ABSTRACT
Several Australian State Road Authorities (SRAs) have implemented ride quality based specifications for the acceptance of newly constructed or rehabilitated pavements. In some instances these specifications not only set the limits for acceptance but also stipulate payment deductions for non-conforming works. The feedback from the pavement construction industry is that many contractors are not fully aware of what ride quality is or how it is measured. This paper explains the concept of ride quality in terms of road roughness and outlines what pavement contractors need to do to construct smoother pavements. Some agencies are requiring roughness to be reported in terms of the world standard International Roughness Index (IRI) rather than the traditional unit of measurement used in Australia, NAASRA roughness. The relationship between these two roughness measures is also discussed along with the benefits of using an accredited roughness measuring device for assessing the ride quality of the pavement.

WHY IS RIDE QUALITY OF IMPORTANCE?
Of all the assets that a government authority is responsible for, the road network is one of the most visible and important. It is also one of the most expensive to build and maintain. There is, therefore, a need to ensure that existing pavements are well maintained and that new construction is structurally sound and of a quality that will result in a significant life expectancy for the pavement.

A smoother road will not excite the suspension components of vehicles, thus reducing the dynamic loads of heavy vehicles in particular on the pavement, and extending its life. As well as the cost reduction to the authority, vehicle operating costs are also reduced, both in fuel and maintenance terms.

However, perception is also reality, and roughness causes user discomfort as well as economic cost.

Better construction techniques create smoother longer lasting roads which both reduce agency and operator costs and increase user satisfaction. With this in mind, several SRAs have incorporated specific clauses into their contracts detailing minimum levels of ride quality for newly constructed or rehabilitated pavements.

RIDE QUALITY AND ROAD ROUGHNESS
The ride quality of a pavement may be defined as the level of ride comfort experienced by the occupants within a vehicle as it traverses the pavement.

The level of comfort will ultimately depend on the vertical acceleration (vibration) that the occupants are subjected to while travelling over the road. This acceleration is attributable to the roughness of the pavement.

What is road roughness? According to one definition roughness is “a condition parameter which characterises deviations from the intended longitudinal profile of a road surface with characteristic dimensions that affect vehicle dynamics (and hence road user costs), ride quality and dynamic pavement loading” (Austroads 2001). In lay terms, bumps on a smooth surface. This definition highlights the relationship between roughness and ride quality.
A BRIEF HISTORY OF ROUGHNESS MEASUREMENT IN AUSTRALIA

The first practical device for measuring roughness in Australia was the NAASRA Roughness meter. This was developed by ARRB in conjunction with the SRAs in the 1970s and is still in use today here and in several other countries. (See Figure 1).

The NAASRA meter is a robust mechanical unit that is mounted in the host vehicle, usually a station wagon, above a solid rear axle and which registers the vertical relative displacement between the rear axle and the body of the vehicle via a wire cable connected to the differential. The positive vertical displacements are accumulated to produce a roughness count for a particular section of road (Prem 1989).

The NAASRA meter is classed as a response type road roughness measuring system (RTTRMS) as the roughness measurements made by the system are dependent on the response of the vehicle to the pavement surface ie factors such as the vehicle’s suspension, tyre pressure, number of people sitting in the vehicle and travel speed all have an affect on the results measured. When these factors change so will the response of the vehicle and therefore the roughness measurement. It is necessary for each vehicle to be re-calibrated at regular intervals eg every 3000 kilometres of travel, and to be operated in a standard configuration to achieve consistency in the results.

In the late 1980’s the first laser profiler was developed by ARRB as a calibration tool for the NAASRA meter. Prior to this a standard reference vehicle with a NAASRA meter was maintained by ARRB against which all other NAASRA meters were calibrated. The laser profiler has the advantage that the measurements it makes are totally independent of tyre pressure and the suspension characteristics of the host vehicle. There is still a low speed limitation yet it operates over a wide speed range.

A basic profiler consists of two measurement transducers, a laser and an accelerometer situated over each of the wheel paths (typically 750 mm either side of the centre line of the host vehicle). These transducers are usually mounted on a beam that is attached to either the front or the rear of the host vehicle. The beam sits approximately 300 millimetres above the road. (See Figure 2). The laser records the height of the beam from the road and the accelerometer the vertical acceleration, or bounce, of the beam. When combined via a process of mathematical differentiation and integration these readings are able to measure the longitudinal elevation profile of the pavement in each of the wheel paths.

Each profiler has a highly accurate distance measuring instrument (DMI) that is attached to one of the wheels of the host vehicle. The DMI is calibrated on a test section measured by a registered surveyor. Based on the output of the DMI, individual readings from the transducers are made every 50 millimetres of travel resulting in a detailed picture of the longitudinal shape of the pavement in each wheel path. It is this elevation profile that allows the ride quality (roughness) of the pavement to be assessed.

From the early 1990s laser profilers became the preferred roughness measurement devices of the SRAs for their network level surveys because of their improved accuracy and ease of use. Further developments have taken place and today’s laser profilers not only measure roughness but also rutting and texture and it is not uncommon for them to be equipped with video imaging and GPS technology.

Simply plotting the profile of each wheel path to try and assess the ride quality of the pavement is impractical, tedious and highly subjective. Fortunately, these profiles can be analysed via computer models to produce a variety of roughness statistics that are a property of the profile, one of these is the International Roughness Index (IRI).
THE INTERNATIONAL ROUGHNESS INDEX (IRI) – WHAT IS IT?

The International Roughness Index is a standard roughness statistic that is calculated from the pavement profile. Development goes back to the late 1970s when the National Cooperative Highway Research Program (NCHRP) sponsored a study of response type road roughness measuring systems in the USA including their calibration. This led to the development of a Golden Car simulation (Sayers 1995).

In the same time period the World Bank funded several large scale research programs relating to the building of roads in developing countries. While road roughness was found to be an important factor contributing to higher road user costs, it was not possible to make meaningful comparisons between data sets collected in different countries because there was no consistency between the roughness measurements (Sayers & Karamihas 1998).

To address this issue the World Bank initiated a correlation exercise that took place in Brazil in 1982 known as the International Road Roughness Experiment (IRRE). Its main focus was to establish correlation and calibration procedures for roughness measurement to enable comparisons to be made between roughness measurements made by different devices. The underlying research from the NCHRP study was revisited and the Golden Car parameters became the basis of the Quarter Car model and subsequently the standard roughness scale we know today as the International Roughness Index (IRI).

IRI is a good indicator of ride quality as it relates well to the vibration response of a motor vehicle (Gillespie 1992) and is highly correlated to vertical passenger acceleration (Sayers & Karamihas 1998). It is also a good indicator of general condition and structural integrity of the pavement condition. According to Sayers & Karamihas 1998 “IRI summarizes roughness qualities that impact vehicle response and is most suitable when a roughness measure is desired that relates to: overall operating cost, overall ride quality, dynamic wheel loads……and overall surface condition.” This last comment ties in well with the definition of roughness that was previously quoted.

The Quarter Car model used in the IRI algorithm is a mathematical model or filter. As the name suggests, it is a model of a quarter of a car which simulates the response of a generic motor vehicle to a profile by calculating the suspension deflection. The simulated speed at which the model travels over the profile was set at 80 km/h because at this speed the IRI is sensitive to the same wavelengths that cause vibrations in vehicles during normal highway use (Sayers 1995).

A schematic of the model is shown in Figure 3 that identifies the various components. The roughness of the pavement is determined by accumulating the simulated suspension motion between the sprung and unsprung masses and dividing by the distance travelled. This yields an index with the units of slope, m/km, mm/m etc (Sayers 1995).

IRI bears a strong linear correlation to the output from an RTRRMS, such as the NAASRA meter, because the parameters of the quarter car model were originally tuned to maximise their correlation with response type systems. However, unlike the NAASRA meter most laser profilers produce an independent roughness statistic for each wheel path. Therefore, to be able to compare IRI with NAASRA roughness counts the IRI values must first be averaged to produce an average IRI for the combined wheel paths.

The correlation between NAASRA roughness counts from a properly calibrated meter and average IRI is

\[
\text{NAASRA} = 26.49 \times \text{IRI}_{\text{ave}} - 1.27
\]

where IRI_{ave} is the average of the passenger and driver wheel path IRI values for a particular interval\(^2\). (See Figure 4).
NAASRA roughness is still a legitimate measure of the roughness or ride quality although it is recommended that it is measured by some form of profiling device rather than a NAASRA meter. However, with the introduction of the Austroads Guidelines for measuring pavement roughness (Austroads 2001) there has been a push to harmonise roughness measurement in Australia and report it in accord with the world standard, IRI.

For instance the VicRoads ride quality specification for pavement construction (Section 180 of VicRoads Standard Specification for Roadworks) now requires that roughness be reported as IRI rather than in NAASRA roughness counts.

The measurement of IRI is not limited to laser profilers. There are other devices such as the Walking Profiler that can be used. (See Figure 5). In fact, any device capable of measuring a valid road profile may be utilised, eg staff and level.

For a more detailed explanation of the IRI, recommended reading is the paper On the Calculation of International Roughness Index from Longitudinal Road Profile (Sayers 1995), Everything You Wanted to Know About IRI but Were Afraid to Ask! (Gillespie 1992) and The Little Book of Profiling (Sayers & Karamihas 1998). The last two may be down loaded free of charge from the University of Michigan Transportation Research Institute (UMTRI) web site.

ROUGHNESS IS MORE THAN CORRUGATIONS AND POTHoles

A road user may limit their view of road roughness to the number of corrugations and pot holes they can see and feel in a road. True, these short wave length defects, whether of a periodic or discrete nature, do affect the roughness of the pavement and the subsequent ride quality. However, these defects are not the only ones to affect ride quality. The IRI, because of its response characteristics, will also be influenced by longer wavelengths in the pavement.

In a mathematical sense the Quarter Car model is a band pass filter that is influenced by wavelengths that range from 1.2 to 30 metres in length (although there is still some response to wavelengths outside this range). As such, surface characteristics like the size of aggregate have little or no influence on IRI and ride quality but long wave lengths, such as dips and bumps that result in the occupants of the car leaving their seats and hitting their heads on the roof of the vehicle, are a form of roughness too as they effect the ride quality experienced. A smooth (low textured) surface will not of itself ensure a pavement with good ride quality nor does a high textured surface due to a coarse chip seal mean that a rough ride will result.

IRI is particularly sensitive to wave lengths of 2.4 and 15.4 metres because of their excitation effect on the model’s suspension and these should be avoided in a newly constructed pavement if a low IRI is to be achieved.

SMOOTHING OUT THE BUMPS

Having a knowledge of IRI and how it is measured should enable a pavement contractor to build a smoother road with a superior ride quality. The simple principle is to avoid any longitudinal deviations in the pavement that excite the suspension characteristics of the Quarter Car model.

In practical terms, for the paving contractor, this means:

**Steps and Construction Joints**

A step may be defined as a change in height that occurs at a discrete point in the pavement. The change in height can be either positive or negative. Steps often occur at a bridge abutment or at the termination of an overlay (Austroads 2002). (See Figure 6).
A step in the pavement fits the Austroads definition of roughness (*deviations from the intended longitudinal profile of a road surface*), and will have a significant impact on the ride quality.

To illustrate the magnitude of that impact, imagine a road that is 100 metres long and perfectly flat. This road will have zero roughness because there are no deviations in the pavement profile to excite the suspension components of the Quarter Car model. If we were to introduce a 15 mm step at a point 50 metres from the start of the road, the IRI of the pavement would increase from 0 to 0.52 m/km because this would be the sum of the resultant movements in the vehicle suspension as the initial “bump” is damped out.

*Table 1* details the IRI for the same imaginary 100 metre section of road with steps of various heights ranging from 5 to 25 millimetres.

<table>
<thead>
<tr>
<th>Step (mm)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI (m/km)</td>
<td>0.17</td>
<td>0.34</td>
<td>0.52</td>
<td>0.69</td>
<td>0.86</td>
</tr>
</tbody>
</table>

In reality, no pavement is perfectly flat and the effect of the step will be less than that seen in the examples above. For example, a 15 millimetre step was introduced into the driver and passenger profiles half way through a 100 metre section of an actual pavement and the IRI for the 100 metre increased from 1.34 to 1.72 m/km. Generally, the effect of the step will be less obvious as the roughness of the surrounding pavement increases.

The fact that the IRI scale is linearly proportional to roughness can also be seen from these results. In each instance the IRI has increased by the same percentage as the step height. The IRI will also be the same whether the step results in a positive or negative displacement.

The localised effect of a step on the ride quality is shown in *Figure 7*. Here the results are shown at 10 metre intervals and it can be seen that the major contribution to the roughness occurs in the 10 metre section immediately after the point of the defect. However, there is also a roll on effect with the step contributing to the roughness of the pavement in a decreasing manner for approximately 40 metres.

Construction joints in both asphalt and concrete pavements often have a negative impact on the ride quality too and should be avoided where possible by using a continuous paving technique. Joints can occur when there has been a discontinuity or break in placement due to lack of supply or completion of the work day and can manifest themselves as a small dip or bump across the pavement and in the worst cases as a step.

A contractor should also be aware that longitudinal deviations may also occur during asphalt placement. For instance, if the supply truck bumps the asphalt paver sufficiently hard it can reduce the layer thickness and introduce a deviation into the surface of the pavement that will decrease the ride quality.

**Dips, Humps and Bumps**

For the purpose of this paper large dips, humps and bumps have been defined as long wavelength features in the pavement. In severe cases these are capable of producing ‘gut wrenching’ heaves that produce accelerations similar to those experienced by a passenger on a joy ride at a theme park. Long wavelength features must also be avoided if a smooth ride is to be achieved.

Unlike steps and joints, long wavelength defects are more likely to be built into the underlying layers of the pavement as a result of the construction technique employed and how well the design levels have been adhered to.
Generally, if the underlying layer contains long wavelength deformations that excite the suspension components of the Quarter Car model, no significant improvement will be seen in the ride quality of the pavement after application of a thin surfacing.

For illustrative purposes consider a continuous section of road which has the shape of a sine wave with an amplitude of 10 mm and a wavelength of 20 metres. Even if this pavement was totally free of surface defects and short wavelength roughness it would still have an IRI of 2.34 m/km.

Some contractors may expect that an asphalt surfacing will automatically improve the ride quality, especially if some type of shape correction is implemented. However, if the shape correction is unable to account for the long wavelength deviations the ride quality will not markedly improve. This is an important fact in situations where one company has been contracted to place the final surfacing and another to construct the underlying layers.

When placing asphalt there is benefit in equipping the paver with a ski that provides feedback to the screed bar on the shape of the pavement. This ski should be as long as practical to smooth out any surface deviations.

In the case of a chip seal surfacing, no shape correction is performed so the roughness of the seal should be very similar to that of the underlying layer. The recommendation is to ensure adequate ride quality for the granular base course before sealing.

**Keeping the Road Surface Clean**

Surface contaminants can contribute to the roughness of the pavement as the measuring device is unable to differentiate whether the contaminant forms part of the surface or not.

If necessary the surface should be first swept to remove loose stones and any build up of sand or gravel prior to testing (Gillespie et al 1999). This is particularly important if a new chip seal has been recently placed.

Contractors need to be especially aware of removing any dirt or lumps of clay which may be present on the pavement surface. Such contaminants are hard to avoid if earthworks have been undertaken as part of the construction or rehabilitation.

To illustrate the effect that a surface contaminant can have on the ride quality think back to our perfectly flat section of road and imagine a 300 mm long piece of clay with a uniform height of 15 millimetres, stuck in the passenger wheel path. The resultant average IRI for the 100 metre section would be 0.14 m/km. If another piece of clay with the same dimensions was found in driver wheel path the IRI value would be doubled.

Cleaning the surface prior to assessing the ride quality should be an easy task for the contractor compared to constructing the pavement and is highly recommended.

**Site Location and Delineation**

It is in the contractor’s best interests to clearly identify the start and end point of each test section rather than simply specifying chainages. This is best done by physically marking the points with paint or some other permanent marker. If such a practice is adhered to there can be no debate as to whether the correct section of pavement was tested or not.

It is also recommended that whenever possible the contractor arranges to meet the testing authority on site to show them the sites to be tested and explain any further needs that they may have.

If testing is to be performed prior to line marking or on an unsealed surface the contractor should ensure that there is some form of temporary guide eg bollards or witches hats to identify
the lane to be surveyed. The guides will help with tracking and improve the repeatability of the results. This practice is highly beneficial in situations where there are multiple lanes to be tested.

Adhering to the above recommendations is particularly important when the same site must be tested at a later date.

**Provide Sufficient Lead-In and Lead-Out**

Lead-in and lead-out are critical factors when a vehicle mounted system such as a laser profiler is used to assess the ride quality of a pavement. Lead-in is defined as the distance prior to the start of the test section which is available for the measuring device to reach test speed and commence acquisition. Lead-out is the distance available for the device to slow down and come to a stop. Of the two, lead-in is the most critical.

The ride quality of the lead-in should be of a similar standard to the section being tested and if possible devoid of any defects. As shown in Figure 7 the effect of a step in the pavement will carry on for approximately 40 metres from the point of the defect. If this step occurs in the lead-in, after data acquisition has commenced, it may be reflected in the IRI that is calculated for the test section.

Due to the mathematics of the Quarter Car model it is preferable that data collection commences at least 20 metres before the start point to allow the effects of the model’s initialisation to diminish (Sayers 1995). The lead-in should be long enough to allow the test vehicle to reach its minimum survey speed (typically 30 km/h but will depend on the device) and, ideally, commence acquisition at least 50 metres before the start of the test site. The lead-out should be of sufficient length to allow the operator to conclude data acquisition before the vehicle brakes and comes to a stop. A minimum length of 50 metres is recommended.

The lead-in and lead-out should also be of sufficient length to avoid the need for sharp acceleration and deceleration respectively which can affect the IRI measurements.

If sufficient lead-in or lead-out is not available then the use of a device such as the Walking Profiler should be considered.

**SUITABILITY OF EQUIPMENT FOR MEASURING RIDE QUALITY**

If the ride quality specification requires the roughness of the pavement to be reported in terms of IRI then a contractor has one of two options – a vehicle mounted laser profiler or a manual device such as the Walking Profiler. Both of these devices have the ability to measure longitudinal profiles in the wheel paths of the test lane and report an average IRI. It is true that the output of the NAASRA meter could be converted using the previously stated relationship, however, the laser profiler is a more accurate and versatile instrument and should be the preferred device for measuring ride quality (Wix 1998). This is recognised by government agencies who specify that a laser profiler must be used for testing.

Even though the laser profiler is the device of choice it still has some limitations. Due to the lasers it can not be used when there is free standing water on the surface of the pavement or in the aggregate. Dust can also have an effect on the measurements and on unsealed sites it is recommended that a front mounted system be used. In such cases it may also be advantageous to wet down the surface with a water truck prior to testing (ensuring that the surface is clear of free standing water prior to testing).

The Walking Profiler is best used for shorter sections of pavement as its data collection rate is less than 1 km/h. It is an ideal device for use in situations where there is insufficient lead-in for a profiler to reach test speed or on bridge decks and approaches.
The accuracy of the equipment used is paramount as the results may ultimately decide whether the contractor will receive full payment or incur a penalty. It is recommended that an accredited supplier be used who is proficient in ride quality testing and has verified the outputs of their test equipment. In fact, VicRoads requires the testing authority to have NATA accreditation for the VicRoads ride quality test method RC 423.05. In NSW the RTA takes a similar approach and each device must be compared against a reference device before it is accepted (RTA NSW 2002).

WHAT HAPPENS IF THE PAVEMENT IS TOO ROUGH?

If the ride quality of the pavement falls outside the limits specified by the superintendent some form of correction will be needed, otherwise a penalty may apply. Typically, such corrections are possible only before placement of the final surfacing and testing prior to placement is highly recommended. As IRI is a linear scale it is possible that a small section of the pavement is responsible for the higher than allowable result and in most instances only these sections need to be re-worked.

Whether this is true or not can be determined by analysing the roughness results at a reduced interval. It is suggested that a 10 metre interval be used. Although it is debatable whether a roughness value representing 10 metres is meaningful it will serve the purpose of identifying the high roughness spots in the pavement, particularly the short wavelength defects such as a step or small bump or corrugation.

This technique has been used to good effect by several contractors.

CONCLUSION

The State Road Authorities have introduced ride quality specifications for the express purpose of constructing smoother longer lasting roads. It is possible for pavement contractors to meet these specifications and avoid any penalties if they are aware of the factors that effect ride quality and have an understanding of IRI and the wavelengths it is susceptible to. In some instances this may require the contractor to modify their construction methods.

The contractor can also assist the testing authority by accurately identifying each test site and ensuring that there is sufficient lead-in and lead-out and that the pavement surface is clean. It is also in the contractor’s best interests to employ a tester which is accredited and has verified the outputs of the measuring device.

Rather than just including penalty clauses it is hoped that in the future the SRAs will offer incentives for any contractor that exceeds the ride quality requirements.

ENDNOTES

1It is true that the level of ride comfort experienced by the occupants will depend on the suspension characteristics of the vehicle. However, it has been shown that the occupants of a vehicle are still capable of separating the role of the vehicle from that of the roughness of the pavement (Sayers & Karamihas 1998).

2The IRI algorithm also contains a moving average filter to simulate the interaction of a pneumatic tyre with the pavement surface to reduce the sensitivity of the IRI algorithm to the sample interval (Sayers 1995).

3IRIave is equivalent to the Lane IRIqc defined in the Austroads Guidelines for measuring pavement roughness (Austroads 2001).

4In a mathematical sense the profile measured by a profiler can be thought of as a series of sinusoids (sine waves) with differing wavelengths, amplitudes and phases. For a more detailed
discussion of wave lengths and profiles it is recommended that the reader refer to the *Little Book of Profiling* (Sayers & Karamihas 1998).

\(^5\)All IRI results were calculated using a 50 millimetre sampling interval.

**ACKNOWLEDGMENTS**

The author would like to express his thanks to Tom Wood and Richard Yeo for their contributions to this work.

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**AUTHOR BIOGRAPHY**

Richard Wix completed a Bachelor of Engineering (Chemical) at Monash University in 1985 and joined ARRB Transport Research in 1990 as a Research Engineer. Previously he had worked for CSR-Humes at their Research and Development facilities where he was involved with material testing and concrete durability.

Since joining ARRB, Richard has been involved in various aspects of automated pavement condition data collection, including research into laser based roughness, rutting and texture measurement systems and their subsequent development. This has included calibration, training and commissioning of data collection vehicles in several different countries including 6 months in the USA. Richard has also represented ARRB at various international conferences and experiments.
At present Richard is a senior member of the Road Management Services team where he plays a major role in contributing to and overseeing large network level pavement condition surveys within Australia and overseas. He also performs the role of Validation Manager with the responsibility of ensuring that the team’s equipment meets ARRB’s own requirements and those of its clients.
Figure 1: NAASRA Roughness Meter Mounted in Rear of Vehicle
Figure 2: ARRB Rear Mounted 3 Laser Profiler (third or centre laser is used to measure rutting)
Figure 3: IRI Computation and the Quarter Car Model
Figure 4: Relationship between Average IRI and NAASRA Roughness (Prem 1989)
Figure 5: ARRB Walking Profilers Measuring Longitudinal Profile
Figure 6: Gross Example of a Step in the Pavement Surfacing
Figure 7: Effect of Step Height on IRI