WARRIP

WESTERN AUSTRALIAN ROAD RESEARCH AND INNOVATION PROGRAM

# Optimising the use of laser profilometer data to report rut depth, roughness and surface texture

## Review of WA practice

AN INITIATIVE BY:

THE GOVERNMENT OF WESTERN AUSTRALIA

mainroads WESTERN AUSTRALIA

arrb

# Optimising the use of laser profilometer data to report rut depth, roughness and surface texture

2019-006

for Main Roads WA

**Reviewed**

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014509-1
October 2019


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# SUMMARY


Main Roads Western Australia (Main Roads) uses various test methods to measure and control the quality and performance of its roads.

These include:

- *Pavement roughness and rutting: laser profilometer method*: Test Method WA 313.3:2012
- *Texture depth*: Test Method WA 311.1:2012
- *Surface shape using a straightedge*: Test Method 313.2:2012

These methods were appropriate at the time considering the available technology.

Since 2012 there have been changes in the technologies used to collect road data and these have been reflected in the adoption of Austroads test methods (AG:AM/T001 to AG:AM/T005 and AG:AM/T009 to AG:AM/T0016).

These new test methods have been adopted by all state road agencies except Main Roads and include methods for the validation of the equipment to ensure harmonisation of all laser profilers used in Australia.

A comprehensive literature review was conducted to review available methods and related test procedures, calibration and validation. Austroads, Main Roads, VicRoads, Roads and Maritime Services New South Wales (RMS NSW), the South African National Roads Agency SOC Limited (SANRAL) and the Federal Highway Administration (FHWA) test methods have been reviewed and compared.

A comparison study was undertaken of roughness, rut depth, texture depth and surface shape measurement methods. Furthermore, a cost benefit analysis of adopting a laser profilometer for road surveys for Western Australia (WA) conditions was undertaken and it is strongly recommended that WA develop its own test methods and specifications or update and adopt the specification to facilitate the use of a laser profilometer vehicle in road surveys.

# CONTENTS

# TABLES



# FIGURES

# 1 INTRODUCTION

## 1.1 Background

Road surface deficiencies and texture have been evaluated with a variety of test methods such as the sand patch and straightedge test (Austroads 2018). In recent years, road agencies have started to use survey vehicles with laser profilometers to evaluate pavement parameters such as rut depth, roughness and texture. The application of non-contact measurements such as ultrasonics and lasers can significantly accelerate the pavement surveying process and therefore, facilitate whole network asset management.

Laser profilometers measure the transverse profile of the road and then convert the optical data to rut depth, surface texture and other pavement parameters.

This report will focus on the assessment of three pavement parameters through laser profilometers namely roughness, rutting and texture.

Main Roads WA has a specific requirement for surface shape measurements using a straightedge and wedge while there is no equivalent test method from Austroads. This report also considers this method.

### *1.1.1 Roughness*

Road roughness is defined as a road condition parameter that indicates deviations from the designed longitudinal profile of a road surface. Roughness also indicates dimensions that influence vehicle movement, ride quality and dynamic loading on the pavement (Austroads 2018).

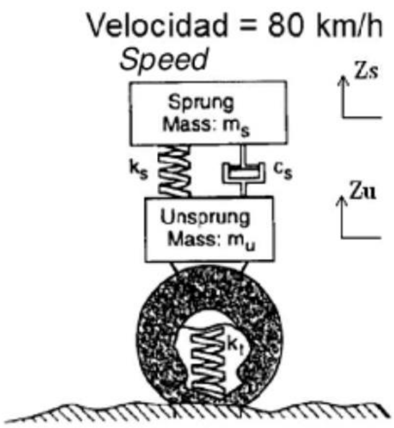
Roughness of the pavement is a means to assess riding quality on the pavement. This parameter is evaluated to characterise factors that influence vehicle dynamics, ride quality and dynamic pavement loadings.

Roughness of the road indicates the deviations from the initial intended longitudinal profile. This parameter measures the surface irregularities usually with a wavelength of 0.5 to 50 m in the longitudinal direction of the road and it can be identified in one or both wheelpaths.

Austroads (2018) recommends that road surface roughness should be expressed in terms of International Roughness Index (IRI) of the measured lane. IRI values are presented in m/km and are determined by averaging two single wheelpaths.

The International Roughness Index (IRI) has been developed as a scale for roughness and is based on the response of a typical motor vehicle to the ride quality of the pavement surface. The IRI value is calculated by collecting an exact measurement of the road profile. This measurement should be processed by an algorithm that simulates the response of a reference vehicle to the input roughness data and then accumulates the suspension travel (Gillespie 1992). Therefore, IRI is calculated using accumulation of responses from a mathematical model of a quarter vehicle (Figure 1.1).

Figure 1.1: Mathematical model to calculate IRI




Source: Sayers (1995).

### 1.1.2 Rutting

Austroads (2018) defines the rut depth as the maximum vertical deflection of the road surface in the transverse direction. This can be measured either across a wheelpath or across a lane width. Rut depth is measured from a reference datum selected perpendicular to the road edge.

Deflection of the asphalt surface in the longitudinal direction is identified as rutting and it usually occurs under each wheelpath. Rutting occurs not only in the asphalt surface but also within the sublayers. The width of the rut is an indication of the origin of the rut, with wider ruts attributed to base or subbase failure. Rutting of the pavement surface affects the serviceability of the road. Rutting or rut depth are measures to describe transverse profile (Austroads 2018).

Rutting can significantly decrease pavement serviceability by ponding water and subsequently reducing skid resistance.

Highway Development and Management (HDM) technology defines rutting as a permanent and unrecoverable deformation which is associated with traffic loading. If this occurs on a wheelpath, rutting accumulates over time and can affect the pavement surface function (Paterson 1987).

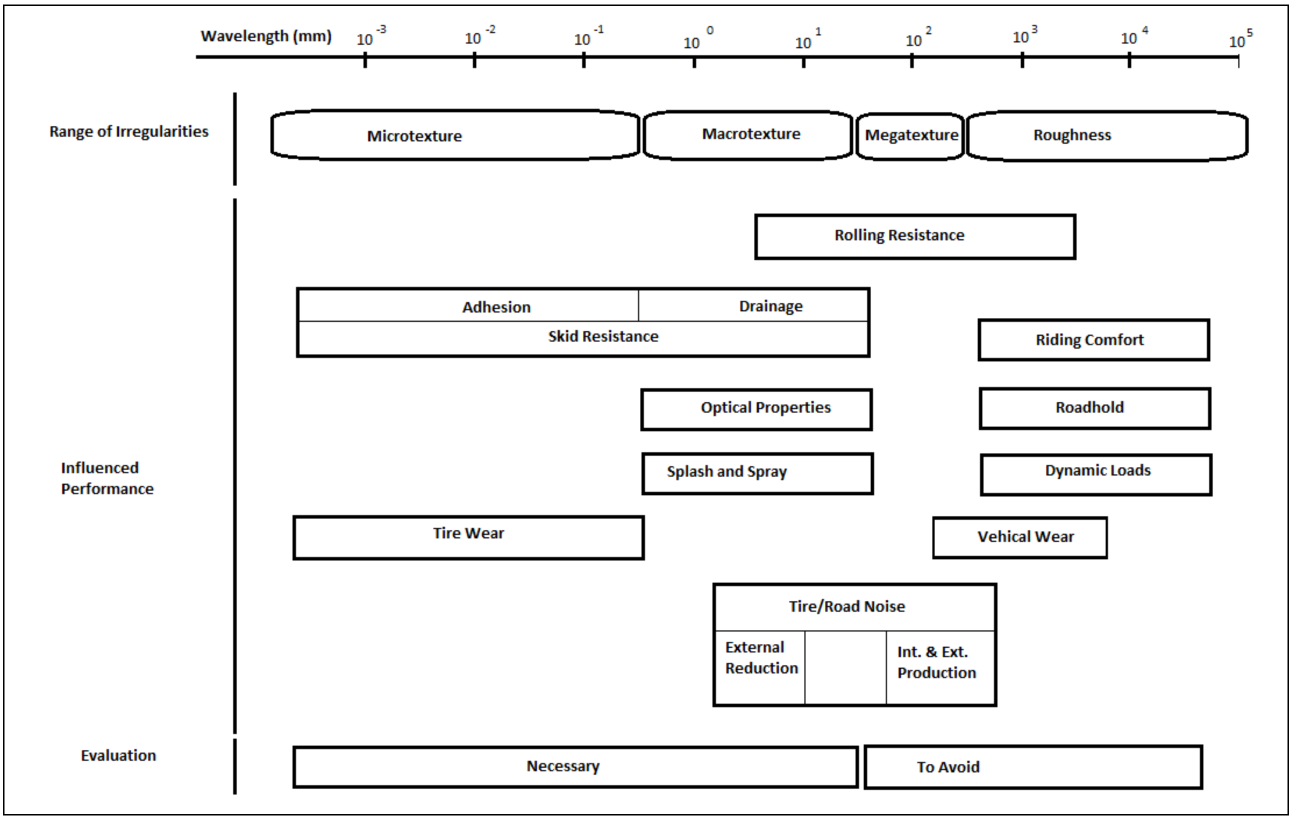
Apparent rutting can be induced by the contribution of different factors including material strength, surface wear or structural performance of the layered system. In the case of severe rutting or shoving, this structural indication can be related to the strength of the pavement (Roberts & Martin 1996, and Koniditsiotis & Kumar 2004).

### 1.1.3 Surface Texture

The road surface texture or texture depth is the main contributor to tyre surface friction which leads to proper handling of the vehicle. Surface texture is particularly important when vehicles drive at higher speeds or in wet conditions.

Macrotexture is defined as irregularities with a wavelength above 0.5 mm, while the irregularities of the surface less than 0.5 mm are identified as microtexture. Figure 1.2 shows the relative size of surface texture and its effect on pavement serviceability. The tyre footprint is usually taken as 100 mm (Austroads 2018).

**Figure 1.2: Surface texture**




Source: Descornet (1989).

Surface texture of a road contributes significantly to the skid resistance between tyre and surface and therefore is an important factor in road serviceability. The tyre-surface friction is one of the key elements in the handling of vehicles and loss of this friction causes potential risk of crashes and slippages. Previous research and international experience have proven a strong relationship between the number of crashes and low road surface texture.

## 1.2 Objective

Main Roads WA uses various test methods to measure and control the quality of its roads.

These include:

- *Pavement roughness and rutting: laser profilometer method*: Test Method WA 313.3:2012
- *Texture depth*: Test Method WA 311.1:2012
- *Surface shape using a straightedge*: Test Method 313.2-2012

These methods were appropriate at the time considering the available technology.

However, since 2012, there have been changes in the technologies used to collect road data. These have been reflected in the latest Austroads test methods and those adopted by other road agencies.

For example:

- The Main Roads method for measuring texture depth is the manual sand patch method whereas the Austroads method (AG:AM/T013) uses laser technology.
- The Main Roads method for measuring rut depth uses a three-laser system and only reports rut index due to the 3 laser limitation, whereas Austroads (AG:AM/T016) uses a minimum of 11 lasers.
- The Main Roads method for estimating surface shape uses the manual straightedge and wedge; there is no equivalent Austroads method.

These new test methods have been adopted by all states except Main Roads and include methods for the validation of the equipment to ensure harmonisation of all laser profilers used in Australia.

## 1.3 Scope

Collecting data with laser profilometers could save in survey costs. To estimate the benefits and costs of these new methods, a comprehensive literature review was conducted. The literature review aimed to:

- review national and international best practice in using laser profilometers to determine road rut depth, roughness and surface texture
- compare recommended test methods with current WA methods in terms of calculation procedure, accuracy and practicality.

## 1.4 Report Structure

This report consists of a literature review on the national and international test methods applicable for measurement of road surface roughness, rutting and texture.

Section 2 deals with Austroads methodologies, including distance measurement validation, road condition monitoring vehicles and methods of roughness, rutting and texture measurement. Section 3 reviews Main Roads WA methods of measuring roughness, rutting and texture. In Section 4, national and international methods to measure these three parameters are reviewed. The methods are compared in Section 5 and the relative benefits and costs of each method are discussed. Section 6 summarises the literature review and its major findings. Finally, in Section 7, the scope of future studies is recommended.

# 2 AUSTROADS METHODS

## 2.1 General

Austroads (AG:AM/T005) describes the process of validation of the distance measurement performance of vehicles conducting road condition monitoring surveys. This includes vehicles fitted with inertial laser profilometers and Falling Weight Deflectometers (FWD). The test methods are adopted from the International Organization for Standardization (ISO) 2015, *Quality management systems: fundamentals and vocabulary* (ISO 9000:2015).

Validation, in ISO 9000:2015, is defined as:

> confirmation, through the provision of objective evidence that requirements for a specific intended use or application have been fulfilled.

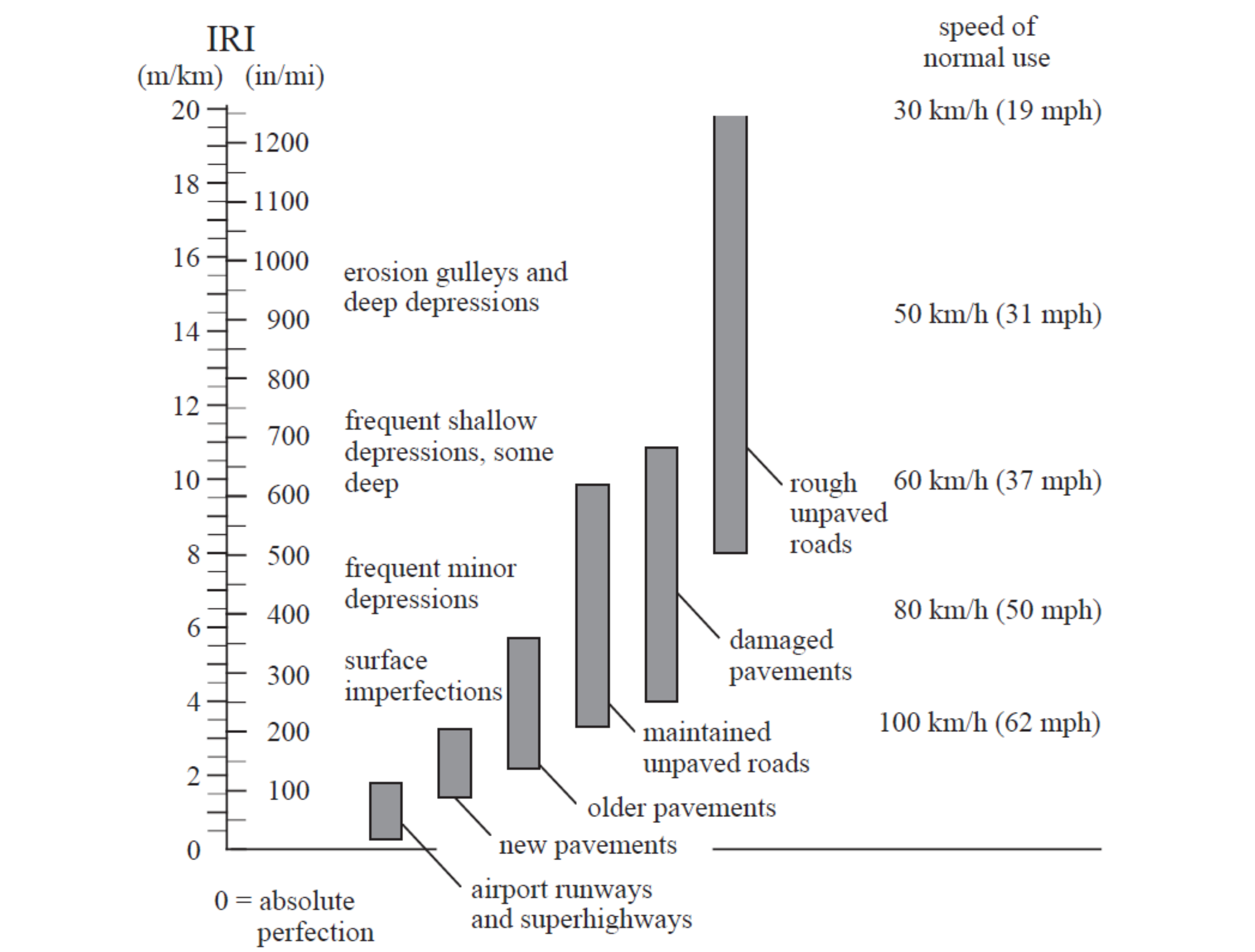
The procedure for the validation of surveying vehicles starts with picking a 1 km section of road, the length of which should be measured using ground surveying within 1 m precision. The surveying vehicle should be able to keep the specified speed in the entire section. Then the true distance is measured, which should include slope, undulation and alignment. This measurement is conducted by accurate geomatic and ground surveying techniques. After this measurement, the same section should be measured using the distance measuring system of the surveying vehicle. Five sets of measured lengths should be collected with ground survey and the surveying vehicle. The difference between the distance measured by vehicle and ground surveying is reported as a percentage of the measurement by ground surveying. The surveying vehicle is validated if this percentage is within 0.1%.

## 2.2 Roughness

Pavement roughness is a means to assess the riding quality of the surface of the road. It is one of the most used measures for assessing the general road condition. Austroads reports roughness in IRI (m/km). The IRI test methods is described in AG:AM/T001.

It should be noted that roughness is measured based on the modelling of a vehicle travelling at 80 km/h. Therefore, a high roughness value at a roundabout, road curvature or other low speed section of the road might feel less severe because the actual speed of cars on the road is below 80 km/h at these locations. In the non-technical context, roughness means the ride comfort, rideability and/or smoothness. Figure 2.1 presents typical values of IRI and their relevant interpretation on the road surface conditions (SANRAL TMH 10, 2007).

**Figure 2.1: IRI range and interpretation**




Source: Sayers & Karamihas (1998).

In Australia roughness values have been measured from the mechanical response of a vehicle to a pavement surface. The response has been reported in terms of the National Association of Australian State Road Authorities (NAASRA) Roughness Meter Counts (NRM, counts/km). Therefore, the roughness calculated by a profilometer vehicle can also be converted to NRM in units of counts/km.

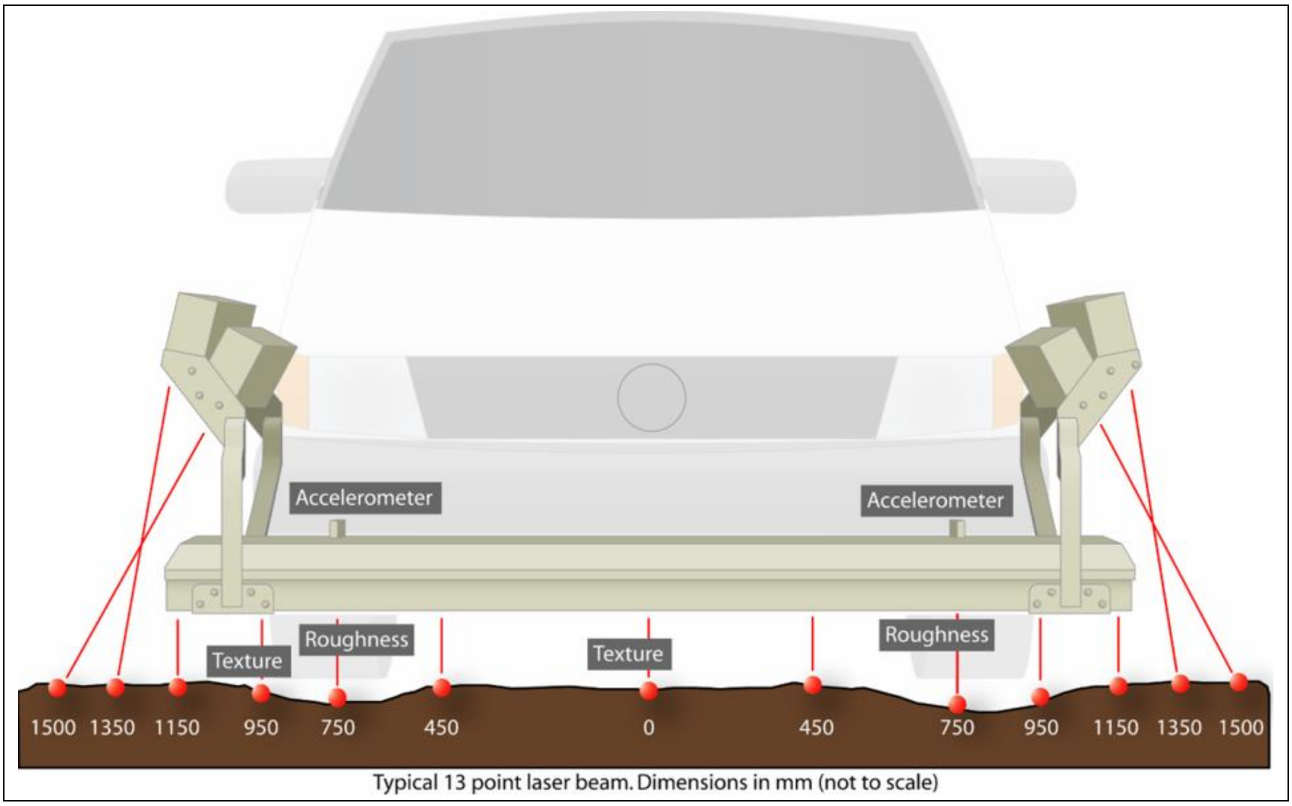
If a profilometer is used to measure roughness, the following factors should be considered:

- In the surveying traffic lane, the wheelpath most commonly used by cars should be followed by the survey vehicle. If the most common wheelpath is not clear, the centreline should be followed.
- Roughness results are usually recorded and reported in 100 m intervals.
- The equipment should record and process data according to one of the recommended test methods (Austroads AG:AM/T001:2016, AG:AM/T002:2016, AG:AM/T003:2016).
- In the range of all operating speeds, the measuring equipment should obtain longitudinal profiles in both wheelpaths at the same time in the wavelength range of 0.5–50 m.
- The wheelpaths should be situated 0.75 m offset from the centre of the vehicle.

- Spacing of sampling distance in the longitudinal direction should not exceed 50 mm increments.
- The accuracy of height measurement should be greater than 0.2 mm.

Figure 2.2 shows the simplest multi-laser profilometer which has three measuring lasers. Two lasers scanning each wheelpath while the third one is mounted between the wheelpaths and measures the surface texture.

**Figure 2.2: Inertial laser profilometer – location of transducers and IMS**




Source: Adapted from AG:AM/T009:2016.

### *2.2.1 Pavement Roughness Measurement with an Inertial Profilometer*

AG:AM/T001 describes the roughness measurement procedure using direct measurement of the longitudinal profile of the road surface with an inertial profilometer. The procedure calculates roughness in terms of IRI, but it also provides the equivalent NRM counts for the calculated IRI. The IRI calculated in this method is an average lane IRI for a 100 m length of road. It should be noted that if a profilometer is used, usually roughness measurements are conducted along with rutting and texture measurements.

This test method is developed based on ASTM E1926-08:2015, *Standard practice for computing International Roughness Index of roads from longitudinal profile measurements*.

IRI is reported in two ways. Single track IRI represents a quarter-car model run on a single wheelpath at 80 km/h. Lane IRI represents the roughness of one lane in the road section. Austroads recommends single track IRI be measured. The lane IRI is the average of two Single

Track IRI values obtained on both wheelpaths. To convert IRI into NAASRA counts Equation 1 can be used (from AG:AM/T001:2016):

$$NAASRA\left(\frac{counts}{km}\right) = 26.49 \times Lane\ IRI\left(\frac{m}{km}\right) - 1.27 \qquad 1$$

The characteristics of the equipment required in this test method are defined in AG:AM/T001. The inertial profilometer should consist of a vehicle with an accelerometer, a displacement transducer (laser device), a data logger and a processing computer. The equipment should be validated according to AG:AM/T002:2016, AG:AM/T003:2016 and AG:AM/T005:2011.

Profile surveys are conducted on the lane with the majority of the traffic. It is usually the slow lane on most roads. The vehicle is driven smoothly and within the speed range defined by the manufacturer. Data is logged with reference to a pre-specified reference point. The surface profile of each wheelpath in the test lane is measured. This test cannot be performed in the rain or on a wet road surface.

The vehicle calculates the single track $IRI_{qc}$ using the quarter-car model for each wheelpath for each 100 m of tested section. The lane IRI is calculated according to Equation 2:

$$Lane\ IRI_{qc} = \frac{IRI_{qcL} + IRI_{qcR}}{2} \qquad 2$$

where

| | | |
|---|---|---|
| Lane $IRI_{qc}$ | = | lane roughness (IRI m/km) |
| $IRI_{qcL}$ | = | roughness of left wheelpath profile (IRI m/km) |
| $IRI_{qcR}$ | = | roughness of right wheelpath profile (IRI m/km) |

This value can be converted to NAASRA roughness using Equation 1.

### *2.2.2 Validation of an Inertial Profilometer for Measuring Pavement Roughness (Reference Device Method)*

Austroads Test Method AG:AM/T002 describes one of the two test methods for validation of an inertial profilometer. In this method, validation is checked by a comparison of the roughness results between the profilometer and a static or manual reference device. The test method was developed based on ASTM E 1364-95:2017 *Standard test method for measuring road roughness by static level method.*

To conduct this validation, the following equipment is required:

1. a calibrated inertial laser profilometer as detailed in Austroads test method AG:AM/T001
2. a standard walking profiler.

Test method AG:AM/T005, which is described in Section 2.1 of this report, should be followed here as well.

The validation requires the selection of 5 specific sections which should have a total of 500 m length and meet specific characteristics as described in AG:AM/T001. These characteristics ensure that the pavement roughness range from 0.9 m/km to 3.4 m/km is covered and the sections are representative of the whole surveyed network. The profilometer should be able to bring its speed up to the maximum test speed in the section. These characteristics are set to ensure reliable validation. It should be noted that the coefficient of determination ($r^2$) statistic parameter is significantly affected by the range of data used in the survey.

The IRI calculated in Section 2.2.1 is to be compared with either a static level (refer to ASTM E1364-95:2017) or a standard walking profiler (refer to test method AGPT/T450). Three test speeds of the inertial profilometer's operating speed range should be selected. Five sets of tests for each of the selected speeds should be conducted. Check limits described in AG:AM/T004 should also be passed for the purpose of validation of the survey vehicle.

For each 100 m length of test section for all the test runs the lane IRI should be calculated from both the inertial profilometer and the reference measurements (ARRB walking profiler or rod and level readings). The calculation is according to Equation 2.

IRI data measured by the inertial profilometer is grouped in a single dataset for each of the three speeds. This leads to 125 records (one speed x five sections x five chainages per section x five repeat survey runs per section).

The two sets of data then should be matched with a line regression using the least squares technique in the form of Equation 3:

$$IRI_{Base} = A \times IRI_{Profilometer} + B \qquad (3)$$

Additionally, the value of $r^2$ should be reported for each of the regression lines.

All IRI data measured by an inertial profilometer should be converted to a single dataset totalling 375 records (three speeds x five sections x five chainages per section x five repeat survey runs per section). A regression line and $r^2$ is calculated for this set of data as well.

Validation is achieved if all the reported values fall within the following ranges:

- individual speeds: $0.95 \le A \le 1.05$, $-0.25 \le B \le 0.25$ m/km, $r^2 \ge 0.95$
- combined results: $0.95 \le A \le 1.05$, $-0.25 \le B \le 0.25$ m/km, $r^2 \ge 0.95$.

#### *2.2.3 Validation of an Inertial Profilometer for Measuring Pavement Roughness (Loop Method)*

Austroads test method AG:AM/T003 describes an alternative method of validation, which is the loop method. The method was first introduced by Roads and Maritime Services (RMS) New South Wales and has since been applied by many agencies. The method ensures the calibration of inertial profilers and installed instruments, evaluating driving consistency and assessing the accuracy of the operator to correlate data. The confidence limit in this method is selected as 95%, which guarantees the data acquisition from both devices are the same. The procedure requires five repeats, 100 m distances between each section and a length of road which should represent all the expected ranges of roughness.

The method requires a calibrated inertial profilometer as detailed in Section 2.2.1 and the RMS Calibration Loop. Other loops longer than 10 km which could represent an adequate range of roughness are also acceptable. The method also needs to have a reference dataset which is developed by averaging the results of an independent inertial profilometer (reference device) in five repeats at 100 m intervals. RMS ensures the validity of the reference data.

In this method, the single track IRI of both left and right wheelpaths are measured as described in Section 2.2.1. The lane IRI is also calculated using the same method. This should be repeated until five sets of measurement data are collected. If the RMS Roughness Calibration Loop is used, the total length is 175 km while it would be 50 km if another calibration road is used.

Excluding data for sections shorter than 100 m, the average roughness value of each 100 m section for all five repeats is calculated. The least squares method is utilised to define a line that best fits between the average 100 m results and the reference dataset. Also, the coefficient of determination of the line ($r^2$) should be identified. The line forms Equation 4:

$$r_{Average} = A.r_{Reference} + B \quad (4)$$

Then the average percentage difference is calculated by Equation 5:

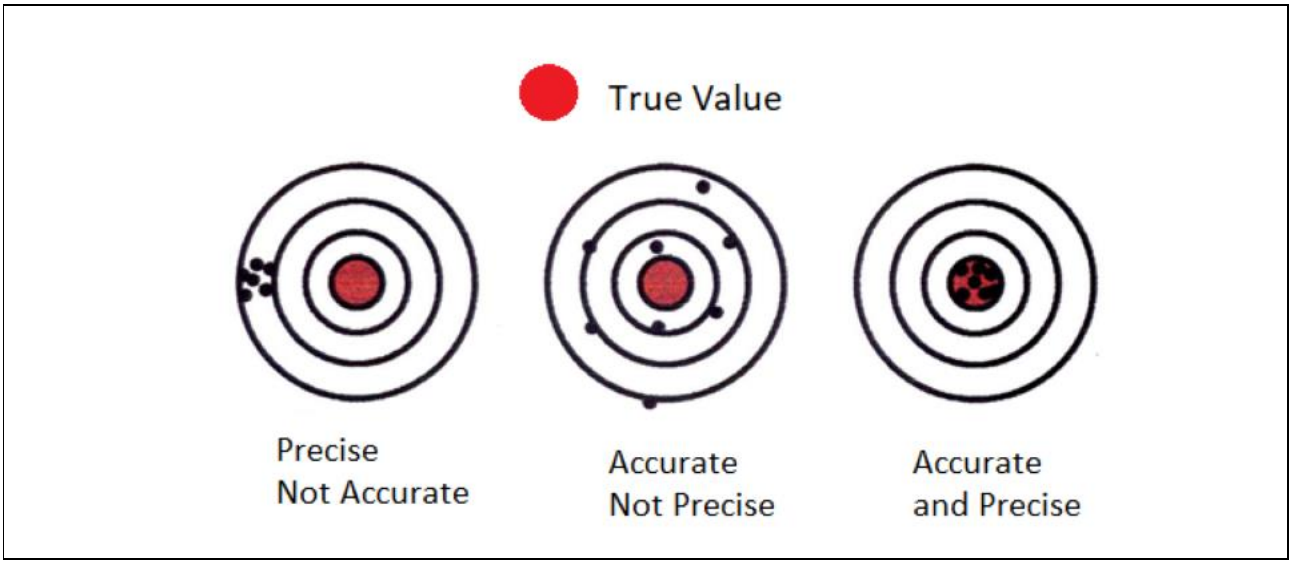
$$Average_{percentage_{difference}} = \frac{100}{n} \cdot \sum_{i=1}^{n} \frac{r_{Average} - r_{Reference}}{r_{Reference}} \quad (5)$$

where n is the number of 100 m sections. The profilometer is validated if the $r^2$ is above 95% and the average percentage difference calculated from Equation 5 is less than 5%.

### *2.2.4 Pavement Roughness Repeatability and Bias Checks for an Inertial Profilometer*

Austroads test method AG:AM/T004 explains a method to check repeatability and bias measurement for roughness measured by an inertial profilometer. This check identifies if there is a systematic drift in an inertial profilometer. The concept of systematic drift causes precise but inaccurate results. The concepts of accuracy and precision are shown in Figure 2.3.

**Figure 2.3: Precision versus accuracy in surveying context**




Source: https://keydifferences.com/difference-between-accuracy-and-precision.html.

For the repeatability check, the single track $IRI_{qc}$ of a clearly defined 100 m section of the road with a range of roughness is identified as described in Section 2.2.1. This is repeated until five sets of data are available. Then the coefficient of variation for each of the 100 m sections for each series of the repeated measurements is calculated using Equation 6:

$$S_n\% = 100 \cdot \frac{S_n}{X_n} \tag{6}$$

where

$S_n$ = $\sqrt{\frac{\sum_{i=1}^{N}(X_{ni} - \bar{X}_n)^2}{N-1}}$

$\bar{X}_n$ = $\frac{\sum_{i=1}^{N}\bar{X}_{ni}}{N}$

n = segment number

N = total number of measurements on segment n

$X_{ni}$ = roughness of segment from measurement i (with i =1 to N)

Then the average coefficient of variation for all the 100 m segments is calculated using Equation 7:

$$\bar{S}\% = \frac{\sum_{n=1}^{n_s} S_n\%}{n_s} \tag{7}$$

where

$n_s$ = total number of segments

Using the least squares method, a regression line is defined between individual roughness values for each segment and mean values for that segment and $r^2$ is determined. The repeatability checks pass if 95% of the reported coefficient of variation calculated in Equation 6 are less than or equal to 10%, while the average coefficient of variation calculated in Equation 7 is less than or equal to 5% and $r^2$ is above 95%.

For the bias error check, an IRI should be calculated on a lane of 10 km length which has enough range of roughness at 100 m sections. This is considered as the reference data. The test is repeated later, at a specified time, to produce a comparison dataset. The BE between the reference data and the comparison data is calculated using Equation 8:

$$\mathrm{BE} = \left|\frac{100}{n_s} \cdot \sum_{i=1}^{n_s}\left(\frac{\bar{X}_{Ri} - \bar{X}_{Ci}}{\bar{X}_{Ri}}\right)\right| \tag{8}$$

where

BE = bias error between the comparison and reference datasets

$\bar{X}_{Ri}$ = reference data mean roughness of segment i

$\bar{X}_{Ci}$ = comparison data mean roughness of segment i

If the BE calculated in Equation 8 is less than 1%, it is acceptable.

## 2.3 Rutting

Rutting depth of a section of the pavement characterises the transverse profile of that section and it can then be related to the structural performance of sublayers of that section. Rutting is defined as vertical depression in the longitudinal direction usually in a wheelpath of a road. The length to width ratio of a rut depth is usually above 4:1 (Austroads 2018). Figure 2.4 illustrates the typical shape of rutting in a road section.

Rutting can develop as a result of traffic loading and environmental conditions. Heavy truck loading can produce depressions on the asphalt and bituminous surface by compressing aggregate and therefore induce rutting in the section. On the other hand, infiltration of water to the subgrade or road shoulder can increase the moisture content and develop vertical depression in the subgrade soil which again induces rutting on the surface of the road.

**Figure 2.4: Rut depth**

Source: Austroads (2018).

### *2.3.1 Pavement Rutting Measurement with a Laser Profilometer*

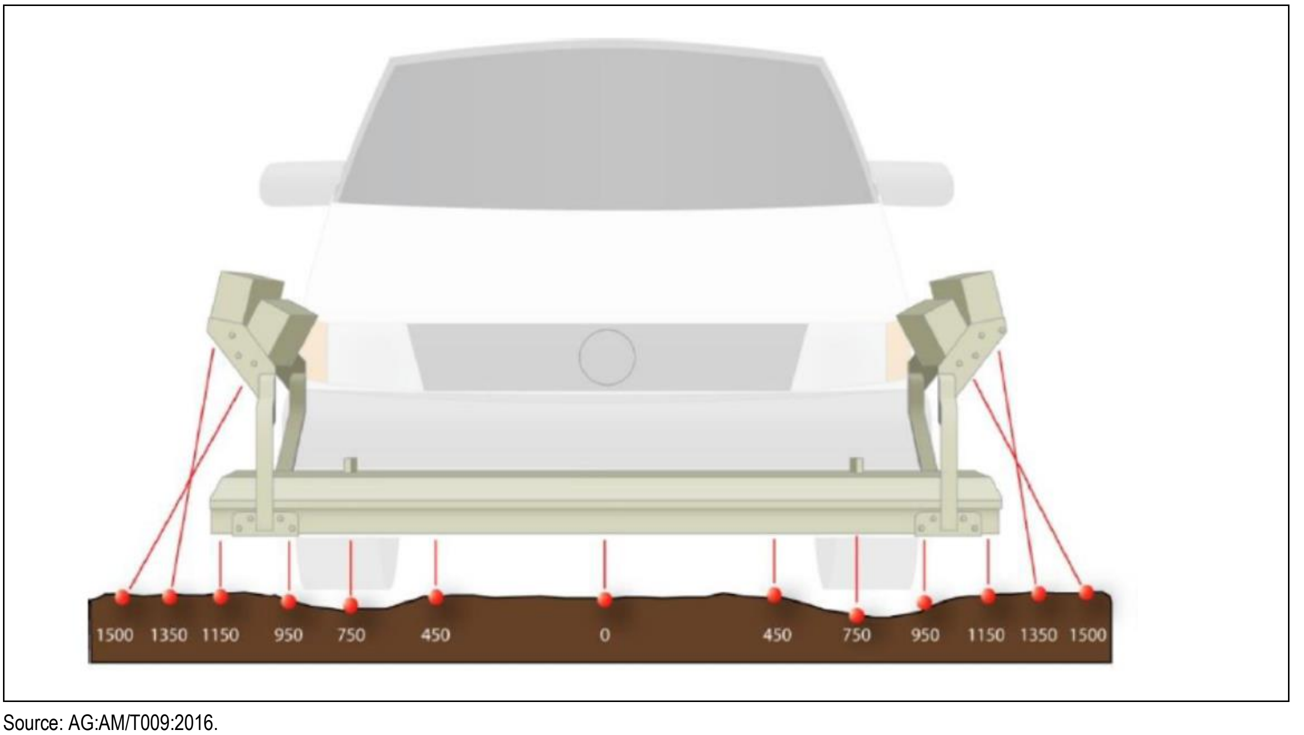
Austroads test method AG:AM/T009 explains the test method to measure rutting with laser profilometers. This device covers at least 3 m of transverse width of a road. Rutting measurement with a laser profilometer is usually conducted along with the roughness and texture depth tests.

The laser profilometer vehicle needs to be capable of carrying testing equipment and requires displacement transducers (laser devices). These are used to assess the distance between a horizontal datum and the travelled surface. The distance measuring transducer needs to be accurate within ±0.1%. The data logger records the data in intervals less than 250 mm.

Like roughness profile surveys, the profile rutting measurement is performed on the lane with the highest traffic, usually the slow lane on most roads. The vehicle needs to be driven smoothly and within the speed range defined by the manufacturer. Data is logged with reference to a pre-specified reference point. The surface profile of each wheelpath in the test lane is measured. This test cannot be performed in the rain or on wet road surfaces.

There are different laser transducer types that can be used for the laser profilometer. One is a multi-laser device. Austroads recommends a minimum of 11 lasers be used in order to cover a transverse direction of 3 m width. The number of lasers affects the quality of measurement and the width of measurements (Austroads 2018). For a multi-laser profiler, the number of lasers mounted on the survey vehicle will impact on both the level of detail of the transverse profile recorded and the width of the profile. Figure 2.5 presents the preferred configuration of lasers in a multi-laser profilometer.

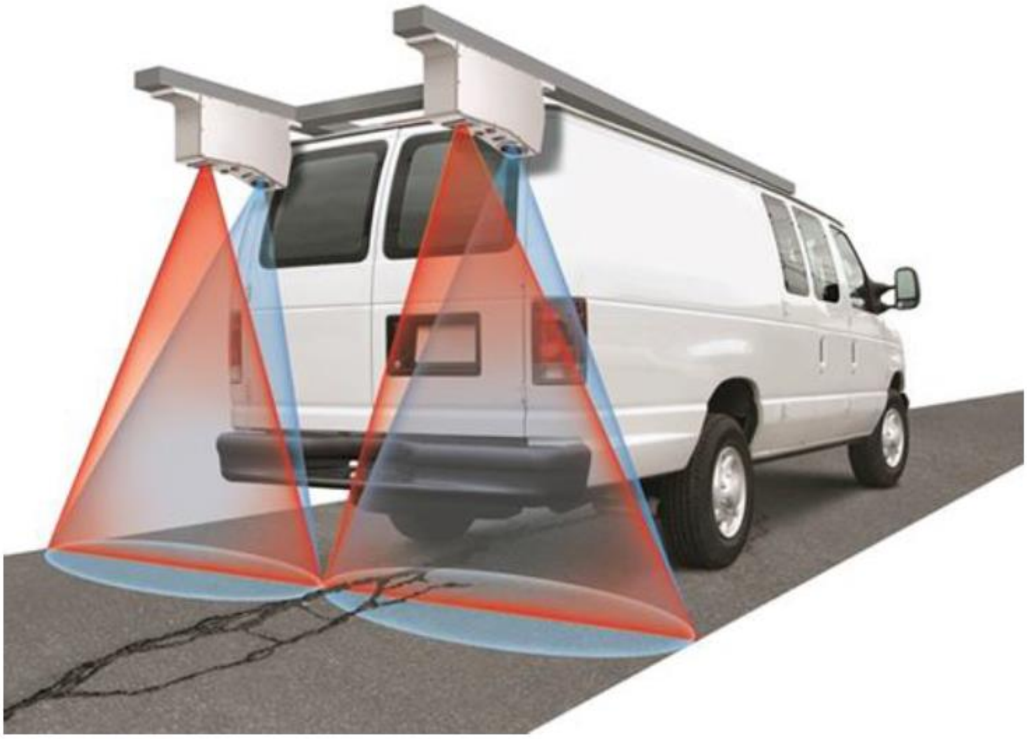
**Figure 2.5: Multi-laser profilometer configuration**




Source: AG:AM/T009:2016.

The other laser transducer type is a line-laser device. This device can measure more than 1000 points across the pavement surface. This leads to a high-quality measurement of the transverse profile. A line-laser device covers at least 3 m of the transverse width. Figure 2.6 illustrates a typical line-laser profilometer.

**Figure 2.6: Line-laser profilometer**

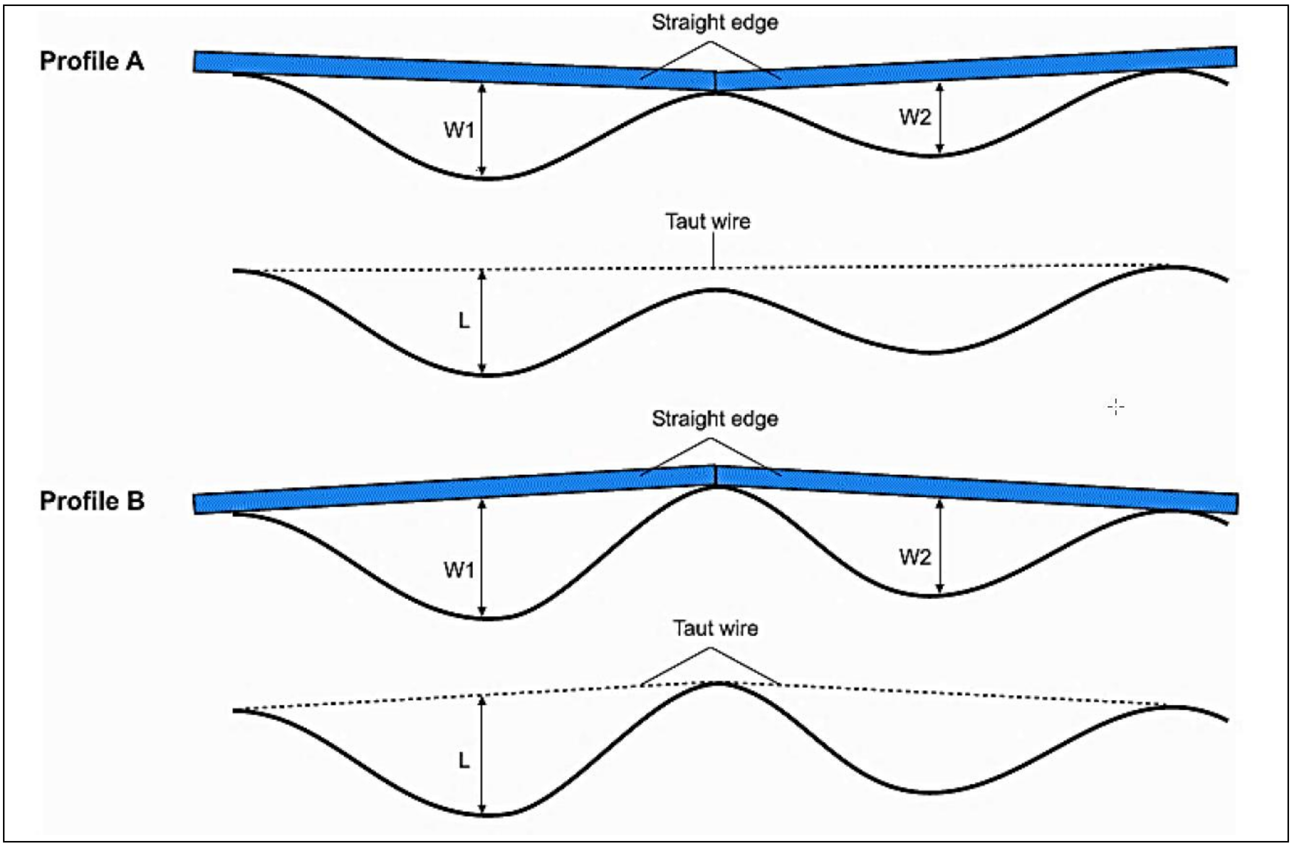


Source: AG:AM/T009:2016.

The calculation of rutting by a laser profilometer is based on either the calculation of rutting by the straightedge or taut wire model (Figure 2.7).

For the calculation of rut depth, the average maximum rut depth in each wheelpath should be recorded. The maximum can be in either of the two wheelpaths. The method assumes an imaginary straightedge between contact points moving across the transverse section. For each 100 m section, the standard deviation of rut depth measurement of each wheelpath is identified. Then the percentages of measured rut which falls in each of the rut bins are reported. Rut bins are defined from 0 to 40 mm with 5 mm increments. Each equipment manufacturer would have developed an algorithm to calculate rut depth. However, reported values should represent the expected values.

**Figure 2.7: Straightedge and taut wire model**




Source: AG:AM/T009:2016.

### *2.3.2 Validation of a Laser Profilometer for Measuring Pavement Rutting (Reference Device Method)*

There are two alternative ways to validate laser profilometers for rutting measurements. The first test method compares the results with the measurements from a static or manual reference device as described in Austroads test method AG:AM/T010.

This validation method requires a calibrated laser profilometer as detailed in Section 2.3.1, a calibrated reference device such as a transverse profile logger or a straightedge for manual measurement of rutting.

The first step of validation is the static validation method which evaluates whether the laser system is capable of measuring rut in the transverse direction with the required accuracy. Five specific locations on the wheelpath should be identified to cover different rut depths of 5 mm, 10 mm, 15 mm, 20 mm and 25 mm. Then the survey vehicle is placed over each of these specific locations and rut depth is measured by the laser system and is recorded. The range of rut depths is selected to ensure the profilometer can cover the range of expected rut depths in the whole road. In the case that these values are not representative of the actual test site, other representative values should be selected.

In addition to static validation, a comparative validation procedure should be conducted. Five specific sites with the length of 500 m or longer should be selected. The profilometer should be able to bring its speed up to the maximum test speed, nominally 100 km/h, in the section. The specific characteristics of sites ensure that pavement ruts ranging from 3 mm to above 15 mm are covered, and the sections are representative of the whole surveyed network. These characteristics are set to ensure reliable validation. It should be noted that the $r^2$ statistic parameter is significantly affected by the range of data used in the survey.

In each of these sites, the maximum rut depth in both wheelpaths should be measured by a laser profilometer. Then it should be measured at the same intervals or the half-intervals with a transverse profile logger, rod and level or straightedge. This should be repeated until five sets of data are available for each site at each of the three selected vehicle speeds.

The rut depth measured by a multi-laser profiler is reported in 1 m segments. The wheelpath rut depth from the reference in the closest 1 m segment is also reported. The set of data for each selected speed would have a total of 500 records (five test sections by two wheelpaths by ten 1 m segment intervals by five repeats). Then a line regression using the least squares method is fitted between the two sets of results using Equation 9:

$$RutDepth_{Base} = A \times RutDepth_{Profilometer} + B \qquad 9$$

where

| | | |
|---|---|---|
| $RutDepth_{Base}$ | = | rut depth calculated from the base reference measurement (i.e. either transverse profile logger, straightedge or rod and level) |
| $RutDepth_{Profilometer}$ | = | rut depth calculated from the operational laser profilometer |
| A, B | = | regression equation coefficients |

The coefficient of determination ($r^2$) should also be calculated. Then the whole dataset for all three speeds are grouped in one set (which has 1500 records) and the line regression and $r^2$ is calculated for this dataset as well.

The device is validated if the following conditions are achieved:

- Each measured rut depth in the static validation step are within ±1 mm or ±10%, whichever is the greater, of the assigned rut depths.
- For the laser profilometer, for all sets of data (with 500 records) and for the combined data (with 1500 records) $0.90 \le A \le 1.10$ and $-2.5 \le B \le 2.5$ mm. Also, $r^2$ should be above 90%.
- For manual measurement (such as a 2 m straightedge), for all sets of data (with 500 records) and for the combined data (with 1500 records) $0.85 \le A \le 1.15$ and $-3.0 \le B \le 3.0$ mm. Also, $r^2$ should be above 80%.

### *2.3.3 Validation of a Laser Profilometer for Measuring Pavement Rutting (Loop Method)*

Austroads test method AG:AM/T011 describes the alternative method for laser profilometer validation. The method was first introduced by RMS and has been applied by many agencies since. The method ensures the calibration of an inertial profiler and its installed instruments, evaluates the driving consistency and assesses the accuracy of the operator to correlate data. The confidence limit in this method is selected as 90% which warrants that the data acquisition from both devices is the same. The procedure requires five repeats, 100 m distance between each section and a length of road which should represent the expected range of roughness.

The method requires a calibrated inertial profilometer as detailed in Section 2.2.1 and the RMS Calibration Loop. Other loops longer than 10 km which could represent an adequate range of rutting is also acceptable. The method also needs to have a reference dataset which is developed by averaging the results of an independent inertial profilometer (reference device) in five repeats on 100 m intervals. RMS ensures the validity of the reference data.

In this method, the rut depth of both left and right wheelpaths is measured as described in Section 2.3.1. This should be repeated until five sets of measurement data are collected. If the RMS Roughness Calibration Loop is used this leads to a length of 175 km while it would be 50 km if another road is used.

Excluding data for sections shorter than 100 m, the average rut depth value of each 100 m section for all the five repeats is calculated. The least squares method is utilised to define a line that best fits between the average 100 m results and the reference dataset. Also, the coefficient of determination of the line ($r^2$) should be identified. The line forms Equation 10:

$$r_{Average} = A.r_{Reference} + B \quad (10)$$

Then the average percentage difference is calculated by Equation 11:

$$Average_{percentage_{difference}} = \frac{100}{n} \cdot \sum_{i=1}^{n} \frac{r_{Average} - r_{Reference}}{r_{Reference}} \quad (11)$$

where n is the number of 100 m sections. The profilometer is validated if the $r^2$ is above 90% and the average percentage difference calculated from Equation 11 is less than 10%.

### *2.3.4 Pavement Rutting Repeatability and Bias Error Checks for a Laser Profilometer*

Austroads test method AG:AM/T012 explains a method to check repeatability and bias measurement for rutting measured by an inertial profilometer. This check identifies if there is a systematic drift in an inertial profilometer.

For a repeatability check, the rut depth of a clearly defined 100 m section of the road with a range of rutting should be identified as described in Section 2.3.1. This should be repeated until five sets of data are available. The coefficient of variation for each of the 100 m sections for each series of repeated measurements should be calculated using Equation 12:

$$S_{nw}\% = 100 \cdot \frac{S_{nw}}{\bar{X}_{nw}} \qquad 12$$

where

$S_{nw}$ = $\sqrt{\frac{\sum_{i=1}^{N}(X_{nwi} - \bar{X}_{nw})^2}{N-1}}$

$\bar{X}_{nw}$ = $\frac{\sum_{i=1}^{N}\bar{X}_{nwi}}{N}$

w = wheelpath

$n_s$ = segment number

N = twice the total number of measurements on segment n

$X_{nwi}$ = rut depth of wheelpath w, segment n from measurement i (with i =1 to N)

Then the average coefficient of variation for all the 100 m segments is calculated using Equation 13:

$$\bar{S}\% = \frac{\sum_{n=1}^{n_s} S_n\%}{n_s} \qquad 13$$

where

w = wheelpath

$n_s$ = segment number

Using the least squares method, a regression line should be defined between individual rutting values for each segment and mean values for that segment and $r^2$ is determined. The repeatability checks pass if 90% of reported coefficients of variation calculated in Equation 12 are less than or equal to 10% while the average of the coefficients of variation calculated in Equation 13 is less than or equal to 10% and $r^2$ is above 90%.

For the bias error check, a rut depth should be calculated on a lane of 10 km length which has enough range of rutting at 100 m sections. This is considered the reference data. The test is repeated later, at a specified time, to produce a comparison dataset. The bias error between the reference data and the comparison data is calculated using Equation 14:

$$\text{BE} = \left|\frac{100}{n_s} \cdot \sum_{w=1}^{2}\left[\sum_{i=1}^{n_s}\left(\frac{\bar{X}_{Rwi} - \bar{X}_{Cwi}}{\bar{X}_{Rwi}}\right)\right]\right| \qquad 14$$

where

BE = bias error between the comparison and reference datasets

$\bar{X}_{Rwi}$ = reference data mean rut depth of wheelpath w, segment i

$\bar{X}_{Cwi}$ = comparison data mean rut depth of wheelpath w, segment i

w = wheelpath

$n_s$ = total segment numbers

The bias error check passes if BE calculated in Equation 14 is less than 5%.

## 2.4 Texture

It should be noted that texture depth is not directly representative of skid resistance, however, the two terms are often looked at together. Texture also plays an important role in surface drainage, which is in turn a contributor in road safety.

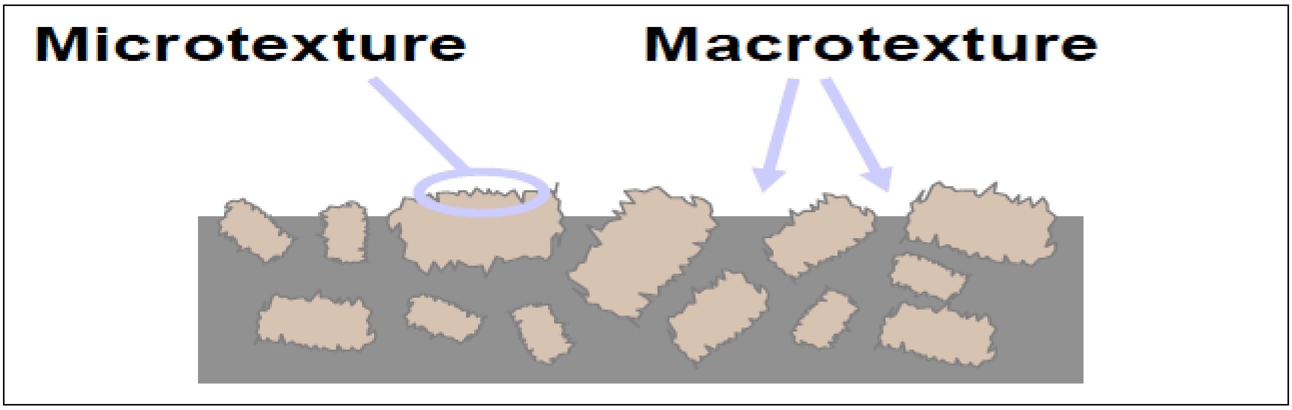
A variety of methods have been used to identify surface texture. This includes the sand patch technique and laser profilometer.

The World Road Association (WRA) has defined four different textures as illustrated in Figure 1.2. The effects on the pavement are as follows:

- Microtexture is defined as the amplitude of deviations from the surface plane with wavelengths less than or equal to 0.5 mm. The texture on this scale is produced by grain surface or sand size particles. This microtexture affects skid resistance by providing friction between tyre and pavement surface. For example, a very high level of microtexture can result in tyre wear.
- The level of microtexture determines the severity of the water film effect on friction and skid resistance. Having higher texture depth can reduce the effect of water film.
- The microtexture itself is experiencing the polishing effect when subjected to traffic loading. Polishing of the aggregate surface leads to a loss of friction. The polishing of aggregate due to traffic loading still has not been verified for Australian conditions and research on this subject is required.
- Macrotexture covers the range of wavelengths between 0.5 mm and 50 mm. Macrotexture is determined by the size, shape and spacing of coarse aggregate particles. Macrotexture also contributes to both tyre-surface friction and water drainage.
- Macrotexture can be either positive or negative (Jellie 2003). If the aggregate surface is exceeding the plane surface of the pavement it is positive. If there are voids between the flat plane of the road surface and aggregate, it is negative texture. Such negative texture can be seen in mastic asphalt surfaces or porous asphalt.
- Surface texture is commonly used to address the macrotexture of the pavement surface. Another important parameter used by practitioners is surface texture profile.
- Megatexture has less significant influence on the road surface friction.

Figure 2.8 shows the nature of macrotexture versus microtexture.

Figure 2.8: Microtexture and macrotexture




Source: Austroads (2018).

The surface friction is deemed to be related to surface texture. Therefore, road agencies have developed standards to ensure high levels of texture (macrotexture) on the road surface. According to Austroads (2019) Minimum Mean Texture Depth should be above 0.6 mm on highways and major roads, and above 0.4 mm on other roads.

A combination of factors can influence the tyre surface interaction and driving safety, including:

- the speed of the vehicle
- the macrotexture of the road surface and its profile
- the depth of the water film on the surface
- tyre characteristics including tyre pressure and tread depth
- existence of surface contaminants including debris and mud.

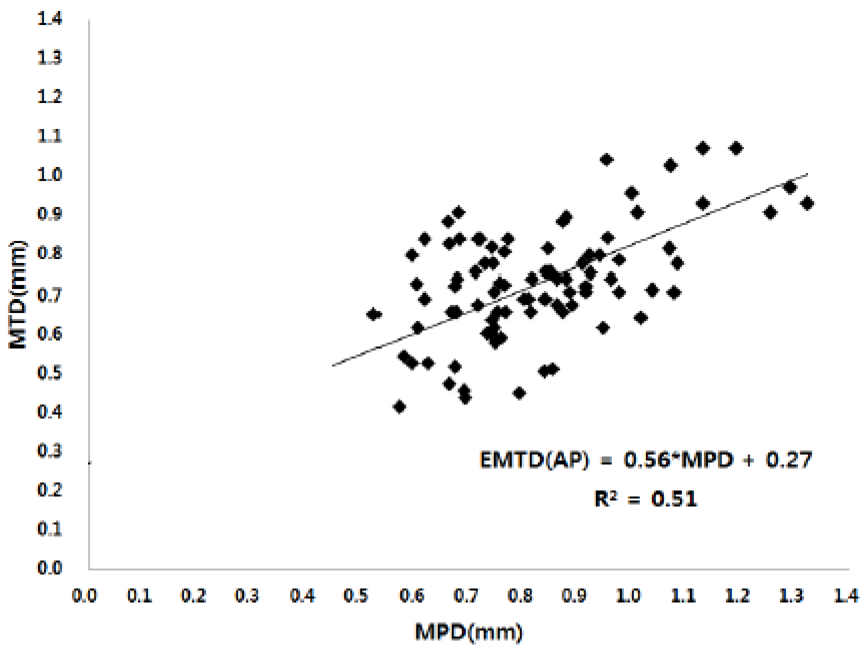
### *2.4.1 Pavement Surface Texture Measurement with a Laser Profilometer*

Austroads test method AG:AM/T013 describes the direct measurement of surface macrotexture by laser profilometer. There are two ways to record macrotexture of pavement surface. One is using Mean Profile Depth (MPD) and the other is Sensor Measured Texture Depth (SMTD). Each uses specific equipment and calculation.

Any single test output from this method is in fact an average of surface texture over a specific length of road (can be 20 m or 100 m sections). Texture measurement using this test method is usually conducted along with rut depth measurement and roughness measurements as described in Section 2.2.1 and Section 2.3.1 of this report. This is one of the significant advantages of using laser profilometers which can significantly save time and facilitate better asset management at the network level.

Pavement roughness measurement with an inertial profilometer has been studied by Freitas et al. (2008). Based on this research, results of MPD and SMTD from different laser profilometers were consistent. However, acceptable correlation could not be established between MPD or SMTD and mean texture depth. Conversely, it was reported that a strong correlation between SMTD and MPD existed in the range of 0.6 to 1.1. A similar conclusion was also drawn by Kim et al. (2013). Figure 2.9 illustrates a typical relationship between Mean Texture Depth (MTD) and Mean Profile Depth (MPD) found by their research.

**Figure 2.9: Relationship between Mean Texture Depth and Mean Profile Depth**




Source: Kim et al. (2013).

In summary, bear in mind that although practitioners are using MPD and SMTD to define texture depth, there may not be strong linear relationships. For example:

- Mean Profile Depth (MPD) is the mean of measured macrotexture on the small segments of pavement surface usually 100 mm long. These segments are analysed and the average mean value for a specific length of pavement is reported.
- Sensor measured texture depth (SMTD) is a continuous measure of macrotexture on segments of pavement 280 mm long. Averaged values of the SMTD for each segment are reported for each length of surveyed pavement.
- Surface profile is defined as a 2D model of the road surface shape measured perpendicular to the surface plane and recorded at equivalent intervals in the traffic direction.
- Volumetric texture measurement is a manual method of texture measurement. This method is conducted by spreading a known mass or volume of sand (or spherical glass) over the surface of the road. Then the ratio of the mass to the covered area in the shape of a circle gives the average texture depth (Refer to Austroads test method AGPT/T250).

The testing vehicle should be able to transport the surface profile measuring equipment, while working at a range of speeds, to the limit of the operating range of the surface profile measuring equipment. Austroads requires laser profilometers to have the following characteristics:

- The profiler should be equipped with a laser-based displacement transducer operating at sufficient speed to measure the distance between the laser and the travelled surface, at the specified interval (≥ 32 kHz for MPD and ≥ 16 kHz for SMTD). The spot size of the laser must be less than or equal to the specified sampling interval.
- Two locations are to be measured which are between the wheelpath of the vehicle (midpoint) and anywhere out of the vehicle range between 750 mm up to 1100 mm.

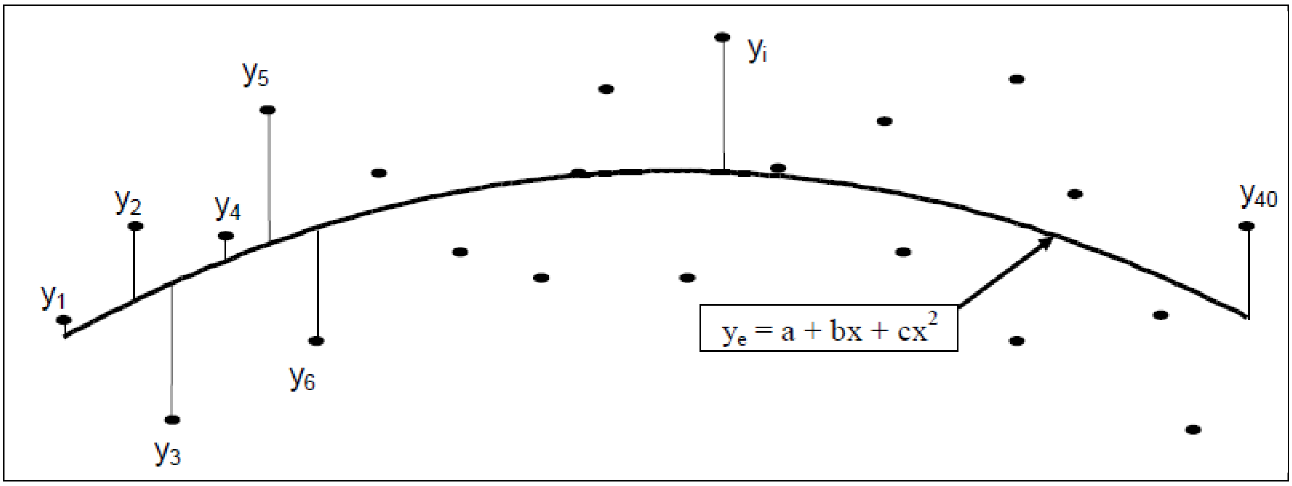
- The distance measuring transducer is required to measure distance with an accuracy of ±0.1%. The travelled distance should be transferred to a data logger from the start of the survey.
- The data logger collects data at equivalent speed within the wavelengths of 0.5 to 50 mm. Also, intervals between samples should not exceed 1 mm for MPD and 10 mm for SMTD.
- The profiler is required to have a processing computer to calculate MPD and SMTD according to the calculation methods described in this section.

In this procedure the lane to be surveyed is labelled as the test lane. This test lane is defined as the lane with the highest traffic loading unless otherwise directed. The surveying vehicle is driven in the usual traffic wheelpaths. The manufacturer's operational speed is to be followed. The driving should be in a smooth and careful manner. The start point of the survey should be identified before the survey and all the points should be collected in reference to this pre-specified reference point. All pavement defects should be profiled and should not be avoided during the survey unless it may introduce a safety issue.

The MPD is calculated based on the method introduced in ASTM E1845:2015 or ISO 13473-1:2019. In this method instead of linear regression, parabolic curve fitting is used. For each transverse location the following steps should be conducted:

- The surface profile is divided into segments with 40 contiguous samples. The resultant base length of the segment then is 40 times the sample interval. A sample interval of 7 mm is recommended or as close as possible to this value.
- A parabolic fit (2$^{nd}$ polynomial curve) is fitted to the data (see Figure 2.10) this parabola is called $y_e$ and is calculated using quadratic least squares regression for the 40 contiguous samples ($y_i$). The difference between these two is calculated as well ($y_i – y_e$).

**Figure 2.10: Calculating sensor measured texture depth**




Source: AG:AM/T013:2016.

- Calculate SMTD according to Equation 15. It should be noted that the SMTD is equal to the root mean square value of the residuals for each segment.

$$\text{SMTD} = \sqrt{\frac{\sum_{i=1}^{40}(y_i - y_e)^2}{40}} \quad (15)$$

- Sum each value of SMTD and report the calculated mean value of each test interval. Test intervals should be less than or equal to 100 m in length.

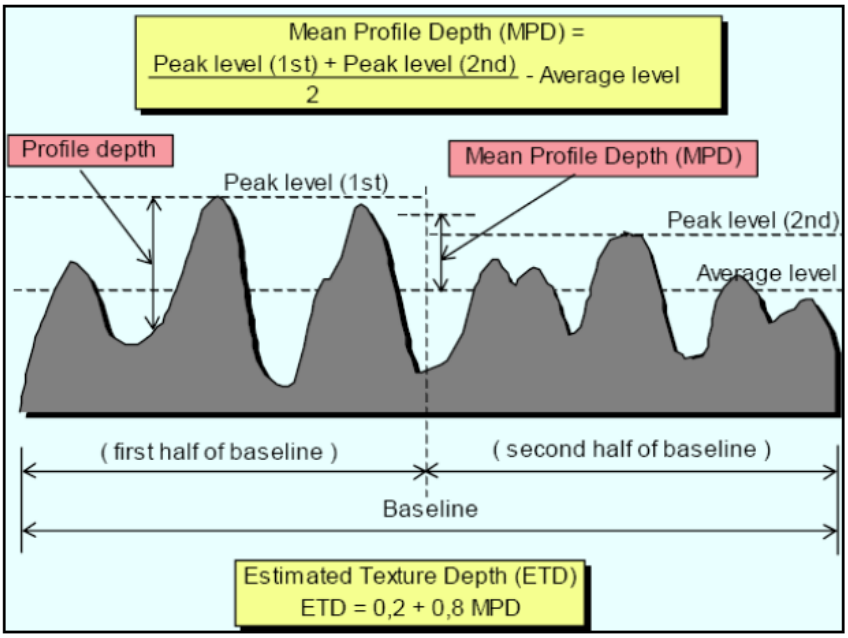
As previously stated, MPD and SMTD can be correlated to an equivalent volumetric sand patch texture depth. MPD can also be directly estimated from SMTD. This requires that a relationship between SMTD and sand patch texture depth (SPTD) be established first. SPTD is also known as estimated texture depth (ETD) and Austroads suggests that it can be obtained from Equation 16:

$$\text{ETD} = 0.8 \times MPD + 0.2 \quad (16)$$

It should be noted that other research has also found a strong linear relationship between MPD and ETD, however, with different coefficients (Freitas et al. 2008, Kim et al. 2013).

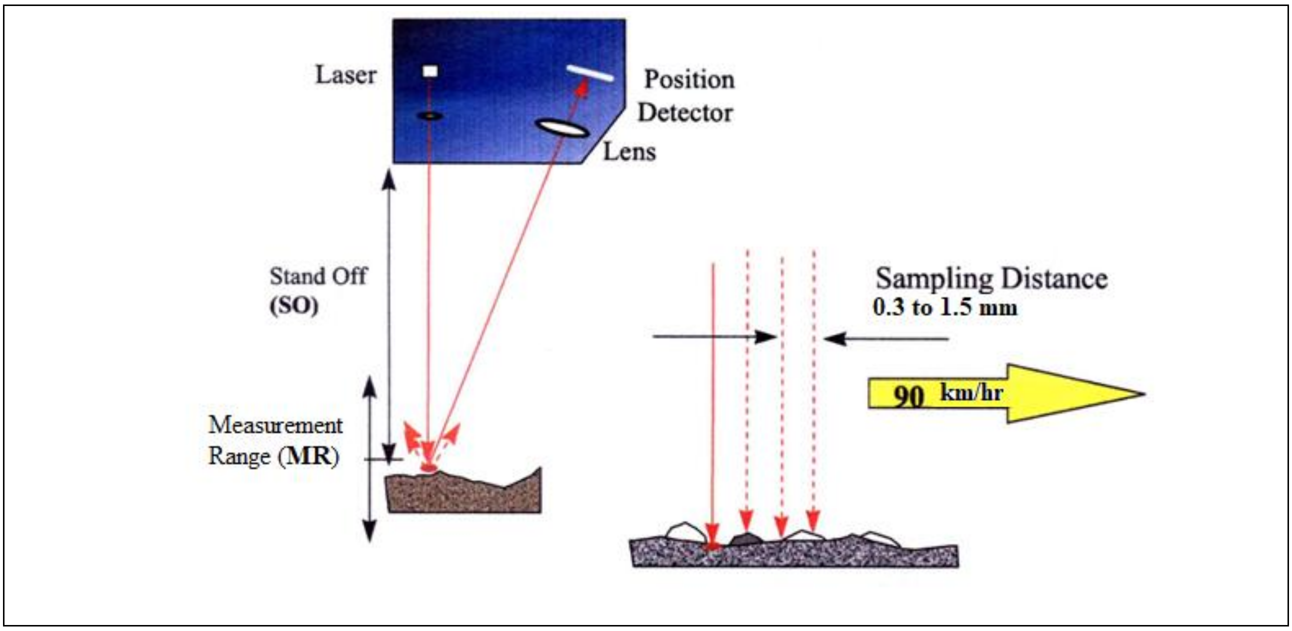
Figure 2.11 represents the concept of MPD and ETD schematically. Figure 2.12 shows how a laser lens collects the texture depth in the surveying vehicle.

**Figure 2.11: Illustration of the concepts of base line, profile depth and the texture indicators mean profile depth and estimated texture depth (in millimetres)**




Source: ISO 13473-1:2019.

**Figure 2.12: Triangulation used for height measurement**




Source: Olivier & van Aswegen (2013.).

### *2.4.2 Validation of a Laser Profilometer for Measuring Pavement Surface Texture (Reference Device Method)*

Austroads test method AG:AM/T014 describes the test method for performing validation checks of the measurements of pavement surface macro-texture determined using a laser profilometer. There are two alternative ways to validate laser profilometers for texture measurements. The first test method compares the results with the measurements from a static or manual reference device.

This validation method requires a calibrated laser profilometer as detailed in Section 2.4.1 and a calibrated reference device such as sand patch or other volumetric measurements.

Five locations each at least 200 m in length should be selected. These locations should cover the range of texture depths from 0.5 mm to 3.0 mm. One of these sections should have a texture depth of below 0.8 mm and one above 3.2 mm. The surfaces of the selected sections should be representative of a typical surface of the roads to be surveyed. The profilometer should bring its speed up to the maximum test speed, nominally 100 km/h in the section. These characteristics are set to ensure reliable validation. Note: the $r^2$ statistic parameter is significantly affected by the range of data used in the survey.

In each of these sites, the texture depth in both wheelpaths is measured by a reference device. If a device such as the WDM Texture Meter is being used, this step must be repeated to collect two sets of data in each of the measurement paths. The surface texture is the average of these two sets.

In the volumetric method, the selected sections are 20 m lengths and the results are reported each 10 m. The texture depth is measured between the wheelpaths and in the left or right wheelpath. A sand patch test should be conducted at 0.5 m intervals, and the results averaged on a 10 m long section.

The laser profilometer is used to record the surface texture in each 100 m segment of all 200 m sections. For each of the three selected speeds, all surface texture data is grouped into one dataset of 100 records (one speed x five test sections x two chainages per section x five repeat survey runs per section x two measurement paths). Then a linear regression will be fitted to the data according to Equation 17:

$$t_{Base} = A \times t_{Profilometer} + B \quad (17)$$

where

| | | |
|---|---|---|
| $t_{Base}$ | = | texture calculated from the base reference measurement (i.e. WDM Texture Meter 2, or Stationary Laser Profiler) |
| $t_{Profilometer}$ | = | texture calculated from the operational laser profilometer |
| B | = | regression equation intercept |

The coefficient of determination ($r^2$) should also be calculated. Then the whole datasets for all three speeds are grouped in one set (which has 300 records) and the line regression and $r^2$ are calculated for this dataset as well.

For the volumetric method, all the above procedures are repeated, but the results from the laser profilometer and the volumetric sand patch are reported in 10 m intervals rather than 100 m.

For validation of speed, the surface texture is averaged for all speeds in five repeat survey runs. The mean surface texture values for each 100 m segment are compared and the maximum variation is reported. Then the variation is averaged for all test sites.

The device is validated for the reference device method if the following conditions are achieved:

- For all sets of data (with 100 records) and for the combined data (with 300 records) $0.95 \le A \le 1.05$ and $-0.25 \le B \le 0.25$ mm and $r^2$ should be above 95%.

The device is validated for the volumetric method if the following conditions are achieved:

- for all sets of data (with 100 records) and for the combined data (with 300 records) $0.90 \le A \le 1.10$ and $-0.25 \le B \le 0.25$ mm and $r^2$ should be above 85%.

The surface texture measurements should not vary with speed. It is considered unaffected by speed if the following conditions are achieved:

- The average variation value is within ±0.2 mm for MPD and ±0.15 mm for SMTD.

### *2.4.3 Validation of a Laser Profilometer for Measuring Pavement Surface Texture (Loop Method)*

Austroads test method AG:AM/T015 describes an alternative method for laser profilometer validation in texture measurement. The method was first introduced by RMS and has been applied by many agencies since. The method ensures the calibration of an inertial profiler and installed instruments, evaluates the driving consistency and assesses the accuracy of the operator to correlate data. The confidence limit in this method is selected as 95%. The procedure requires five repetitions, 100 m distance between each section, and a length of road which represents all the expected range of surface texture.

The method requires a calibrated inertial profilometer as detailed in Section 2.2.1 and the Roads and Maritime NSW Roughness Calibration Loop. Other testing loops longer than 10 km which could represent adequate ranges of texture are also acceptable. The method also needs to have a reference dataset, which is developed by averaging the results of an independent inertial profilometer (reference device) in five repeats at 100 m intervals. RMS ensures the validity of the reference data.

The laser profilometer then follows the method explained in Section 2.4.1 and measures the surface texture in the left wheelpath and between the wheelpaths. This is repeated until five sets of data are recorded.

Excluding the data for sections shorter than 100 m, the average texture value of each 100 m section for all the five repeats is calculated. The least squares method is utilised to define a line that best fits between the average 100 m results and the reference dataset. Also, the coefficient of determination of the line ($r^2$) should be identified. The line forms Equation 18:

$$r_{Average} = A.r_{Reference} + B \qquad 18$$

Then the average percentage difference is calculated by Equation 19:

$$Average_{percentage_{difference}} = \frac{100}{n} \cdot \sum_{i=1}^{n} \frac{t_{Average} - t_{Reference}}{t_{Reference}} \qquad 19$$

where

$t_{Average}$ = average surface texture of five repeat runs for the 100 m section

$t_{Reference}$ = reference surface texture of the 100 m section from the reference data

n = twice the total number of 100 m sections in the analysis

The profilometer is validated if the $r^2$ is above 95% and the average percentage difference calculated from Equation 19 is less than 5%.

### *2.4.4 Pavement Surface Texture Repeatability and Bias Error Checks for a Laser Profilometer*

Austroads test method AG:AM/T016 defines the procedure for conducting repeatability and bias of measurement checks for pavement surface texture measurements made by a laser profilometer.

The bias check included in this method is used to determine whether there is a systematic drift in a laser profilometer's measurements over time. It does not cover the collection of reference data from a separate measurement device.

For the repeatability check, the surface texture depth of a clearly defined 100 m section of the road with a range of texture should be identified as described in Section 2.4.1. This should be repeated until five sets of data are available. Then the coefficient of variation for each of the 100 m sections for each series of repeated measurements should be calculated using Equation 20:

$$S_{nm}\% = 100 \cdot \frac{S_{nm}}{\bar{X}_{nm}} \qquad 20$$

where

$S_{nm}$ = $\sqrt{\frac{\sum_{i=1}^{N}(X_{nmi}-\bar{X}_{nm})^2}{N-1}}$

$\bar{X}_{nm}$ = $\frac{\sum_{i=1}^{N}\bar{X}_{nmi}}{N}$

m = measurement path

n = segment number

N = total number of measurements in measurement path m on segment n

$X_{nmi}$ = texture of measurement path m, segment n from measurement i (with i = 1 to N)

Then the average coefficient of variation for all the 100 m segments is calculated using Equation 21:

$$\bar{S}\% = \frac{\sum_{m=1}^{m_t}\left[\sum_{n=1}^{n_s} S_n\%\right]}{N} \quad (21)$$

where

m = measurement path

$m_t$ = number of measurement paths

$n_s$ = total number of segments

N = $n_s \times m_t$

Using the least squares method, a regression line is defined between individual texture values for each segment and mean values for that segment and $r^2$ is determined.

The repeatability checks pass if:

- 95% of the standard deviations for each measurement path and 100 m segment for each series of repeat measurements are less than or equal to 0.15 mm.
- 95% of the coefficients of variation for each measurement path and 100 m segment for each series of repeat measurements are less than or equal to 10%.
- All the coefficients of determination $r^2$ are equal to or greater than 95%.

For the bias error check, a surface texture should be calculated on a road of 10 km length which has enough range of texture at 100 m sections. This is considered as the reference data and the test is conducted one more time for the purpose of comparison. Then the bias error between the reference data and the comparison data is calculated using Equation 22 :

$$\mathrm{BE} = \left| \frac{100}{N} \cdot \sum_{m=1}^{m_t} \left[ \sum_{i=1}^{n_s} \left( \frac{\bar{X}_{Rmi} - \bar{X}_{Cmi}}{\bar{X}_{Ri}} \right) \right] \right| \qquad 22$$

where

| | | |
|---|---|---|
| BE | = | bias error between the comparison and reference datasets |
| $\bar{X}_{Rmi}$ | = | reference data mean texture depth of measurement path m, segment i |
| $\bar{X}_{Cmi}$ | = | comparison data mean texture depth of measurement path m segment i |
| m | = | measurement path |
| $m_t$ | = | number of measurement paths |
| $n_s$ | = | total number of segments |
| N | = | $n_s \times m_t$ |

The bias error check passes if BE calculated in Equation 22 is less than 5%.

# 3 MAIN ROADS METHODS

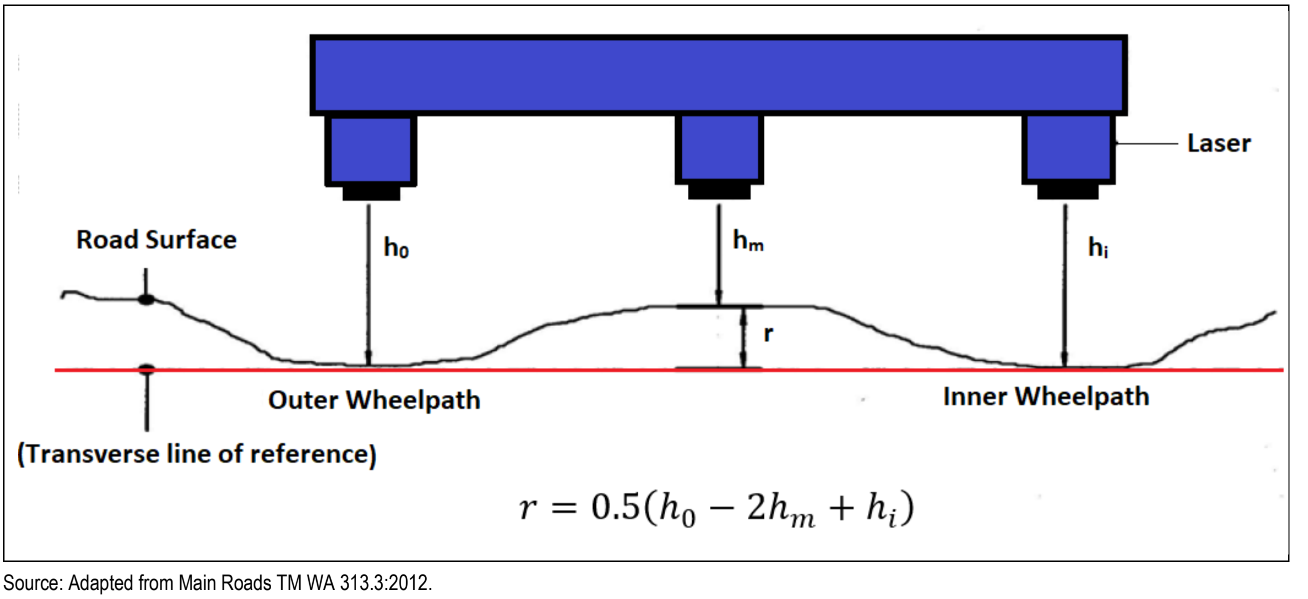
Main Roads mainly has been using its in-house test methods to assess roughness, rutting and texture depth. In the following sections these methods are reviewed.

## 3.1 Roughness and Rutting

Test method WA 313.3:2012 describes the pavement roughness and rutting measurement using a laser profilometer. In this method measurements are made in terms of National Research Council (NRC) and IRI. The method was developed based on test method T187 *Measurement of Ride Quality of Road Pavements by Laser Profiler*.

In this test method the rutting index is estimated from three longitudinal profiles. These three profiles consist of two outer profiles which are 1.50 m distance from each other and a third one in the centre. Figure 3.1 shows the location of these three profiles schematically. The height of the two outer profiles should be averaged and subtracted from the central one. If this number is a positive number (which means, there is a depression on the pavement surface) then it is reported as rutting index. In this method, the measurement lane is the trafficable lane within a pavement, for which measures of pavement conditions are taken. Segment is defined as a variable length of a measured lane.

**Figure 3.1: Profilometer beam**




Source: Adapted from Main Roads TM WA 313.3:2012.

Main Roads WA has adapted test method T187 from Road and Traffic Authority (RTA) of New South Wales to be followed for roughness and rutting measurement using a laser profilometer. The rutting index (r in Figure 3.1 ) is an extra option in this test method which is available in the software. In each segment, a single value resulting from the average of all roughness or rutting indices in that segment is reported.

RTA test method T187 requires laser-based non-contact displacement transducers for vertical distance measurement to the road surface, an accelerometer for vertical acceleration measurement and a horizontal linear distance measurement device with the accuracy of ±0.1%.

The test method specifies that data be collected with reference to the ROADLOC system and the distance measurement set to zero at each ROADLOC control point. This will prevent an accumulation of error in recording distance.

The surveying section is divided into 100 m segments. The surveying vehicle should be able to operate at all speed ranges in each tested section. The measurement of surface is conducted on each wheelpath while the vehicle is in the centre of the tested lane. In this test method, the procedure is repeated until three sets of data are recorded. The average IRI and NRC in each 100 m segment are reported. The surveying system is required to record distance to an accuracy of ±0.1%. The distance transducer is calibrated by recording a known distance of 1 km while driving. The recorded distance should be within 999 m to 1001 m. The calibration factor then is calculated and applied to all following measurements.

Vertical displacement transducers are calibrated after any change that can influence the vertical position of the vehicle including wheel or tyre adjustment. The accepted tolerance on all dimensions of the gauge block is within ±0.2 mm. If the measured value is within ±0.5 mm, a scale factor can be accepted. The recommended size for the gauge block is 25 mm × 50 mm × 100 m. In addition, the gauge block and base plate should not be reflective.

Roughness data in terms of IRI and NCR is to be reported each kilometre as a whole number. The interval in reporting is 100 m and if the final interval is less than 100 m it is omitted from the report.

The operational verification is conducted according to a bounce test and NCR/km equal or less than 5 is within the accepted range of verification. A flat plate is used for transducer calibration.

Two validation passes are required in this method. In the first, a roughness test from the proposed operational profilometer calculated in each 100 m is plotted against reference data and the $r^2$ is calculated from the correlation of these two sets of data. This $r^2$ must be equal or greater than 0.95. The second pass requires calculation of the average percentage difference as in Equation 23:

$$\text{Average percentage difference} = \frac{\sum_1^n \frac{A_n - B_n}{B_n} \times 100}{n} \tag{23}$$

where

$A_n$ = average of five readings of roughness of $n^{th}$ 100 m segments, evaluated by the roughness measuring device

$B_n$ = RMS reference roughness value for $n^{th}$ 100 m segments

$n$ = total number of 100 m segments

It passes if the average percentage difference is within 5%.

## 3.2 Texture

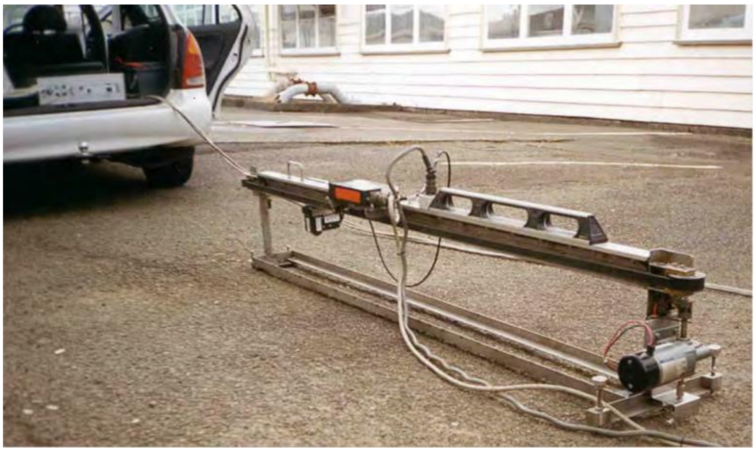
Test method WA 311.2:2012 describes measurement of surface texture using a stationary laser profilometer (SLP). This is the electronic equivalent of the manual sand patch method to calculate texture depth of the road surface (test method WA 311.1:2012). Figure 3.2 depicts the two methods.

This method requires a stationary laser profilometer, laptop computer, data acquisition system, data processing software (Main Roads SLP processing software – advanced.vi), calibration block, measuring tape, distance measuring wheel and road marking paint. Main Roads WA has a specific set-up procedure for the stationary laser profilometer as outlined in WA 311.2:2012. Once the surveying vehicle is set up correctly, the set-up should be calibrated. A saw tooth calibration block is used to collect a calibration file. Then the calibrated data is saved in the data acquisition system (DAS). The calibration file is checked to see if MPD is within 10 mm ± 0.05 mm. Once the calibration is conducted, the SLP can be used in testing. SLP is manoeuvred in the test location using the wheel, rested on its legs and the road surface is scanned. The initiation point and stopping point are recorded.

The scan length reported by software has 100 mm intervals and the last interval less than 100 mm will be disregarded. Multiple adjoining scans are conducted by repeating the same process. The SLP frame is moved along the road in scan length intervals (usually 1400 mm). Main Roads WA uses inbuilt data processing in the vehicle to produce the texture depth report.

Main Roads WA does not have any specified method to measure MPD, while these methods exist in Austroads and are described in Section 2.4 of this report.

**Figure 3.2: SLP (left) versus sand patch method (right)**



Source: Patrick, Cenek and Owen (2000) (left); Hanson and Prowell (2005) (right).

## 3.3 Surface Shape

Test method WA 313.2:2012 describes measurement of surface shape using a straightedge. It should be noted that this test has not been mentioned in Austroads documents and it is a specific requirement from Main Roads WA. Surface shape measurement consists of five measurements, which are defined by Main Roads WA as follows:

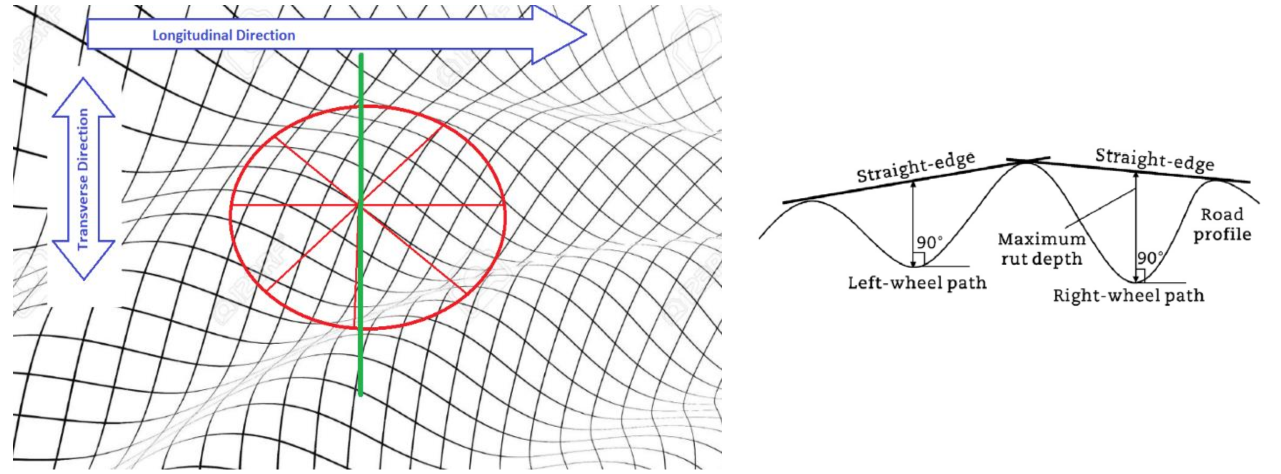
- Rut – a vertical deformation of a pavement surface formed by the wheels of vehicles.
- Transverse surface profile – the shape of a pavement surface measured in a vertical plane transverse to the traffic flow.
- Crossfall – the slope, at right angles to the alignment, of the surface of any part of a carriageway.

- Shoving – lateral displacement of pavement structure by braking, accelerating or turning vehicles.
- Maximum deviation from straightedge – the greatest deviation (space) between the top of a road surface and the lower side of a straightedge placed on the road surface.

Therefore, maximum deviation measurement indicates the maximum deflection from the designed road surface in all possible road profile directions, while rut depth is the maximum depression of the surface in the transverse profile of the road. Figure 3.3 represents this concept schematically. Maximum deviation is the maximum measured depression in any arbitrary red line in the red circle (Figure 3.3 left), while rut depth can be understood as a specific case of surface shape where the profile is set in the transverse direction of the road, which is along the green line in the red circle (Figure 3.3 left). The cross-section of the road in the transverse direction would look like Figure 3.3 (right) which is used to report maximum rut depth in Austroads and Main Roads WA.

Assuming a hypothetical case, where a machine can scan the whole road surface continuously (scanning intervals = 0 mm), the rut depth and surface shape converge to an equal value which is the maximum deflection of the road surface.

**Figure 3.3: Surface shape (left) versus rut depth (right).**




Source: Wang et al. (2017).

Main Roads WA specify the required equipment for the measurement as follows:

- Straightedge 3.00 m ± 0.010 m in length, 2.00 m ± 0.010 m in length or 1.2 m ± 0.005 m in length. The width of the straightedge shall not be greater than 25 mm and the depth of the straightedge shall be not less than 50 mm. The straightedge shall not deviate by more than 1.00 mm from a flat surface (the recommended straightedge is 50 × 25 × 3 mm hollow rectangular aluminium). However, for the purpose of maximum deviation measurement only a 3.00 m straightedge is accepted.
- Spirit level 600 mm ± 2 mm in length made of light metal construction with the vial visible from the top surface or an electronic 'smart level' of the same length and fitted with a crossfall function. Smart levels used shall have a calibration error, of less than or equal to ±0.1 degrees, when calibrated at increments of 45 degrees within the range 0 to 315 degrees.
- Wedge measuring device with graduated markings to show deviation and crossfall.
- Broom.

- A 25 mm spacer block manufactured from aluminium is an optional equipment.

The procedure of maximum deviation measurement is described in the method. A sample site should be selected according to test method WA 0.1:2019. Then the straightedge is placed in any orientation on the surface of the pavement. The straightedge needs 25 mm contact with the pavement surface. If the sample site is within the crowned section of the road, the straightedge is placed parallel to the road centreline. The contact surface immediately beneath the straightedge is swept to be free of single stones or any other debris. The position of the maximum deviation is determined visually by the operator. Then the maximum deviation is measured using the sliding wedge device. The reading is rounded to the nearest 1 mm.

The procedure of rut measurement is described in the method. A sample site is selected according to test method WA 0.1:2019. Then the straightedge is placed perpendicular to the traffic flow direction on the surface of the pavement. The straightedge needs 25 mm contact with the pavement surface. The straightedge should be longer than the width of the measured rut. The contact surface immediately beneath the straightedge is swept free of single stones or any other debris. The position of the maximum rut is determined visually by the operator. Then the maximum rut is measured using the sliding wedge device. The reading is rounded to the nearest 1 mm.

The procedure to determine crossfall is described in the method. A sample site is selected in accordance with test method WA 0.1:2019. Then the straightedge is placed perpendicular to the road centreline, free of the road crown. The straightedge requires 25 mm contact with the pavement surface. The spirit level is placed on the straightedge parallel to the edge of the straightedge. The wedge measuring device is pushed under the lower end of the spirit level until the indicator bubble in the vial is centred. The crossfall is reported to the nearest 0.25%, where the bottom surface of the spirit level touches the upper surface of the wedge measuring device. This is recorded as $C_1$. The sprit level, then, is reversed and the procedure is repeated. The crossfall is read to the nearest 0.25%, where the bottom surface of the spirit level touches the upper surface of the wedge measuring device. This is recorded as $C_2$. The crossfall is then calculated as per Equation 24:

$$\text{Crossfall\%} = \frac{C_1 + C_2}{2} \tag{24}$$

A smart level also can be used to measure crossfall. The procedure to determine crossfall is described in the method. A sample site is selected in accordance with test method WA 0.1:2019. Then the straightedge is placed perpendicular to the road centreline, free of the road crown. The straightedge is placed with 25 mm contact with the pavement surface. The smart level is placed on the straightedge parallel to the edge of the straightedge. The crossfall is measured directly in percentage by the smart level and is recorded as $C_1$. Then the smart level is reversed, and crossfall is measured again. This is then recorded as $C_2$. The crossfall is then calculated as Equation 24.

The surface shape report, according to Main Roads WA includes the following:

- the maximum deviation of the road surface from the straightedge, at each sample site, to the nearest 1 mm
- the rut depth, at each sample site, to the nearest 1 mm. Record the presence of any shoving on the edges of the wheelpath
- the surface profile at 0.1 m intervals, at each sample site, to the nearest 1 mm. Where the calculated deviation is less than zero report the value as negative

- the crossfall of the road surface, at each sample site, to the nearest 0.25%
- the size of straightedge used for the testing
- the location of each sample site with at least the following information:
  - road name
  - carriageway and lane
  - chainage or SLK
  - wheelpath if tested.

# 4 NATIONAL AND INTERNATIONAL METHODS

A literature review was conducted to review available methods and related test, calibration and validation procedures. Austroads, Main Roads, VicRoads, Roads and Maritime Services New South Wales (RMS NSW), the South African National Roads Agency SOC Limited (SANRAL) and the Federal Highway Administration (FHWA) test methods have been reviewed and compared.

## 4.1 Roughness

### 4.1.1 VicRoads

VicRoads has two technical notes regarding roughness measurement. The first is test method RC 422.06 *Pavement Roughness (ARRB TR Walking Profiler Method)* and the second is test method RC 422.03 *Pavement Roughness (Inertial Laser Profiler Method)*.

VicRoads defines the single track IRI, lane IRI and vehicle apparatus similarly to Austroads. According to VicRoads, surveying needs to be performed between 25 km/h and 100 km/h. The required precision for the combination of accelerometer and the displacement measurement is within 0.2 mm. The lateral distance between the displacement transducers to measure the wheelpaths is 0.75 m from the centreline of a lane. The distance transducer measures the distance with the accuracy of 0.1% (1 m in each 1 km). The data logger should be capable of collecting data at intervals not greater than 50 mm and within the wavelength range of 0.5 m to 50 m.

Calibration requirements are as follows:

- The vertical displacement transducer must be calibrated in the laboratory at least every two years.
- The vertical displacement transducer must be checked using step gauge blocks and flat plate at least each 3000 km.

Verifications are conducted according to test methods RC 422.10, RC 422.11 and RC 422.12.

The surveying procedure is very similar to the Austroads procedure. It requires data to be recorded in 50 mm intervals. Both single track and lane IRI are reported for each 100 m. VicRoads recommends Equation 1 to correlate NAASRA and IRI.

### 4.1.2 Roads and Maritime Services New South Wales (RMS)

RMS has three methods to measure roughness. The first is test method T182 *Road Roughness Testing* and the second is test method T187 *Measurement of Ride Quality of Road Pavements by Laser Profiler*. The second method, which is of interest in this literature review, has been used as the basis of Main Roads WA test method for measuring roughness and is already reviewed in Section 3.1 of this report. RMS requires at least 11 laser transducers on the profilometer (QA Specification M922). The sensors are required to be synchronised to sample at a frequency independent of vehicle speed.

The third method is test method T188 *Project Ride Quality (Vehicular Laser Profilometer)*. This method is used to measure the roughness of a pavement surface by laser profilometers. It also can be applied as a quality assurance of a construction or maintenance project. This method is developed based on Austroads test method AG:AM/T001 and RMS T187.

The method uses a single track IRI track averaging (quarter-car) calculation. The test sections are 100 ± 1 m. Ride quality is measured based on 3 runs in each test lane. Path L and Path R are parallel and 1.5 m apart.

The following is required for the apparatus:

- a vehicle able to carry the testing equipment and the profile measuring equipment. The vehicle should be able to travel a range of speeds up to the limit of the operating range of the profile measuring equipment
- accelerometer(s)
- a displacement transducer (laser device), which measures the distance between the accelerometer and the travelled surface. The lateral distance between the displacement transducers to measure in the wheelpaths should be 0.75 m from each side of the centreline of the vehicle
- a distance measuring transducer capable of measuring the distance travelled to an accuracy of ±0.1%
- a data logger capable of capturing the output data from the transducers at intervals of 50 mm or less and with wavelengths of 0.5 m to 50 m.

Calibration is conducted by driving the vehicle over a known distance (1 km to an accuracy of ±1 m) and recording the number of pulses or ticks produced by the transducer. The calibration should be conducted each 4 weeks or after any change to any part of the vehicle and profilometers.

The system is validated according to Austroads test method AG:AM/T003.

Each test section and test lane is measured by 3 runs and data is recorded with corresponding location references. The vehicle is driven at a constant speed and in a smooth manner. No defect is avoided unless for safety reasons. Any unusual event or incident is recorded.

After the data is downloaded Equation 25 is used to determine the quarter-car roughness IRI of the sections.

$$IRI_L = \frac{\sum IRI}{n} \qquad 25$$

$$IRI_R = \frac{\sum IRI}{n}$$

where

| | | |
|---|---|---|
| $IRI_L$ | = | average quarter-car roughness for the left path within a section (m/km) |
| $IRI_R$ | = | average quarter-car roughness for the right path within a section (m/km) |
| $IRI$ | = | Quarter-car roughness results for the path (m/km) |
| $n$ | = | 3 (number of runs) |

The ride quality of the section is then calculated by Equation 26 as follows:

$$IRI_s = \frac{\sum IRI}{2 \times n} \tag{26}$$

or

$$IRI_s = \frac{IRI_L + IRI_R}{2}$$

where

| | | |
|---|---|---|
| $IRI_s$ | = | ride quality for the section (m/km) |
| $IRI_L$ | = | average quarter-car roughness for the left path within a section (m/km) |
| $IRI_R$ | = | average quarter-car roughness for the right path within a section (m/km) |
| $IRI$ | = | Quarter-car roughness results for the path (m/km) |
| $n$ | = | 3 (number of runs) |

Finally, the coefficient of variation (CVs) is calculated using Equation 27:

$$CV_S = \frac{SD_s}{IRI_s} \times 100\% \tag{27}$$

where

| | | |
|---|---|---|
| $CV_S$ | = | coefficient of variation for the section (%) |
| $SD_s$ | = | standard deviation of ride quality for the section (m/km) |
| $IRI_s$ | = | ride quality for the section (m/km) |

The following is then reported:

- the location of the test including start and end of the test, transverse position and direction of testing
- equipment identification
- name of driver and operator
- date and time of testing
- surface type
- for each test lane:
  - start and end chainage, length of section in m
  - the average quarter-car roughness in the left path ($IRI_L$) and the right path ($IRI_R$) to 2 decimal places
  - the ride quality ($IRI_S$) to 2 decimal places

- the standard deviation ($SD_S$) to 2 decimal places and coefficient of variation ($CV_S$) rounded to the nearest whole %
- the lowest test speed during the 3 runs
- any unusual features and events that might affect the results.

### *4.1.3 South African National Roads Agency SOC Ltd (SANRAL)*

SANRAL has specific guidelines about roughness measurements of the roads. The test methods, calibration and validation have been published in the SANRAL's suite of Technical Methods for Highways TMH 10:2007 *Guidelines for Network Level Measurement of Road Roughness*.

SANRAL categorises the roughness measurement into four classes (Table 4.1).

**Table 4.1: Roughness measurement classes**

| Device Class | Class Requirements or Characteristics |
|---|---|
| Class 1: Precision Profiles | ▪ Highest standard of accuracy measurement<br>▪ Requires precision measurement of road profiles and computation of the IRI<br>▪ 2 per cent accuracy over 320 m<br>▪ IRI repeatability of roughly 0.3 m/km on paved roads<br>▪ IRI repeatability of roughly 0.5 m/km on all road types |
| Class 2: Non-precision Profiles | ▪ Requires measurement of road profiles and computation of the IRI<br>▪ Includes profiling devices not capable of Class 1 accuracy |
| Class 3: IRI Estimates from Correlations | ▪ Does not require measurement of the road profile<br>▪ Includes all response type devices<br>▪ Devices are calibrated by correlating outputs to known IRI values on specific road sections |
| Class 4: Subjective Ratings and Uncalibrated Devices | ▪ Includes subjective ratings of roughness<br>▪ Includes devices for non-calibrated response and profilometric devices |

Source: SANRAL TMH 10:2007.

SANRAL also recommends specific interval requirements for each of the classes, which are based on ASTM E950:1998 (Table 4.2).

**Table 4.2: Accuracy requirements for inertial profilometers**

| Device Class | Maximum Longitudinal Sampling Interval (mm) | Vertical Resolution (mm) |
|---|---|---|
| Class 1 | < 25 | ≤ 0.1 |
| Class 2 | 25 < and ≤ 150 | 0.1 < and ≤ 0.2 |
| Class 3 | 150 < and ≤ 300 | 0.2 < and ≤ 0.5 |
| Class 4 | > 300 | > 0.5 |

Source: SANRAL TMH 10:2007.

According to SANRAL, validation of the profiler is achieved if the measured IRI values over various segments of each validation section fall in an acceptable range of bias and precision. The bias and precision are checked at different speeds and the acceptable range is summarised in Table 4.3.

In the SANRAL method the regression refers to a linear regression by least squares method. For this regression, the variable (Y) is the reference IRI over each 100 m of the calibration section. The variable (X) is the measured IRI by the surveying vehicle over each 100 m segment, and for each repeat run. Thus, there is one data point for each repeat measurement on each 100 m segment of each calibration section.

If the relationship between Y and X is not linear (for instance a curved or logarithmic relationship), then the calibration data and equation are not applicable, and the surveying vehicle and other equipment should be checked for faults. Also, if the data drifted consistently on one side of the line of equality, then this indicates a systematic measurement error, and the equipment should be checked.

**Table 4.3: Validation criteria for a laser profilometer**

| Check For | Parameter | Suggested Accepted Criterion | Scope of Calculations |
|---|---|---|---|
| Error of IRI over 100 m segments | Absolute difference between measured and benchmark IRI over 100 m for each repeat run | 80% of values to be less than 8% | Check for each 100 m segment at each speed and on each validation section. |
| Bias and Variability in measured IRI over 100 m segments (all parameters are calculated from a linear regression between average 100 m IRI from repeat runs and benchmark 100 m IRI values) | $R^2$ of linear regression | >0.95 | Check for the combined validation data set which includes all repeat runs and all measurement speeds. In this data set, each data point represents a pair of measured (X-axis) and benchmark (Y-axis) values over a 100 m segment of each calibration section. There should be a data point for each 100 m segment of each calibration section and for each measurement speed and repeat run. |
| | Standard Error of Linear Regression | <0.3 | |
| | Slope of linear regression | Between 0.9 and 1.1 | |
| | Intercept of linear regression | Between –0.1 and 0.1 | |
| | 95% Confidence interval of Slope of linear regression | Should bracket 1.0 | |
| | 95% Confidence interval of intercept of linear regression | Should bracket 0.0 | |
| Bias in measured IRI over 100 m segments | Difference in mean 100 m IRI value from repeat runs measured on different days | <3% | Check for each speed and on individual validation sections |

Source: SANRAL TMH 10:2007.

### *4.1.4 Federal Highway Administration (FHWA)*

FHWA use AASHTO R 56:2014, which describes the test method and validation procedure to measure roughness by a laser profilometer. The surveying vehicle is equipped with a distance measuring instrument (DMI) with an accuracy of 0.15%.

The test sections should cover roughness in the range of 30 to 75 in/mi (equivalent of 0.47 m/km to 1.18 m/km which is considered as smooth surface) and 95 to 135 in/mi (equivalent of 1.5 m/km to 2.13 m/km which is considered medium surface). The reference section must not have major deficiencies. Then the reference data is collected along the wheelpaths and the profiler collects the repeat runs on the section.

The validation is achieved if:

- Accuracy check: 95% of IRI collected with the two methods (profiler and reference data) correlate with $r^2$ above 90%.
- Repeatability check: 95% of IRI collected from the surveying vehicle should correlate with $r^2$ above 92%.

## 4.2 Rutting

### *4.2.1 VicRoads*

VicRoads test method RC 422.04:2001 *Pavement Rutting (Inertial Laser Profiler Method)* describes the method and requirements to measure the rutting of a road surface by a laser profiler.

The equipment requirements are similar to Austroads vehicle requirements. According to VicRoads, the profilometer is required to cover a 3.0 m width in the transverse direction and should be able to perform up to the maximum legal speed (100 km/h). The required precision for the displacement measurement should be within 0.2 mm. Displacement transducers are to be placed to measure the transverse direction at the centreline of the vehicle and approximately 450 mm, 750 mm, 950 mm, 1150 mm, 1350 mm and 1500 mm offset either side from the centreline (6 laser transducers are required). The distance transducer has an accuracy of 50 mm/km. The data logger should be capable of recording data from the transducer while the maximum interval is not greater than 250 mm. A computer is required to calculate the rut depth for each 100 m segments.

Calibration requirements are as follows:

- The vertical displacement transducer requires calibration in the laboratory at least every two years.
- The vertical displacement transducer is checked using step gauge blocks and a flat plate at least each 300 km.

Verifications are conducted according to test method RC 422.10, RC 422.11 and RC 422.12.

### *4.2.2 Roads and Maritime Services New South Wales (RMS)*

RMS does not have any specific procedure to measure rut depth with a laser profiler. However, the test method T183:2012 *Surface Deviation Using a Straightedge* provides the surface deviation of the road surface. This is similar to the method used by Main Roads WA and described in Section 3.3 of this report.

The length of the straightedge is 3 m in this method and the surface being tested should be free of any loose granular particles and debris. The bottom face of the straightedge has a width not greater than 25 mm. A scaling wedge is used to measure the deviation. It requires a flat base from 37 to 52 mm wide and length from 135 to 200 mm. The upper face is inclined at 1:4.5 (V:H) or less slope to the base with height increments marked on the face starting at 3 mm and then every 1 ± 0.1 mm up to at least 24 mm.

To measure the surface deviation at a required angle, the straightedge is placed on the surface with that angle. If there is a convex void beneath the straightedge, it is reported with no further measurement. The scale wedge is inserted until it touches the straightedge and then the reading is recorded as the maximum deviation.

RMS requires at least 11 laser transducers on the profilometer (QA Specification M922). The sensors should be synchronised to sample at a frequency independent of vehicle speed.

### 4.2.3 South African National Roads Agency SOC Ltd (SANRAL)

SANRAL currently has no published guideline for a laser profiler method for surface deflection measurement.

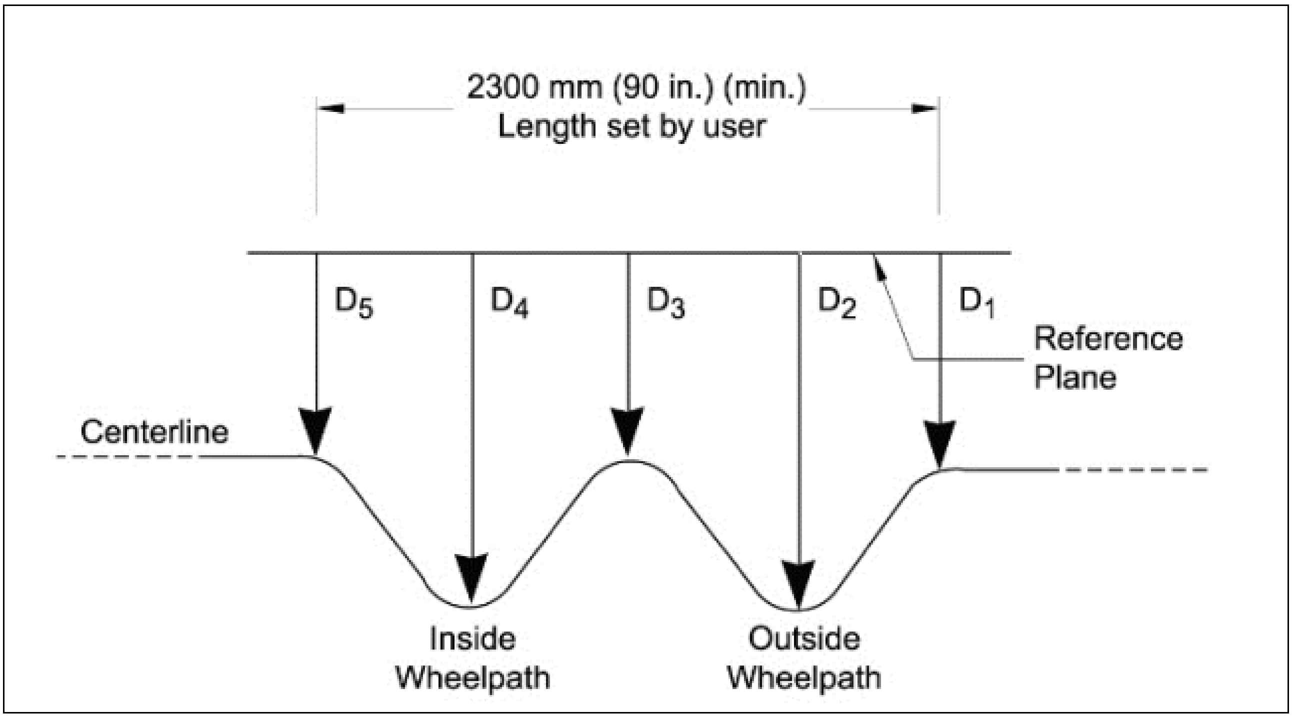
It is expected that new TMH 13 *Guidelines for Network Level Measurement of Pavement* would cover the measurement of rutting by laser profilometer. However, this version is still under review and to the date of this report, is not available on the SANRAL website.

### 4.2.4 Federal Highway Administration (FHWA)

FHWA uses AASHTO standard R 48-10:2010 for measuring rut depth, which describes transverse profile measurement by a laser profiler. The profiler's accuracy should fall within ±0.08 inch (2 mm) compared to a manual survey. It should have the resolution of at least 0.01 in (0.25 mm) and its repeatability should fall within ±0.08 in (2 mm) for run-to-run comparison over at least three repeats.

AASHTO R 48 requires at least five transverse profile points to evaluate the rut depth. Figure 4.1 shows the configuration requirements for the laser profiler.

**Figure 4.1: AASHTO configuration requirements in rut depth measurement**




Source: Daleiden, Burchett and Mergenmeier (2015).

## 4.3 Texture

### *4.3.1 VicRoads*

VicRoads have two test methods for texture measurement, namely test method RC 317.01:2012 *Surface Texture by Sand Patch* and test method RC 422.05:2001 *Texture Depth (Non-contact Laser Method)*. Test method RC 422.05:2001 includes procedures and requirements for texture measurement.

The profilometer vehicle requirements are similar to Austroads requirements. According to VicRoads, it should possess displacement transducers (the minimum number of transducers are not specified) to measure the surface texture depth by measuring the distance between the mounting of the transducer and the travelled surface in the left wheelpath and between wheelpaths. The displacement measurement transducers need to be precise to 0.1 mm or smaller. It needs to be able to perform up to the maximum legal speed (100 km/h). The distance transducer needs to have an accuracy of 50 mm/km. The data logger needs to be capable of recording data from the transducer while the maximum interval is not greater than 250 mm. A computer is needed to calculate the rut depth for each 100 m segment.

Calibration requirements are as follows:

- The vertical displacement transducer needs to be calibrated in the laboratory at least every two years.
- The vertical displacement transducer needs to be checked using step gauge blocks and a flat plate at least each 3000 km.
- The accelerometers need to be checked daily to ensure they are vertically placed on the profiler if the profilometer is subjected to any impact or modification.

Verifications are conducted according to test method RC 422.10, RC 422.11 and RC 422.12.

The procedure requires the vehicle to travel at a constant speed. The measurement of texture depth is conducted at the left wheelpath and between the wheelpaths. Then the average texture depth in the left wheelpath and between the wheelpaths for each 100 m segment is reported. Also, the texture depth is averaged for the total surveyed section if required.

### *4.3.2 Roads and Maritime Services New South Wales (RMS)*

RMS has three test methods to measure texture depth. These are:

1. Test Method T240:2013 *Road Surface Texture Depth (Sand Patch)*
2. Test Method T232:2012 A*verage Texture Depth of Road Surface Using the Textural Depth Meter*
3. Test Method T192:2012 *Determination of the Texture Depth of Road Surfacing by the TRL Mini-texture Meter*.

However, RMS does not provide any specific test method for texture measurement by laser profilometer. Instead, it recommends collection of the texture data in the two longitudinal paths and then, following Austroads test method AG:AM/T013, to report mean profile depth (MPD), sand patch texture depth (SPTD) and sensor measured texture depth (SMTD).

RMS requires at least 11 laser transducers on the profilometer (RMS QA Specification M922). The sensors need to be synchronised to sample at a frequency independent of vehicle speed.

#### *4.3.3 South African National Roads Agency SOC Limited* (SANRAL)

SANRAL does not have a specific guideline for the laser profiler method of texture depth measurement.

It is expected that new TMH 13 *Guidelines for Network Level Measurement of Pavement* would cover the measurement of rutting by laser profilometer. However, this version is still under review and to the date of this report, is not available on the SANRAL website.

#### *4.3.4 Federal Highway Administration (FHWA)*

FHWA uses the ASTM E1845:2015 method for calculation of texture depth and mean texture depth by laser profiler. ASTM E1845 is the reference method which is used by Austroads, and it is reviewed in Section 2.4 of this report.

# 5 ANALYSIS OF THE TESTING METHODS

In this section, the comparison of the test methods used by different road agencies is presented. The comparison covers differences between recommended equipment, calculation, calibration and validation methods. Then the advantages and disadvantages of application of a laser profiler is analysed for WA conditions. The application of a laser profiler has been investigated for measuring roughness, rutting and texture depth in WA.

## 5.1 Methodology Comparison

Table 5.1 demonstrates the differences and similarities amongst reviewed test methods for roughness measurements.

**Table 5.1: The comparison of different test methods for roughness measurement**

| Test method | Roughness measurement |
|---|---|
| Austroads<br>TEST METHOD AG:AM/T001<br>TEST METHOD AG:AM/T002<br>TEST METHOD AG:AM/T003<br>TEST METHOD AG:AM/T004<br>TEST METHOD AG:AM/T005 | ▪ applicable for ride quality and network<br>▪ allows for validation by reference device or any established loop<br>▪ allows for distance validation<br>▪ uses a minimum of 11 lasers on the profiler |
| Main Roads WA<br>TEST METHOD WA 313.3:2012 | ▪ refers to TMR Method T187<br>▪ only applicable for ride quality<br>▪ allows for validation by loop method using the RMS loop only (in Sydney)<br>▪ no distance validation method |
| VicRoads<br>TEST METHOD RC 422.03<br>TEST METHOD RC 422.06<br>TEST METHOD RC 422.10<br>TEST METHOD RC 422.11<br>TEST METHOD RC 422.12 | ▪ applicable for ride quality and network<br>▪ allows for validation by reference device or any established loop<br>▪ allows for distance validation<br>▪ uses a minimum of 11 lasers on the profiler |
| RMS NSW<br>TEST METHOD T182<br>TEST METHOD T187<br>TEST METHOD T188<br>QA SPECIFICATION M922 | ▪ refers to TMR Method T187<br>▪ only applicable for ride quality<br>▪ allows for validation by loop method using the RMS loop only (in Sydney)<br>▪ uses a minimum of 11 lasers on the profiler |
| SANRAL<br>TMH 10 | ▪ applicable for ride quality and network<br>▪ allows for validation by reference device or any established loop<br>▪ allows for distance validation |
| FHWA<br>AASTHO STANDARD R 56 | ▪ applicable for ride quality and network<br>▪ allows for validation by reference device or any established loop<br>▪ allows for distance validation<br>▪ uses a minimum of 11 lasers on the profiler |

Table 5.2 demonstrates the differences and similarities amongst the reviewed test methods for rut depth measurements.

**Table 5.2: Comparison of different test methods for rutting measurement**

| Test method | Rut depth measurement |
|---|---|
| Austroads<br>TEST METHOD AG:AM/T005<br>TEST METHOD AG:AM/T009<br>TEST METHOD AG:AM/T010<br>TEST METHOD AG:AM/T011<br>TEST METHOD AG:AM/T012 | ▪ both point and line lasers<br>▪ based on a minimum of 11 lasers over 3 m or more than 1000 points over 3 m (line laser) |
| Main Roads WA<br>TEST METHOD WA313.3:2012 | ▪ MRWA in-house method<br>▪ point laser only<br>▪ based on 3 lasers over 1.5 m (Main Roads WA uses rut index, not rut depth) |
| VicRoads<br>TEST METHOD RC 422.04<br>TEST METHOD RC 422.10<br>TEST METHOD RC 422.11<br>TEST METHOD RC 422.12 | ▪ point lasers only<br>▪ based on a minimum of 13 lasers over 3.0 m |
| RMS NSW | ▪ no specific method for laser profiler<br>▪ uses surface deviation instead measured with a straightedge |
| SANRAL<br>TMH 10 | ▪ no specific method for laser profiler |
| FHWA<br>AASHTO STANDARD R 48-10 | ▪ point lasers only<br>▪ based on a minimum of 5 lasers over 2.3 m |

Table 5.3 summarises the differences and similarities amongst the reviewed test methods for texture depth measurements.

**Table 5.3: The comparison of different test methods for texture depth measurement**

| Test method | Texture depth measurement |
|---|---|
| Austroads<br>TEST METHOD AG:AM/T013 | ▪ laser-based measure<br>▪ report sand patch (through correlation) or mean profile depth depending on equipment used<br>▪ equivalent sand patch 1 test every 280 mm, MPD 1 test every 100 mm at speed > 5 km/h (no traffic management required)<br>▪ report average and statistics over any nominated interval > 1 m |
| Main Roads WA<br>TEST METHOD WA 311.2:2012 | ▪ MRWA in-house method<br>▪ manual sand patch only<br>▪ report sand patch only<br>▪ number of tests and intervals are time dependent and requires traffic management |

| Test method | Texture depth measurement |
|---|---|
| VicRoads<br>TEST METHOD RC 317.01<br>TEST METHOD RC 422.05<br>TEST METHOD RC 422.10<br>TEST METHOD RC 422.11<br>TEST METHOD RC 422.12 | ▪ laser-based measure<br>▪ requires application of an appropriate arithmetic model to provide mean values of surface texture depth which correlates to the results obtained using VicRoads Test Method RC 317.01<br>▪ report average and statistics over any nominated interval > 1 m |
| RMS NSW<br>TEST METHOD T240<br>TEST METHOD T232<br>TEST METHOD T192 | ▪ uses both manual and laser-based measures<br>▪ recommends using Austroads AG:AM/T013 method<br>▪ report sand patch (through correlation) or mean profile depth depending on equipment used<br>▪ equivalent sand patch 1 test every 280 mm, MPD 1 test every 100 mm at speed > 5 km/h (no traffic management required)<br>▪ report average and statistics over any nominated interval > 1 m |
| SANRAL<br>TMH 10 | ▪ no specific method |
| FHWA<br>ASTM E1845 | ▪ similar to AUSTROADS TEST METHOD AG:AM/T013 |

Table 5.4 demonstrates the differences and similarities amongst the reviewed test methods for surface shape measurements.

**Table 5.4: The comparison of different test methods for surface shape measurement**

| Test method | Surface shape measurement |
|---|---|
| Austroads | ▪ no method available – requires new method to be written for MRWA outside of Austroads<br>▪ laser-based measure using either 3 m or 2 m SE only in a transverse or longitudinal direction<br>▪ test every 25 mm longitudinally or ~100 mm transversely at speed > 5 km/h (no traffic management required)<br>▪ report average and statistics over any nominated interval > 1 m |
| Main Roads WA<br>TEST METHOD WA 313.2:2012 | ▪ MRWA in-house method<br>▪ manual method using 3 m straightedge and wedge in any direction<br>▪ number of tests and interval time-dependent and requires traffic management |
| VicRoads | no specific method |
| RMS NSW<br>TEST METHOD T183 | ▪ manual method using 3 m straightedge and wedge in any direction<br>▪ number of tests and interval time-dependent and requires traffic management |
| SANRAL | no specific method |
| FHWA | no specific method |

## 5.2 Advantages and Disadvantages for WA Application

There are advantages and disadvantages for using high-speed laser profilometer data in WA.

The major advantages are:

1. Higher volume of network-level monitoring due to a faster testing procedure.

2. High precision and accuracy of a validated high-speed profiler.
3. Shorter surveying intervals compared to other devices which leads to a more continuous picture of the road surface profile.
4. Use of computer-based calculation which ensures consistency in processing the data.
5. Enabling more scheduled monitoring of road deterioration at the network level.
6. Simultaneous measurement of transverse and longitudinal profile.
7. Simultaneous report of roughness, rutting and texture depth (which can then be used to calculate the surface shape of the road).
8. Well-documented survey quality by recording a high-resolution video from the surface survey in some vehicles.
9. No requirement for traffic control and therefore involves a lower safety risk.

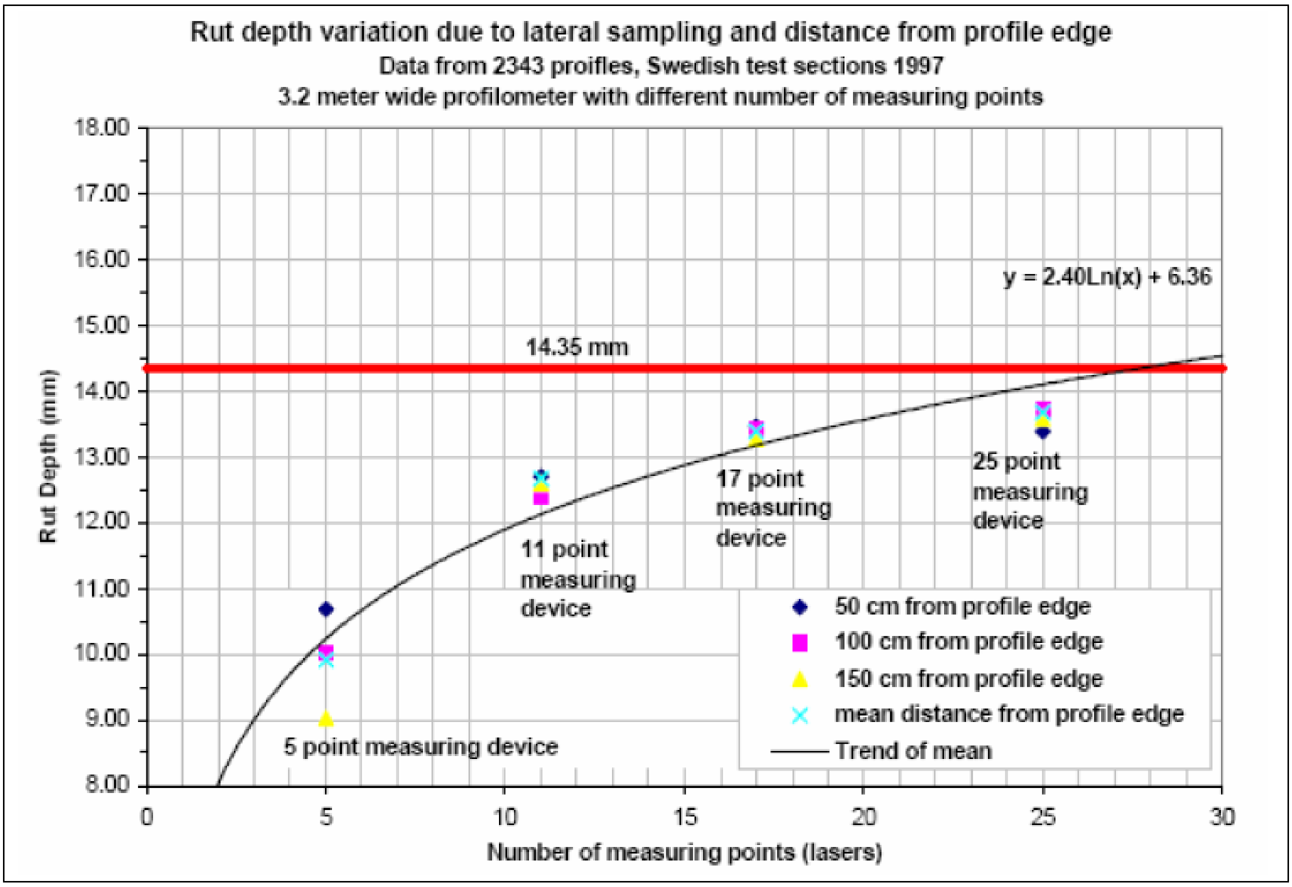
The major disadvantages are:

1. The laser profilers cannot be successfully employed to survey gravel roads. Gravel roads make up approximately 5% of state roads in WA.
2. The device is expensive and therefore fewer contractors across WA would be able to afford it. That leads to relatively higher cost of surveying with a laser profiler. However, its cost is balanced with the saving in the cost of traffic control.
3. Complex and extensive validation and calibration procedure impose extra cost on the process.
4. Complex surveying procedures require a specifically trained technician and professionals.

There is a possibility to use laser profilometers with a different number of transducers. The number of transducers would directly affect the accuracy and continuity of survey.

Experiments proved (Willet, Magnusson & Ferne 2000) that increasing the number of laser sensors can better the accuracy and precision of the measurement (Figure 5.1).

**Figure 5.1: Effect of laser sensors number on the accuracy and precision of rut depth measurement**




Source: Willet, Magnusson & Ferne (2000).

It is obvious that increasing the number of sensors from 11 to 17 improved the accuracy of the results by less than 1 mm. This can be compared to an increase in the number of lasers from 5 to 11 where the accuracy is improved by more than 2 mm. The other factor is precision, while both 11 and 17 laser sensors reported precise results with less than 0.5 mm difference, the precision of 5 sensors was not enough and varied within ±2 mm.

In conclusion, it is highly beneficial for Main Roads WA to develop a laser profiler test method for road surveys. It is also of benefit to have at least 11 laser sensors for surveying.

# 6 SUMMARY OF THE LITERATURE REVIEW

Main Roads Western Australia (MRWA) use various test methods to measure and control the quality of its roads. These methods were appropriate at the time considering the available technology. However, development of laser technology has enabled laser profilometers to survey road surface parameters.

A comprehensive literature review was conducted to review available methods and related test procedures, calibration and validation. Specifically, two series of test methods from Austroads and Main Roads WA have been reviewed and compared. The following methods have been reviewed:

- Austroads test method AG:AM/T001 *Pavement Roughness Measurement with an Inertial Profilometer*
- Austroads test method AG:AM/T002 *Validation of an Inertial Profilometer for Measuring Pavement Roughness (Reference Device Method)*
- Austroads test method AG:AM/T003 *Validation of an Inertial Profilometer for Measuring Pavement Roughness (Loop Method)*
- Austroads test method AG:AM/T004 *Pavement Roughness Repeatability and Bias Checks for an Inertial Profilometer*
- Austroads test method AG:AM/T005 *Distance Measurement Validation of Road Condition Monitoring Vehicles*
- Austroads test method AG:AM/T009 *Pavement Rutting Measurement with a Laser Profilometer*
- Austroads test method AG:AM/T010 *Validation of a Laser Profilometer for Measuring Pavement Rutting (Reference Device Method)*
- Austroads test method AG:AM/T011 *Validation of a Laser Profilometer for Measuring Pavement Rutting (Loop Method)*
- Austroads test method AG:AM/T012 *Pavement Rutting Repeatability and Bias Error Checks for a Laser Profilometer*
- Austroads test method AG:AM/T013 *Pavement Surface Texture Measurement with a Laser Profilometer*
- Austroads test method AG:AM/T014 *Validation of a Laser Profilometer for Measuring Pavement Surface Texture (Reference Device Method)*
- Austroads test method AG:AM/T015 *Validation of a Laser Profilometer for Measuring Pavement Surface Texture (Loop Method)*
- Austroads test method AG:AM/T016 *Pavement Surface Texture Repeatability and Bias Error Checks for a Laser Profilometer*
- Test method WA 311.1:2012 *Texture Depth*
- Test method WA 311.2:2012 *Surface Texture Depth Stationary Laser Profilometer Method*
- Test method WA 313.3:2012 *Pavement Roughness and Rutting: Laser Profilometer Method*

In addition, the review included similar methods in VicRoads, RMS NSW, SANRAL and FHWA.

It was found that the Austroads method of using laser profilers for road surface surveys is one of the well-accepted procedures across Australia. Its principles are comparable to international codes such as SANRAL and FHWA.

The review looked at four different road surface parameters namely roughness, rut depth, texture depth and surface shape.

Roughness can be reported in IRI or NRC. The various methods of reporting roughness including NRC and IRI and their relationship were covered. The review described the various requirements for the surveying vehicle by each of the road agencies.

Rut depth can be measured both manually and by laser profilometers. The requirements of calibration, validation and the methods of calculating rut depth recommended by each of the road agencies were investigated.

Texture depth can be reported by volumetric methods or by laser profilometers. The texture may be reported in MPD or SPTD. The relationship between these two parameters and the methods of calculation recommended by different agencies have been reviewed.

Main Roads WA and RMS NSW have test methods to measure road surface shape. The codes and procedures regarding the measurement of this parameter have been reviewed as well.

Finally, a comprehensive comparison of all the test methods used by different road agencies was provided. The comparison was presented in four tables for roughness, rut depth, texture depth and surface shape measurement. The advantages and disadvantages of adopting the laser profilometer in road surveys for WA conditions were analysed. It is strongly recommended that WA develops its own test methods and specifications to facilitate the use of laser profilometers.

# 7 SCOPE OF FUTURE WORK

As previously mentioned, there is a need for Main Roads WA to develop its own test methods and specification to regulate and facilitate the application of laser profilometers in measurement of roughness, rut depth, texture depth and surface shape. There are four tasks that can be considered as a further development of this report:

1. Update Main Roads WA roughness measurement test method:
   - Currently the roughness measurement method used by Main Roads WA is based on RMS Method T187. It only allows validation using the RMS loop and is not applicable to network surveys. Other methods such as Austroads AG:AM/T001 can be adapted easily to update the current method.
2. Develop new test methods for rut depth measurement:
   - Currently the rut depth measurement method used by Main Roads WA is based on using 3 point laser profilers. Therefore, there is room to develop at least two test methods and related specifications:
     - The first to regulate and specify the use of 11 (or more) points laser profiler to measure rut depth across the transverse profile and should cover at least 3 m of the road width.
     - The second to regulate and specify the use of a line laser profiler in rut depth measurement. It also should be able to cover at least 3 m of transverse profile.
3. Develop new test methods for texture depth measurement:
   - Currently the texture depth method used by Main Roads WA is based on an in-house test method WA 311.2:2012. It only accepts the sand patch method which is a very time-consuming process and it is riskier for the surveyors. There are two methods that need to be developed:
     - The first is for the equivalent volumetric measurement which uses laser profilometers to report SPTD.
     - The second is for linear scanning which uses a laser profilometer to report MPD.
4. Develop new test methods for surface shape measurement:
   - Currently the texture depth method used by Main Roads WA is based on an in-house test method WA 313.2:2012. It only uses a straightedge and scaling wedge to measure the surface shape and the maximum surface deviation in any direction. Laser profilometers can only measure the surface deflection in two perpendicular directions (namely longitudinal and transverse directions). This can be by either 13 point lasers or a line laser. Based on this there are two ways to estimate the surface shape by laser profilometer:
     - The first method is to estimate surface shape and maximum deviation from the transverse profile scan. Transverse profiles are scanned each 100 mm (25 mm in case of the line laser) and the estimation would be a close approximation of the actual value.
     - The second method uses third party software (developed by FHWA) to calculate the shape surface from 2 longitudinal profiles 750 mm from the centreline of the vehicle.

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