3m straight-edge graph

Fig. 2. Airport M - 3m N CL - 45m straight-edge graph
At Airport B, for the left and right wheel tracks (3m each side of centreline), the 45m straight-edge was applied along the runway using the ProFAA software. The graph of 3m north of centreline is shown in Fig. 4 (3m S CL is similar and is omitted...
for reasons of space); the upper graph is the rough runway before rehabilitation (Y axis ranges from 0mm to 111.18mm) and the lower graph is the smooth runway after rehabilitation (Y axis ranges from 0mm to 29.763mm).

Clearly the 25-30mm tolerable limit was exceeded for the rough/before case. The maximum surface irregularity height (or depth) of 80 mm over 45m was also exceeded at a few localised points along the runway, but the temporary limit of 130mm was not exceeded. Corrective action was needed to be undertaken as soon as reasonably practicable to improve the ride quality, but the runway did not require immediate corrective measures.

D. Boeing Bump Index

1) Introduction

Boeing developed a criteria that describes runway roughness as a single event condition [3]. FAA took the Boeing bump procedure and created the “Boeing Bump Index” (BBI). Fig. 5 shows the acceptable, excessive, and unacceptable evaluation zones in terms of BBI. When the BBI value is below 1.0, the Boeing bump criteria is in the acceptable zone. Values of BBI greater than 1.0 fall in either the excessive or unacceptable zones.

The Boeing Bump Index quickly identifies roughness that can produce poor aircraft ride quality, but it should be noted that there are some fundamental issues that limit its effectiveness. Because this index only evaluates the event's wavelength and amplitude, the Boeing Bump Index can only evaluate one event at a time. Many roughness investigation projects find that the poor aircraft response is due to several events in succession; each of which could be found acceptable by the Boeing Bump Index. But in reality, the aircraft responds to the chain of events as a whole and as a result, can produce some very poor ride quality. Unfortunately, the Boeing Bump Index can declare a runway as acceptable that, in reality, would fail the aircraft response threshold of +/- 0.4 g (gravitational forces) of aircraft response [2].

2) Airport M

At Airport M, for the left and right wheel tracks (3m each side of centreline), the Boeing Bump Index was calculated along the runway using the ProFAA software. The graph of 3m north of centreline is shown in Fig. 6 (3m S CL is similar and is omitted for reasons of space); the Y axis ranges from 0 to 0.2876. This is smooth, and well below the BBI limits of Fig. 5, and the runway is acceptable.

3) Airport B

At Airport B, for the left and right wheel tracks (3m each side of centreline), the Boeing Bump Index was calculated along the runway using the ProFAA software. The graph of 3m north of centreline is shown in Fig. 7 (3m S CL is similar and is omitted for reasons of space); the upper graph is the rough runway before rehabilitation (Y axis ranges from 0 to 0.7521) and the lower graph is the smooth runway after rehabilitation (Y axis ranges from 0 to 0.2612). The runway before rehabilitation was known to be rough and pilot complaints were being received, but is considered acceptable by BBI.

The BBI for the two new/rehabilitated runways were remarkably close at 0.2876 and 0.2612, even though the surfacing on one was built to a higher standard than the other. This suggests that BBI is a good measure of the intrinsic smoothness of the runway since, despite the difference in surfacing quality, both runways were intrinsically new and smooth.

E. Aircraft response

Aircraft response was simulated using ProFAA. The aircraft modelled was a Boeing 727 which is representative of narrowbody jet airliners; the aircraft was modelled at high speed (100 knots, which is 180 kph). Key outputs of the simulation are a graph along the runway of the vertical acceleration at the pilot’s station (cp), and a second graph of the vertical acceleration at the aircraft’s centre of gravity (cg). To these was applied a +/- 0.4g limit, which is defined as the “threshold of discomfort” as reported by Goldman [9].

1) Airport M

At Airport M, for the left and right wheel tracks (3m each side of centreline), the vertical acceleration at the pilot’s station (G cp) was calculated along the runway. The high speed graph of 3m north of centreline is shown in Fig. 8 (3m S CL is similar and is omitted for reasons of space). The Y-axis ranges of G cp is from -0.3256g to 0.2361g (a range of 0.56g). This has some evident bumps, but is below the suggested limit of +/-0.4g and so the runway is acceptable, although this is not considered a good result for a new runway. Vertical acceleration at the aircraft centre of gravity (G cg) was measured and was always lower than G cp.

Airport B

At Airport B, for the left and right wheel tracks (3m each side of centreline), the vertical acceleration at the pilot’s station (G cp) was calculated along the runway. The high speed graph of 3m north of centreline is shown in Fig. 9 (3m S CL is similar and is omitted for reasons of space). The upper graph is the rough runway before rehabilitation (Y axis ranges from -0.6629g to 0.3765g) and the lower graph is the smooth runway after rehabilitation (Y axis ranges from -0.2306g to 0.1632g). The runway roughness before rehabilitation was well in excess of the suggested limit of +/-0.4g, and this corresponds with the pilot complaints about that runway; the runway roughness was unacceptable. However after rehabilitation, the roughness was below the limits and acceptable. In this respect, aircraft response simulation can detect complex roughness problems which BBI would miss.

The aircraft simulation also picked up the surfacing quality differences between the two airports, with the range of acceleration at Airport M with the lower quality surfacing construction being 0.56g and Airport B with high quality surfacing construction being 0.39g.
Fig. 7  Airport B - 3m N CL – Boeing Bump Index – upper graph is before/rough and lower graph is after/smooth

Fig. 8  Airport M - 3m N CL – vertical acceleration at the pilot’s station (cp) for Boeing 727 aircraft at 100 knots

Fig. 9  Airport B - 3m N CL – vertical acceleration at the pilot’s station (Cp) for Boeing 727 aircraft at 100 knots– upper graph is before/rough and lower graph is after/smooth

Fig. 10  Airport M - 3m N CL - IRI averaged every 100m
At Airport M, for the left and right wheel tracks (3m each side of centreline), the International Roughness Index (IRI) was calculated using ProVAL 3.5. This was checked using ProFAA with excellent agreement. Data was collected immediately after construction in 2013 using a Dynatest Road Surface profiler. The airport is served by narrow-body aircraft, so the 3m offset wheeltracks were the appropriate ones to measure. The IRI was averaged every 100m and plotted so that the data could be evaluated against Table 1, with IRI=1.6 mm/km shown as a red line (Fig. 10 and Fig. 11).

Using the acceptance criteria of Table 1, the runway was smoother (better) than the criteria after the runway end effects were discounted (detailed analysis showed that high average IRI values were limited to 50m start/stop at the ends).

IV. DIRECT COMPARISON OF ROAD AND AIRPORT MEASUREMENTS

Chen and Chou [4] compared the aircraft simulation outputs of the APRas software (similar to ProFAA) with IRI. They concluded that it was clear that an aircraft’s vertical acceleration and pavement loading responses were not identical to the responses of IRI, and concluded that IRI is not suitable for evaluating airport pavement roughness.

In this paper, a direct comparison was made of road and airport measurements at Airport M. The measures were compared by plotting the raw data (un-averaged) for IRI and Boeing Bump Index (upper and lower graphs respectively of Fig. 12). There is no comparable trend or correspondence between the two measures. However the BBI graph does show three locations where some bigger ‘bumps’ are – two near the left hand side and one at the centre.

The two ICAO straight-edge measurements give more insight as to where the bumps really are, and where corrective action should be taken (Fig. 13). The long wavelength ‘bumps’ show up on the 45m straight-edge graph and are the same as the BBI graph – two near the left hand side and one in the centre. The small discontinuities, possibly due to poor construction such as stop/start asphalt paving, show up at a number of places on the 3m straight-edge graph.

Aggregated data, in the form of 100m segment averages, was used to compare IRI and Boeing Bump Index. At Airport M, for both the left and right wheel tracks (3m each side of centreline), IRI and Boeing Bump Index were averaged for 100m segments and compared (in Fig. 14 and Fig. 15). It is evident that the general trend is similar for both measures; this is not unexpected since in the simplest of terms, smooth is smooth and rough is rough. However the two measures are still not directly comparable, as the left hand side of Fig. 14 clearly shows.
The use of segment or section averages raises the concern that they serve to mask the effect of bumps, which get lost in the process. The raw data BBI and straight-edge measurements show where bumps really are, and it is evident in Fig. 12 and Fig. 13 that several large/long wavelength ‘bumps’ really do exist, as well as a number of small/short wavelength discontinuities. The averaged IRI data do not show these at all, and while the BBI pattern shows the large/long wavelength ‘bumps’, the BBI segment averages are so low in value that the runway appears to be very smooth. Averages are considered unacceptable for bump analysis.

V. RECOMMENDED AIRPORT ROUGHNESS SPECIFICATIONS

The assessment of runway roughness is complex and no single index is sufficient to describe the roughness of runways. The Boeing Bump Index (BBI) gives an overall measure of the runway’s acceptability, and shows the location of long wavelength ‘bumps’ but not small discontinuities such as poor paving or light fittings. BBI can only evaluate one event at a time, and often poor aircraft response is due to several events in succession; each of which could be found acceptable by the BBI. But in reality, the aircraft responds to the chain of events as a whole and as a result, can produce some very poor ride quality.

Aircraft response simulation of aircraft travelling at high speed can calculate vertical accelerations and strut forces. The aircraft simulation gives a good measure of acceptability, relates to pilot concerns, and shows up long wavelength bumps as well as surfacing quality differences between the two airports. The two ICAO straight-edge measurements give insight as to where bumps really are, and where corrective action should be taken. The long wavelength ‘bumps’ show up on the 45m straight-edge graph and are the same as the BBI graph – two near the left hand side and one in the centre. The small discontinuities, possibly due to poor construction such as stop/start asphalt paving, show up at a number of places on the 3m straight-edge graph.

It is recommended that:
- Boeing Bump Index be used to give an overall measure of the runway’s acceptability, although it is noted that it can give false positives.

- Aircraft response simulation must also be done to confirm the acceptability of the roughness to pilots, and override the false positives of the Boeing Bump Index.

- ICAO 3m and 45m straight-edge tools are used to find the location of bumps, detect whether they are long wavelength bumps or short discontinuities, and confirm the BBI and aircraft simulations.

- Segment averages should not be used for runways because averaging serves to mask the effect of bumps.

- International Roughness Index (IRI) should not be used for runways.

- Probabilistic measures not be used as acceptance criteria (such as shown in Table 1) since they assume a certain statistical distribution (usually the normal distribution) and it is evident from the raw data graphs in this paper that this distribution does not exist for any roughness measure.

REFERENCES


