Guidelines for Network Level Measurement of Road Roughness

Version 1.0

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Roughness Measurement Guidelines

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Disclaimer

This document provides guidance for the planning and execution of road network roughness measurement. The document is neither a specification nor a manual for network level surveillance in general. The views and recommendations provided are based on opinions and methodologies documented in available literature, and on the experience of the committee and the authors. The guidelines do not necessarily cover the entire spectrum of knowledge and application related to road roughness measurement. The information contained in this document is given in good faith. No responsibility will be accepted by the Committee or the authors for any damage or adverse consequences arising from the use of this document.
Roughness Measurement Guidelines

Table of Contents

1. BASIC CONCEPTS OF ROUGHNESS MEASUREMENT ..................................................... 2
   1.1. THE ROAD PROFILE ..................................................................................................... 2
   1.2. PROFILE AND RIDE COMFORT .................................................................................. 3
   1.3. MEASUREMENT APPROACHES ................................................................................... 4
   1.4. THE INTERNATIONAL ROUGHNESS INDEX (IRI) ....................................................... 5
   1.5. THE HALF CAR INDEX (HRI) ...................................................................................... 7

2. ROUGHNESS MEASUREMENT CLASSES AND DEVICES ............................................. 9
   2.1. MEASUREMENT CLASSES .......................................................................................... 9
   2.2. RESPONSE TYPE DEVICES ...................................................................................... 10
   2.3. HIGH SPEED PROFILING DEVICES .......................................................................... 12
   2.4. STATIC PROFILING DEVICES .................................................................................... 14

3. PLANNING A ROUGHNESS SURVEY ........................................................................... 19
   3.1. SURVEY OBJECTIVES ................................................................................................. 19
   3.2. DEVICE SELECTION .................................................................................................... 20
   3.3. SPECIFICATIONS .......................................................................................................... 21
   3.4. CALIBRATION SECTION REQUIREMENTS .................................................................. 24

4. CALIBRATION AND CONTROL TESTING FOR RESPONSE TYPE DEVICES .............. 27
   4.1. CALIBRATION REQUIREMENTS .................................................................................. 27
   4.2. VALIDATION OF POSITIONING EQUIPMENT ............................................................ 27
   4.3. CONTROL TESTING .................................................................................................... 29

5. VALIDATION AND CONTROL TESTING FOR PROFILERS ........................................ 31
   5.1. VALIDATION REQUIREMENTS ..................................................................................... 31
   5.2. VALIDATION CRITERIA .................................................................................................. 31
   5.3. VALIDATION OF POSITIONING EQUIPMENT .............................................................. 33
   5.4. CONTROL TESTING ..................................................................................................... 34

6. OPERATIONAL AND QUALITY CONTROL PROCEDURES ........................................ 37
   6.1. OPERATIONAL PROCEDURES FOR RESPONSE TYPE DEVICES ......................... 37
   6.2. OPERATIONAL PROCEDURES FOR PROFILERS ..................................................... 38
   6.3. DATA CAPTURE AND DOCUMENTING .................................................................... 39
   6.4. DATA CHECKING AND TROUBLESHOOTING .......................................................... 40
   6.5. PAVEMENT AND ENVIRONMENTAL INFLUENCES .................................................. 40

7. REFERENCES .................................................................................................................. 43

8. GLOSSARY ...................................................................................................................... 45

Appendix A: Analysis of Road Profiles: Basic Concepts
Appendix B: Calibration Report Details (Response Type Devices Only)
Appendix C: Validation Calculation Details (Profilers Only)
Appendix D: Guidelines for Checking of Data Consistency
List of Figures

Figure 1-1  Road Profile Measurement ................................................................. 2
Figure 1-2  Profile Measurement Concepts .......................................................... 3
Figure 1-3  Measurement Types (Response and Profilometric Types) .................... 4
Figure 1-4  Aspects of the IRI Calculation (after Sayers and Karamihas, 1988) ...... 6
Figure 1-5  The IRI Interpretation Scale ............................................................... 7
Figure 2-1  Basic LDI Components, showing vertical distance measurement transducer, odometer and data capturing components ........................................................................ 11
Figure 2-2  Attachment of LDI suspension monitoring device to rear axle .......... 11
Figure 2-3  ARAN Surveillance Vehicle ................................................................. 13
Figure 2-4  Road Surface Profiler ....................................................................... 14
Figure 2-5  Operation of the Precision Rod and Level (after Sayers and Karamihas, 1998) .......................................................................................................................... 15
Figure 2-6  Face DipstickTM .................................................................................. 16
Figure 2-7  ARRB Walking Profiler ..................................................................... 16

List of Tables

Table 2-1  Classes of Roughness Measurement .................................................... 9
Table 2-2  Accuracy Requirements for Inertial Profilometers (ASTM E950-98) ....... 9
Table 3-1  Network Level Planning Considerations .............................................. 20
Table 3-2  Equipment Specification Considerations for Roughness Survey Equipment .... 21
Table 3-3  Equipment Specification Considerations for Global Positioning Systems .... 22
Table 3-4  Roughness Ranges for Calibration Section Selections .......................... 25
Table 4-1  Guidelines for Calibration Acceptance Criteria ................................... 28
Table 4-2  Calibration Requirements for Response Type Devices ....................... 28
Table 5-1  Validation Requirements for Profilers .................................................. 32
Table 5-2  Guidelines for Validation Acceptance Criteria .................................... 32
Table 6-1  Checklist for Operational Control Checks on Response Type Devices .... 39
Table 6-2  Checklist for Operational Control Checks on Profilers ....................... 40
Table 6-3  Troubleshooting Procedure for Inconsistent Data ............................... 42
OBJECTIVES AND SCOPE

The primary objective of these guidelines is to assist road network management personnel to plan, execute and control the measurement of road roughness (or riding quality) over a road network. These measurements are typically intended for use in the network’s Pavement Management System (PMS) to assess the network condition and prioritize maintenance and rehabilitation actions. Secondary and associated objectives of these guidelines are to provide a definition and clarification of key concepts and methodologies.

These guidelines are thus primarily concerned with the needs of roads agencies or managers of road networks. Although some details of measurement procedures are discussed, the emphasis remains on the needs of the network manager, and not on the needs of the contractor in charge of the actual roughness measurement. The scope of the guidelines is also limited to roughness measurement at the network level, and does not cover applications such as roughness measurement at the project level or for research purposes.

STRUCTURE OF THE GUIDELINES

The level of technical detail adopted for these guidelines was selected to suit network managers that are relatively new to the field of roughness measurement. As such, complex, but non-essential aspects are relegated to appendices to ensure that the guidelines can be helpful on the first reading. As much as possible, the guidelines are written in a concise format that would enable network managers to use this document firstly as a practical guide, and only secondly as a source of general information on roughness measurement.

Extensive use is made of concept summaries and checklists, which are clearly highlighted. The discussion of basic concepts is limited to the most essential and frequently used aspects of roughness measurement. A comprehensive reference list is provided and more complex but non-essential aspects are discussed in appendices. Sidebar boxes are used to highlight useful references for further reading, and other essential supporting information. The guidelines are structured as follows:

- **Section 1** provides a brief overview of the main concepts related to roughness measurement. Key definitions are provided, and the road profile and its relation to roughness is discussed. The International Roughness Index (IRI) is also discussed in this section. **Appendix A** provides an in-depth outline of the basic elements discussed in Section 1.

- In **Section 2**, the main types of measuring devices for network level use are discussed. The two main device types covered are Response Type devices and Profiler devices. A brief discussion of static or slow moving devices is also provided.

- **Section 3** covers aspects related to the planning of network level surveys. An emphasis is placed on the adequate and upfront assessment of survey objectives, and how these can be addressed through appropriate planning and device selection. Contractual aspects (specifications, validation and control) are also discussed.

- The process of device calibration and measurement control for Response Type devices is discussed in **Section 4**. The section covers the selection of calibration sections, calibration procedures and control procedures. Supporting details for the methods provided in this section are provided in **Appendix B**.

- **Section 5** covers the validation and control of profiler devices. The selection of validation sections is discussed, and schemes for different levels of device validation and measurement control are outlined. Supporting details for the methods presented in this section are provided in **Appendix C**.

- **Section 6** covers operational procedures for different device types, and also discusses data capture, troubleshooting and documenting aspects.

- References are provided in **Section 8**, while **Section 9** provides a glossary.

- **Appendix A** provides a more detailed discussion of profile analysis. Appendices B and C provide example calculations for calibration and validation of measurement devices, respectively.
1. BASIC CONCEPTS OF ROUGHNESS MEASUREMENT

Road roughness, or roughness, is the term used to describe the relative degree of comfort or discomfort experienced by a road user when using a road. Roughness is one of the most important aspects of a road network to monitor, since it directly relates to the experience of road users. As such, roughness serves as a collective measure of several aspects of road condition, including rutting, cracking, potholes, local failures and undulations.

The term riding quality is often used instead of roughness. The term roughness will be used in these guidelines, as it is used most often in the international context.

1.1. THE ROAD PROFILE

An uncomfortable ride, or high degree of roughness, is a result of variations in surface elevation along the wheelpaths of a road. Whilst there are many approaches to measuring or quantifying the degree of discomfort a road user will experience, the cause of such roughness will always be variations in surface elevation. The most direct method of quantifying the variations in surface elevations is by measuring the profile of the road surface.

The road profile is measured along a fixed line in the direction of vehicle travel, as shown in Figure 1.1. This figure also shows the difference between the lateral profile and the longitudinal profile.

The transverse profile is measured in a direction perpendicular to the direction of vehicle movement, while the longitudinal profile is measured in the direction of movement. Roughness is primarily concerned with the longitudinal profile while transverse profiles are mainly used to assess rutting.

Key concepts related to the measurement of a road profile include the following (illustrated in Figure 1.2):

- Along any line on the road, there exists a “true profile” (top graph in Figure 1.2). The true profile is approximated by the measured profile, which is a profile measured at a predetermined sampling interval (middle graph in Figure 1.2).
- The sampling interval is the spacing between measurement points along the line of measurement. Most modern profiling devices can sample elevations at intervals less than 250 mm when moving at speeds of up to 120 km/h.

![Figure 1-1 Road Profile Measurement](image-url)
• A profile can be subdivided into a number of sinusoidal curves, each with a different wavelength. The top graph in Figure 1.2 shows that the true profile consists of curves with a long wavelength as well as curves with shorter wavelengths.

• Not all of the sinusoid curves that make up a profile are important for road roughness measurements. The wavelengths that have the greatest influence on road user comfort are those between 1 m and 30 m. Very long wavelengths related to vertical alignment or slope are typically not important, as are very short wavelengths related to surface texture.

• When a road profile is processed to compute roughness, the wavelengths outside of the critical range are typically filtered out. There are many types of filters that can be applied to a measured profile. These filters can be a mathematical function (like a moving average) or a mechanical filter consisting of the suspension of a measurement vehicle. The bottom curve in Figure 1.2 shows the measured profile after the very short wavelengths and grades have been filtered out.

1.2. PROFILE AND RIDE COMFORT

The longitudinal profile contains the information that can be used to assess the relative degree of comfort or discomfort that a road user would experience if the road is being travelled at a certain speed. The variations in the road profile lead to vibrations in the vehicle body, which in turn are transmitted to the road user.

As noted earlier, not all wavelengths in a road profile are important for road user comfort. Vehicle suspension systems are designed to remove or dampen the effect of many of the wavelengths in a profile. Certain wavelengths in a road profile will thus have a greater impact on perceived roughness than others.

To quantify the degree of comfort or discomfort, the measured profile first needs to be processed or filtered to isolate and “add-up” the amplitudes and variations of the most important wavelengths in the profile. The processing of the road profile typically results in a number or parameter which is used as an indication of road roughness.

Figure 1-2 Profile Measurement Concepts
A roughness parameter is always determined over a segment of a profile. For example, modern roughness measuring devices can typically report the roughness over every 10 metres travelled. Some of the older types of measurement devices determine a roughness parameter every 100 metres.

The parameter most widely used as an indicator of road roughness is the International Roughness Index (IRI) which will be discussed in detail in Section 1.4.

### 1.3. Measurement Approaches

The measurement of road roughness can be classified into two basic types (also illustrated in Figure 1.3):

- **Response Type Measurement** is used to directly measure the response of a measurement vehicle to a travelled section of road. In this type of measurement, the profile as shown in Figure 1.2 is never actually measured. Instead, the measurement vehicle’s response to the profile is measured and quantified. In essence, this means the measurement vehicle’s suspension is used to filter out the unimportant wavelengths and quantify the effect of the important wavelengths. The parameter measured by response type devices is the Average Rectified Slope (ARS), which is the total up and down movement of the suspension normalized by the distance covered. ARS is therefore typically expressed in m/km.

**Further Reading: SINUSOIDS and FILTERS**

For a more in-depth discussion of the basic aspects of sinusoid curves (e.g. wavelength, amplitude, frequency), see Appendix A.

A comprehensive discussion of sinusoids and different filter types can be found in the “Little Book of Profiling” [Sayers and Karamihhas, 1998].
Roughness Measurement: Version 1.0

• **Profilometric Type Measurement** involves the measurement of the road profile after which the profile is filtered (as shown in Figure 1.2) and then further processed to determine the road roughness parameter over segments of the measured profile. The filtering and processing of the road profile is designed to simulate the response of a standard vehicle to the measured profile.

Each of the above-noted approaches have distinct advantages and disadvantages, which are discussed in more detail in Section 2. The key difference between the two methods is that Response Type devices apply a physical filter to the actual road profile, while profilometric methods apply a mathematical filter to a measured profile.

In general, the profilometric approach is more modern and sophisticated, and provides more consistent data. However, the approach requires significantly more expensive equipment and in-depth understanding and monitoring of the measured data.

1.4. **THE INTERNATIONAL ROUGHNESS INDEX (IRI)**

The IRI is a roughness index which is determined from a road profile measured in a wheelpath. In the IRI calculation, the measured profile is processed using a mathematical transform which filters and cumulates the wavelengths encountered in the profile. This transform was developed and calibrated in a manner that ensures that the output (i.e. the IRI) is closely correlated with (i) road user perception of roughness and (ii) tyre load dynamics, which impact on vehicle control and safety.

The IRI calculation is thus associated with profilometric methods, as illustrated in the bottom graph sequence of Figure 1.3. The IRI is characterized by a *specific processing algorithm*, which simulates the physical properties and displacement of a vehicle wheel and suspension system, *when moving at 80km/h*. This concept is illustrated schematically in Figure 1.4.

Thus, in essence, the IRI is calculated though a mathematical simulation of the physical response of a typical vehicle to a road profile. The IRI calculation thus mimics the physical processing and filtering of a measurement vehicle, as illustrated in the top graph of Figure 1.3, to produce a *simulated ARS value*. However, since the IRI calculation employs a computer algorithm – as opposed to an actual vehicle – to transform the profile into an ARS value, the IRI calculation has several distinct advantages over a response type measurement.

A key advantage of the IRI is that the transformation of the road profile is done through a computer algorithm which naturally remains constant over time. This offers a distinct advantage over the response type measurement which is dependent on the damping and stiffness properties of the measurement vehicle, which are sure to change over time, and also from one vehicle to another. The IRI parameter, when calculated from a profile that is accurately sampled, is thus *stable with time*.

Another advantage of the IRI is that it is reproducible, meaning that the IRI can be measured with different types of profiling devices, provided that the device measures the profile accurately. The IRI is also widely used internationally, and provides a fairly universal measure of road roughness that can be understood in many parts of the world.

It can be noted from Figure 1.4 that the algorithm used to process the profile in the calculation of the IRI, simulates the displacement of one wheel (i.e. one quarter) of a typical passenger car. Because of this, the IRI computation model is often referred to as the “quarter car model”.

It should be noted that, during the development of the IRI using the quarter car model, another index, called the Quarter Car Index (QI) was initially developed. The QI is conceptually the same as the IRI, and the two parameters are closely correlated. However, unlike IRI, the QI was based on readings taken from a particular type of equipment during the development study. Because of this, the original QI measure cannot be replicated today, and this index has been replaced by the IRI (Sayers et al., 1986).

Further Reading: IRI

The details of the IRI calculation are specified in ASTM E1926-98. This standard provides background to the IRI calculation and provides computer source code for calculating the IRI from a measured profile.

The Road Ruf Public domain software can be used to calculate the IRI and related parameters from a measured profile. The software can be downloaded from the UMTRI Road Roughness User Site located at:

[http://www.umtri.umich.edu/erd/roughness/index.html](http://www.umtri.umich.edu/erd/roughness/index.html)

More detailed theoretical background on the IRI calculation and the HRI calculation can be found in Sayers, 1989 and in the Little Book of Profiling [Sayers and Karamihas, 1998].
The IRI interpretation scale is illustrated in Figure 1.5. More detailed scales for IRI interpretation for paved and unpaved roads can be found in ASTM E1926-98. As shown in Figure 1.5, the IRI scale generally ranges from zero to 16. For paved roads in a good to moderate condition, the measured IRI generally ranges from 1.5 to 3.5. For unpaved roads the measured IRI generally ranges from roughly 4 to 12.

It is important to note that the IRI algorithm effectively filters the raw roughness data and in the process highlights the roughness elements that impact most on the roughness perception of road users. As such, the IRI algorithm eliminates all wavelength components that do not contribute to the roughness experienced by road users at speeds close to 80 km/h. According to Sayers [Sayers, 1986], these non-critical wavelength components (i.e. the ones filtered out by the IRI algorithm), consist of all those that fall outside the 1.3 m to 30 m wavelength band.

Because the IRI algorithm filters out wavelength components outside 1.3 to 30 m, IRI values should not be interpreted for section lengths shorter than 30 m, even though modern profilometers can record IRI values at 10 m intervals. It is recommended that, for interpretation of road roughness, IRI values be averaged over 100 m sections.

![Diagram of IRI calculation process](image-url)
1.5. **The Half Car Index (HRI)**

It was noted earlier that the IRI calculation simulates the motion of one quarter of a normal passenger car, and that the calculation uses the profile calculated in a single wheelpath. Many modern profilometers, however, can measure the profile in both wheelpaths simultaneously.

Theoretically, a more accurate assessment of roughness can be obtained if the roughness index is calculated from both wheelpaths, as opposed to only the left or right wheelpath. This is because the overall vehicle response is actually determined by the profile input from both left and right wheelpaths simultaneously. The IRI calculation, however, uses only a single wheelpath for its calculation.

The HRI is a parameter that uses the same processing algorithm as the IRI, but instead of using only the left or right wheelpath profile, the HRI uses the point-by-point average of profiles in the two travelled wheelpaths [Sayers, 1989]. By using both wheelpaths, the HRI provides a closer match to the way response type devices sense and measure roughness.

The HRI requires that the profile be measured in both wheelpaths simultaneously, or that the two profiles be perfectly synchronized in some other way. The latter process is difficult to perform if the two wheelpaths are profiled independently.

As expected, there is a close correlation between IRI and HRI, although HRI is always slightly lower than IRI. This is because each wheel track has unique roughness features that contribute to the bounce and roll of a motor vehicle. The IRI measured in individual wheel tracks quantifies the total magnitude (both bounce and roll) of the surface deviations. By contrast, the HRI simulates the response at the centre of the vehicle, and thus only measures the bounce component (and not the roll component) associated with the average deviation of the left and right wheels.
Summary of Concepts: Section 1

- Roughness is used to describe the relative degree of comfort or discomfort experienced by a road user when using a road.
- Roughness is a key aspect to monitor in network surveys, since it serves as a collective measure of road condition and its effect on road users and road user cost.
- Roughness is a result of variations in surface elevation along the wheelpaths of a road.
- The variations along the wheelpaths can be quantified through a measured profile of the road in the direction of vehicle travel (i.e. the longitudinal profile). The profile contains the information that can be used to assess the perceived road roughness.
- Not all of the wavelengths that make up a profile are important for roughness estimation. In general, only the wavelengths between 1 m and 30 m are important for roughness measurement.
- A measured profile is typically filtered to remove non-critical wavelengths from the profile, after which a roughness parameter is calculated.
- A roughness parameter is always determined over a fixed segment (e.g. a 10 or 100 m length) of a profile.
- There are generally two types of roughness measurement devices: (i) Response Type devices and (ii) Profiler Devices.
- Response Type devices do not measure the road profile, but uses the vehicle suspension to filter the actual road profile and convert this into a roughness parameter. The parameter is called the Average Rectified Slope (ARS) and is typically expressed in m/km.
- Profiler devices measure the road profile on one or both wheelpaths. The profile is then filtered and processed mathematically to produce a simulated ARS value, or other roughness parameters.
- The roughness parameter most widely used is the International Roughness Index (IRI), which is obtained by applying a mathematical transform (computer algorithm) to a measured profile in a single wheelpath. The transform is designed to simulate the movement of the suspension system of one wheel of a typical passenger car when moving at 80 km/h. The IRI model is therefore often referred to as the Quarter Car Model.
- The IRI scale generally ranges from zero to 16. For paved roads in a good to moderate condition the measured IRI generally ranges from 1,5 to 3,5. For unpaved roads the measured IRI generally ranges from roughly 4 to 12.
- The Half Car Index (HRI) is another roughness parameter that is calculated from the point-by-point averages of profiles measured in both wheelpaths. The HRI uses the same transform as the IRI and is thus closely correlated to the IRI. However, the HRI is always less than the IRI and provides little information in addition to that of the IRI.
2. ROUGHNESS MEASUREMENT CLASSES AND DEVICES

In this section, the different classes of measurement accuracy for roughness are first defined. The two main types of roughness measurement devices that are used for network level surveys are then discussed. These two types were defined in Section 1 and are (i) Response Type devices and (ii) High Speed Profiler Devices. For each type of device, a brief background or history is provided. The operational principles are then discussed and the advantages and disadvantages of the equipment are noted.

Other types of roughness measurement devices include slow-moving profilers, which are not used to conduct network level surveys, but which are important for purposes of setting out calibration sections and general benchmarking of measured profiles. These device types are discussed in Section 2.4.

2.1. MEASUREMENT CLASSES

Over roughly the past 50 years, many approaches to the measurement of roughness were developed worldwide. These methods of measurement differ in terms of the methods of operation as well as the repeatability and reproducibility of the measurements.

Sayers et al (1986) developed a general classification of roughness measurement devices that distinguish between all types of roughness measurement on the basis of (i) whether or not the profile is measured; and (ii) the required precision and reproducibility of the devices. The main classes of roughness measurement devices, as defined by Sayers et al (1986) are summarized in Table 2.1.

It will be noted from Table 2.1 that all devices that are capable of measuring an accurate road profile fall into Classes 1 and 2. Response type devices that have been calibrated before measurement fall into Class 3. Subjective ratings and uncalibrated response type devices constitute Class 4.

Since profiler devices fall into two classes (Classes 1 and 2), a further definition is needed to distinguish between Class 1 and Class 2 profilers. This classification is generally based on the sampling interval and the precision of the elevation measures. Sayers et al. (1986) developed accuracy requirements for Class 1 and 2 devices. These requirements are specified in terms of the required sampling interval and vertical measurement resolution, and are summarized in Table 2.2.

Table 2-1 Classes of Roughness Measurement

<table>
<thead>
<tr>
<th>Device Class</th>
<th>Class Requirements or Characteristics</th>
</tr>
</thead>
</table>
| Class 1: Precision Profiles | - Highest standard of accuracy measurement  
| | - Requires precision measurement of road profiles and computation of the IRI  
| | - 2 per cent accuracy over 320 m  
| | - IRI repeatability of roughly 0.3 m/km on paved roads  
| | - 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  
| | - Includes profiling devices not capable of Class 1 accuracy |
| Class 3: IRI Estimates from Correlations | - Does not require measurement of the road profile  
| | - Includes all response type devices  
| | - 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  
| | - Includes devices for non-calibrated response and profilometric devices |

The measurement devices in Class 3 generally include response type devices (as defined in Section 1.3), provided that the devices are properly calibrated by correlating the measurements to known IRI values on several calibration sections. Details of this calibration procedure are provided in Section 4.

Given the options for roughness measurement that currently exist, Class 4 measurements are no longer regarded as being suitable for network level surveillance, and the use of Class 4 methods is therefore not covered in these guidelines.

Table 2-2 Accuracy Requirements for Inertial Profilometers (ASTM E950-98)

<table>
<thead>
<tr>
<th>Device Class</th>
<th>Maximum Longitudinal Sampling Interval (mm)</th>
<th>Vertical Resolution (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>&lt; 25</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>Class 2</td>
<td>25 ≤ and ≤ 150</td>
<td>0.1 ≤ and ≤ 0.2</td>
</tr>
<tr>
<td>Class 3</td>
<td>150 ≤ and ≤ 300</td>
<td>0.2 ≤ and ≤ 0.5</td>
</tr>
<tr>
<td>Class 4</td>
<td>&gt; 300</td>
<td>&gt; 0.5</td>
</tr>
</tbody>
</table>
2.2. RESPONSE TYPE DEVICES

Background

Response type devices were the first type of device used to measure road roughness. These types of devices almost always consist of an instrument installed in a vehicle or trailer to record the up-and-down movement of the suspension (called the suspension stroke). These device types appeared as early as the 1920s, and are still widely used today.

Response type systems are relatively inexpensive and can measure roughness of up to 300 km per day. Although modern profilometric devices tend to overshadow response type devices, the latter type is widely acknowledged to provide a reasonable estimate of roughness. Engineers generally agree that measures obtained with response type systems match their experience of pavement roughness and overall condition [Sayers and Karamihas, 1998].

Response type devices are also called Response- Type Road Roughness Measuring Systems (RTRRMS), or Road Meter systems. In these guidelines, the term Response Type devices will be used throughout.

Operational Concepts

A response type system consists of the following main components (Sayers et al, 1986):

- The measurement vehicle;
- A transducer that detects the relative movement of the suspension;
- A recording system and display which is connected electronically to the transducer, and
- Automatic speed control and accurate distance measuring instruments.

The transducer, recording system and display are normally manufactured and sold as a single system (often called a Roadmeter), which measures the response of the vehicle to the road profile at the measurement speed.

The transducer measures the movement of the suspension in “counts” or millimetres. When the counts or total mm are summed, a parameter is obtained which gives an indication of the total suspension stroke that occurred over the length of road travelled. When the total count of summed mm of travel is divided by the length of the test section, the Average Rectified Slope (ARS) is obtained.

Further Reading: Response Type System Operations

A comprehensive discussion of the operation and guidelines for daily operation of response type devices can be found in World Bank Technical Paper 46 [Sayers et al., 1986]. It should be noted that this reference is aimed mainly at the system operators. Guidelines for controlling and monitoring the operation of response type devices, from the perspective of the network manager, are provided in Section 6 of these guidelines.

ASTM Standard E1082-90 specifies a procedure for measurement of roughness using a response type device. This standard covers device calibration and preparation before testing.

In South Africa, the Linear Displacement Integrator (LDI), which is manufactured and sold by the CSIR, is a popular and cost effective response type device. The LDI is installed in a passenger car with an independent rear axle and a coil spring suspension system. Figures 2.1 and 2.2 show some aspects of the LDI device.
The process of calibrating a response type device provides an equation which can be used to calculate an estimated IRI from the response type device output. It is critical to note that the calibration of a response type device is valid only as long as key aspects of the measurement vehicle (shock absorbers, tyres, loading, etc.) remain unchanged. The calibration is also performed only for a specific speed, which should be 80 km/h since this is the speed for which the IRI transform is designed.

Details of the calibration process for response type devices are provided in Section 4.

**Advantages of Response Type Devices**

- Response type devices have been used in many parts of the world for many years. Many engineers are therefore well acquainted with the operation and output of these devices.
- In general, response type device outputs are known to agree with engineers’ assessment of roughness and pavement condition.
- Response type devices are relatively inexpensive. A reliable, modern response type device can generally be obtained for less than R100 000 (2006 prices, excluding the measurement vehicle). The cost of response type systems is generally less than 1/10th of the cost of a high speed profiling device.

**Important!**

It is critical to note that the calibration of a response type device is valid only as long as key aspects of the measurement vehicle (shock absorbers, tyres, loading, etc.) remain unchanged. The calibration is also performed only for a specific speed, which should be 80 km/h since this is the speed for which the IRI transform is designed.

- Although response type devices require frequent maintenance and care of operation to ensure that the calibration remains valid, the maintenance and care of the equipment is relatively simple and inexpensive to perform.
- The calibration process for response type devices is relatively easy and inexpensive to perform once calibration sections have been set out and measured.

Although the basic operational principles of most response type devices are similar, the output obtained may differ. Some devices provide an output in counts/km while others may provide output in m/km or HRI (as defined in Section 1.5).

Since the preferred parameter for quantifying roughness is IRI, the output from response type devices needs to be converted to IRI. This is done by means of a procedure known as “correlation by calibration”. In this procedure, the output from a response type device is correlated with the known IRI values of several selected sections of road. These sections are known as calibration sections and the IRI values of these sections need to be determined beforehand using one of the high precision profiling devices discussed in Section 2.4.
In South Africa, response type devices appear to be more successful on gravel roads than profiling devices.

Response type devices can be used on gravel roads whilst Inertial Profilometers cannot.

Disadvantages of Response Type Devices

- The precision (and hence repeatability) of response type devices is significantly lower than that of a Class 1 profiling device. Furthermore, the annual deterioration of IRI on a typical road section is often smaller than the measurement error of response type devices (the measurement error occurs because of the lack of high precision, and also because of errors inherent in the calibration to correlate with IRI). This means that response type devices generally cannot track the deterioration of a road network on an annual basis (although it can perhaps do so over a 3 or 5 year period).

- In response type devices, the transformation of the road profile to an IRI value is completely dependent on the properties of the vehicle suspension system. These properties are known to change over time, and also from one response type vehicle to the next. The output of response type devices thus has a tendency to shift over time (i.e. it is not stable). Because of this, response type devices require calibration at least on an annual basis.

- Response type roughness measurement devices only measure road roughness. By contrast, many modern high speed surveillance devices can measure the lateral and longitudinal profile, and obtain high resolution photographs or videos of the road surface at the same time.

2.3. HIGH SPEED PROFILING DEVICES

Background

High speed profiling devices are capable of measuring a precision profile of one or more wheelpaths while moving at speeds in excess of 100 km/h. The first high speed profiling device appeared in the 1960's [Sayers and Karamihas, 1998]. Since this time, significant advances in precision measurement technology have greatly aided the design of high speed profilers and today these devices are used for road surveillance in many parts of the world.

High speed profilers are also referred to as Inertial Profilers, owing to the use of accelerometers to determine an inertial reference which provides the instantaneous height of the measurement base at all times when the vehicle is moving.

Operational Concepts

A high speed longitudinal profiling device consists of the following main components:

- The measurement vehicle;
- A height sensor (called a transducer) to measure the distance from the measurement base to the road surface. There are four types of height sensors commonly in use. These are: laser, optical, infrared and ultrasonic.
- Accelerometers to measure vertical acceleration of the measurement base. The accelerometer reading is used in conjunction with the height sensor output to determine the elevation of the road surface.
- A distance measuring system to measure the longitudinal distance along the road.
- A computer and data storage system to process the output from the height sensor, accelerometer and distance measuring system, compute the surface profile (or profiles, if both wheelpaths are being measured), and store the computed profile with other parameters such as vehicle speed, position coordinates, etc.

The height sensors, accelerometers and distance measuring equipment are calibrated in the factory by the equipment manufacturer, and remain calibrated for a long time. For this reason, and unlike response type devices, precision high speed profilers should not be calibrated as part of the measurement process. Instead, the output of the device is validated by measurement of test sections with known IRI values to determine if all of the components of the system work correctly and that the device is capable of measuring the road profile to the required level of precision.

Most high speed profilers need to move at speeds in excess of 15 km/h to function properly. However, while static these devices can be operated in "test mode" to check that the height sensor and accelerometers are functioning properly.

Figures 2.3 and 2.4 show two types of high speed profiling devices that have been used for network level roughness measurement in South Africa.
The most often used type of height sensor uses laser technology. Ultrasonic height sensors do not operate accurately on rough surfaces like chip seals and therefore cannot be employed for roughness measurement on many South African roads. Optical sensors are sensitive to white pavement markings (leading to “spikes” in measured profiles) and also do not always function well on dark pavement surfaces like new asphalt surfacings [Research Results Digest No. 244, 1999].

Advantages of High Speed Profiling Devices

- A validated high speed profiler is capable of measuring the surface profile very precisely. Also, since the IRI transform uses a fixed computer algorithm, the processing constants remain unchanged, and thus the measured IRI is consistent over time.

- Owing to the stability and precision of IRI values obtained with a validated high speed profiler, such IRI values can be used to track the deterioration of network sections from one year to the next.

- Modern high speed profilometers are often capable of measuring the longitudinal and transverse profile at the same time, thereby providing a roughness and rutting assessment simultaneously. Some devices are also capable of obtaining a high resolution video of the pavement surface at the same time.

Further Reading: High Speed Profiler Operations

Guidelines for the operation of high speed profiling devices can be found in NCHRP Research Results Digest No. 244 (1999). It should be noted that these guidelines are aimed at the persons responsible for daily operation of the profiler. Guidelines for controlling or monitoring the operation of profilometers, from the perspective of the network manager, are provided in Section 6 of these guidelines.

ASTM Standard E950-98 specifies a standard test method for measurement of longitudinal profiles using an inertial profiling device. The standard covers aspects such as component calibration, system checks, test sections, data acquisition and data evaluation and reporting.
Disadvantages of High Speed Profiling Devices

- Inertial profiling devices using laser height sensors are not successful for profiling gravel roads.

- Modern high speed devices are relatively expensive, and – unlike response type devices – few network agencies can afford to purchase and maintain their own profiler. In South Africa, there are relatively few contractors capable of performing high speed profile measurements, and equipment availability is often a problem. In the past, equipment was often imported for a few months to perform measurement on a network in South Africa. The cost of testing is therefore relatively high compared to that of response type measurements.

- Although the components of high speed profilers are calibrated by the manufacturer, extensive validation testing and control procedures are still needed to ensure that the measured profile is accurate. If rigorous validation procedures are not followed, the results of a profiler are often of little more use than those of a calibrated response type device. These validation procedures are costly and require more up-front investment of time and funds by the owner of the road network (see Section 5 for details).

- The procedures for operation and control of high speed profiling devices are relatively complex, and require that the network manager invests time to understand and participate in the validation and control procedures (see Section 6 for details).

2.4. Static Profiling Devices

It was noted in Section 2.3 that response type devices need to be calibrated by correlating the outputs of these devices to known IRI values on several test sections. Similarly, the outputs of high speed profiling devices need to be validated by comparing the measured profile and IRI values to the known profile and IRI values of several test sections.

A vital aspect of roughness measurement at the network level is thus the identification and profiling of test sections (or calibration sections). The profiles and IRI values obtained on these calibration sections then become the benchmark values used for the calibration of response type devices and for the validation of profilers.

Naturally, the measurement of the profile and IRI values of the calibration sections must be performed to the highest level of precision and under the highest level of control. Class 1 profiling devices (see Section 2.1) are therefore used to measure the profiles on network calibration sections.
Many high speed profiling devices are capable of Class 1 measurements. However, since the devices move at speeds in excess of 25 km/h, the line of measurement can never be 100 per cent controlled. Thus, to increase repeatability of measurements on calibration sections, static or slow-moving profiling devices are mostly used. Three such Class 1 profiling devices that are often used to measure the profile on calibration sections are the Precision Rod and Level, Face Dipstick™ and ARRB Walking Profiler devices.

### Precision Rod and Level

The operational principles of the precision rod and level are illustrated in Figure 2.5. As shown in this figure, the operation is very similar to that of a normal rod and level operation, as used for surveying, etc. However, in view of the high precision required for the profile of calibration sections, the precision rod and level equipment has a higher precision and the operation should follow the standard test method (ASTM E1364-95).

It should be noted that the test method described in ASTM Standard E1364-95 requires at least two persons and is time consuming and labour-intensive. A typical profile measurement will involve around 260 readings, and an experienced team can profile approximately 600 m per day. The method is therefore only suited for measuring profiles on calibration sections or for research or construction control purposes.

Once the profile of a calibration section has been measured, the profile is processed to determine the IRI of the section. The IRI can then be used to calibrate response type systems, while for profiling validation, both the measured profile and the IRI can be used.

### Important!

Since profiler components are calibrated in the factory, these devices are never calibrated as part of network survey operations, but only validated (i.e. correct operation is validated in the field). Response type devices, on the other hand, are calibrated as part of the survey process. For conciseness, however, the test sections on which such validation and calibration are performed will be generally referred to as calibration sections in these guidelines.

Further Reading: Precision Rod and Level

ASTM Standard E1364-95 describes a standard test method for the measurement of profiles to determine the IRI using precision rod and level equipment.

ProVal public domain software can be used to calculate the IRI and related parameters from a measured profile. The software can be downloaded from the following site: http://www.roadprofile.com

It is important to note that the profile measured with a rod and level device cannot be compared to the profile measured with a high speed profiler in a simplified manner (e.g. using simple elevation plots). This is because the inertial systems automatically filter out the longest profile wavelengths (e.g. vertical alignment). The profiles therefore have to be filtered identically before they can be compared using simple plots of elevation versus distance. [ASTM E1364-95].
Other Static or Slow Moving Devices

Two other devices that conform to the requirements for Class 1 devices and are often used to measure reference profiles on calibration sections are the Face Dipstick™ and the ARRB Walking Profiler devices.

The Face Dipstick™ (patented, manufactured and sold by the Face Corporation) is illustrated in Figure 2.6. When used, the device is “walked” along the line being profiled. The device contains a precision inclinometer that measures the height between the two support feet at the base of the instrument [Sayers and Karamihas, 1998]. These feet can be spaced 20 to 500 mm apart, and in South Africa a spacing of 250 mm is typically used.

The Dipstick™ is moved by leaning all of the device weight onto the front foot, and then pivoting the rear foot around the front foot by 180 degrees. When the instrument has stabilized, the change in elevation is automatically recorded and a beep is sounded. The longitudinal distance is determined by multiplying the number of measures made with the known spacing between the contact feet [Sayers and Karamihas, 1998]. The Dipstick™ can record at approximately 200 m per hour.

The ARRB Walking Profiler is shown in Figure 2.7. This device was developed by the Australian Road Research Board Ltd. and is roughly the size of a lawnmower. Profile measurements are performed at walking pace or roughly 800 metres per hour, with a practical production rate of approximately 4 km per day. A built-in data acquisition system captures and stores profile data while measurements take place.

The ARRB Walking Profiler outputs include distance, grade and IRI. The profile accuracy is ± 1.0 mm/50 m and the IRI accuracy is ± 0.1 m/km.
Summary of Concepts: Section 2

- Roughness measurement devices can be divided into four measurement classes.
  - Class 1 devices provide the highest level of accuracy and have a precision of 0.1 mm.
  - Class 2 devices are suitable for high accuracy network level measurements, and have a precision of 0.1 to 0.2 mm.
  - Class 3 devices do not explicitly measure the road profile, but provide an estimate of IRI using correlations with the device output.
  - Class 4 measurements include subjective visual evaluations of roughness and devices are not calibrated in a rigorous manner.

- Measurement devices are generally of three types: (i) response type devices; (ii) high speed profilers; and (iii) static or slow moving devices.
  - Response Type devices measure the response of the measurement vehicle to the road profile. The response is typically expressed as the total up-down movement of the vehicle suspension over a measurement section. This parameter is known as the average rectified slope (ARS).
  - High Speed Profilers are capable of measuring the road profile at typical highway speeds. The road profile is measured and then converted to IRI using the IRI transform to simulate vehicle response to the measured profile.
  - Static or Slow-Moving devices include Precision Rod and Level, the Face DipstickTM and the ARRB Walking Profiler. These devices are time consuming to use but provide the highest level of precision and accuracy. They are generally used to measure the profile of calibration and validation sections, and the measured profiles then serve as a benchmark for other measurements.

- Response Type devices are relatively inexpensive, and provide outputs that relate well to the experience of engineers. The operation and maintenance of the devices are less expensive and complex than those of high speed profilers and the calibration of the devices is relatively simple to perform. However, output from response type devices is not precise enough to provide an indication of the annual deterioration of a network section. Measurements are highly sensitive to small changes in the configuration of the measurement vehicle (e.g. changes in suspension, tyres, load, etc.).

- High Speed Profilers can measure the road profile with a high precision. IRI values from a validated profiler can be used to monitor network deterioration from one year to the next, and such values can serve as inputs into network planning models. Most high speed profilers are designed to measure not only the longitudinal profile, but also the lateral profile and obtain a video of the road in the same operation. High speed profilers are relatively expensive. Compared to response type devices, the validation process of profilers requires a slightly greater upfront investment of time, and more in-depth understanding, by the network manager.
3. **PLANNING A ROUGHNESS SURVEY**

In this section, guidelines are provided for the planning of network level roughness surveys. The guidelines emphasize the need to define realistic objectives for the survey upfront. Once the objectives of the survey are clear, planning can proceed to determine the following essential elements of a roughness survey:

- **Device Selection**
- **Specifications**
- **Equipment Validation or Calibration**
- **Measurement Control**
- **Data storage and reporting**

Since all of the above aspects need to be defined in a contract document, this section deals to a large extent with issues that need to be resolved in order to complete a contract document or specification for network level roughness survey.

### 3.1. **SURVEY OBJECTIVES**

Network level roughness data can be used for three main purposes [Sayers et al., 1986]:

- To provide a summary of the network condition, either on a regular basis (e.g. annually) or on an irregular basis (e.g. every four years).
- Roughness measurements can serve as inputs for models that evaluate the effectiveness of pavement design standards and maintenance policy, and to assess the relative cost of transporting goods.
- Roughness measurements can be used to prioritize and/or optimize maintenance and rehabilitation actions on the network.

Bearing these potential uses of the data in mind, the objectives of a network level roughness survey should be determined through careful consideration and synthesis of the following aspects:

### 1. Budget and Manpower Constraints

This consideration is intimately linked to the intended use of the data. There is probably at least an order of magnitude difference between the cost of a survey conducted with a response-type system and that of a survey conducted with a precision high speed profiling device. Budget constraints are therefore a primary consideration.

Manpower requirements (in terms of time and expertise) are also important. Even when a network level survey is performed by an independent contractor, some level of involvement from the network manager will be necessary to monitor calibration or validation actions and to exercise process and quality control.

The level of involvement and expertise required from the network manager will depend on the sophistication and quality of the equipment involved, as well as the complexity and quantity of data generated by the survey. Even when network management services are contracted out, some level of involvement will be needed, and in any event the cost implication will remain. Thus budget and manpower constraints are a primary consideration.

### 2. Intended Use of the Data

This is an obvious consideration in determining the survey objectives. At the most basic level, the data could be used to obtain a once-off, relative assessment of the roughness of different sections of the network. Such information could be used to compare the relative roughness of different sections, and to prioritize maintenance and rehabilitation actions.

At the most detailed level, roughness data could be collected annually to provide an absolute indication of the roughness of different network sections. Such information could be used not only to prioritize maintenance and rehabilitation, but also to assess network deterioration, effectiveness of policy, etc.

Obviously, a once-off, relative assessment would require less precision than an annual, absolute assessment of network roughness. As a result, the cost of the survey will differ greatly depending on the intended use of the data.

### 3. Equipment Availability

Few road network agencies can afford to buy and maintain their own network level surveillance equipment. Most agencies contract out surveillance services to specialists. However, within South Africa there are a limited number of surveillance vehicles. Coupled with this is the fact that the surveillance of some networks can take several months to complete.
The availability of equipment is thus a practical consideration that should be taken into account when planning a network level survey. A first action would thus be to determine what equipment will be available. This consideration is especially important if the survey is to be performed on an annual basis.

In Table 3.1, the basic survey types with their potential data uses and recommended devices are summarized. This table also shows the recommended levels of calibration or validation to be considered for different survey types. These levels are discussed in detail in Section 4 (for response type devices), and in Section 5 (for profilers).

### Table 3-1 Network Level Planning Considerations

<table>
<thead>
<tr>
<th>Frequency of Measurement</th>
<th>Data Uses</th>
<th>Type of Devices</th>
<th>Validation and Calibration Requirements (Notes 1 and 2)</th>
</tr>
</thead>
</table>
| Once-off assessment of network roughness | • Prioritization of maintenance and rehabilitation | • Response type devices  
• Class 1 and 2 Profilers | • Level 1 Calibration (response type devices)  
• Level 1 Validation (profilers) |
| Three-to-five yearly assessment of network roughness | • Prioritization of maintenance and rehabilitation  
• Monitoring of relative network deterioration | • Response type devices  
• Class 1 and 2 Profilers | • Level 2 Calibration (response type devices)  
• Level 2 Validation (profilers) |
| Annual or biennial assessment of network roughness | • Prioritization of maintenance and rehabilitation  
• Monitoring of absolute network deterioration  
• Inputs into planning models | • Class 1 and 2 Profilers | • Level 2 Validation (profilers)  
• Level 3 Validation (optional) at contract start or when device type is changed (Note 3) |

**Note 1:** Levels of calibration for response type devices are defined and discussed in Section 4. Levels of validation for profilers are discussed in Section 5.

**Note 2:** In all cases, operational checks and controls as defined in Section 4 (for response type devices) and Section 5 (for profilers) should be strictly implemented.

**Note 3:** Level 3 validation requires specialist analysis of profile data, and is recommended only where the highest level of precision is needed (for annual surveys, and to be performed at the contract start or when there is a change in device type or major maintenance on the equipment).
3.3. **SPECIFICATIONS**

Once the survey objectives, survey frequency and device type have been decided on, the practical aspects of the survey planning can commence. Foremost of these is the compilation of contract specifications, which would lay down criteria for the quality and acceptance of the survey.

To optimize measurement consistency, a network surveillance contract period should preferably cover several years. It is not advisable to appoint a different contractor and/or device type each time a survey is undertaken. It is thus important that contract documentation be comprehensive and should cover all aspects to ensure high quality data over several years of a contract.

A multi-year contract with a single contractor – as opposed to a single year contract, or re-tendering with each survey year – is thus strongly recommended as it will justify the considerable effort needed to compile comprehensive specifications and to perform adequate calibration or validation. It also provides an incentive for the contractor to implement long term quality improvement plans and incorporate network specific experience into the survey process.

The specifications for roughness surveys should cover the following aspects:

- Equipment specification
- Calibration or validation
- Measurement control
- Survey procedures
- Contract quality plan
- Reporting and data reporting format

Guidelines for the specification of each of these aspects are provided in the following paragraphs. It should be noted that these paragraphs are not intended to constitute an actual specification. Network managers should use the guidelines to ensure that all relevant aspects are covered by their specifications, and that the specification details are appropriate for the defined survey objectives.

**Equipment Specification**

The equipment specification should define the minimum requirements for equipment, and should cover aspects such as instrument type, precision and recording intervals. Tables 3.2 and 3.3 provide a summary of key aspects to consider when defining equipment specifications.

It is vital that the equipment specification be compatible with the survey type and objectives. It is meaningless to specify a level of precision that is not achievable with available equipment.

**Calibration or Validation**

This part of the specification should deal with the procedures to be followed for component calibration, system calibration (in the case of response type devices) or system validation (profilers). Component calibration deals with the calibration of individual components of the system (e.g. lasers or accelerometers or distance measuring transducers). System calibration or validation deals with the checks to ensure the accuracy of the measurement system as a whole.

<table>
<thead>
<tr>
<th>Importance or Relevance</th>
<th>Parameter</th>
<th>Example Specification for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required (some parameters may not apply to response type devices)</td>
<td>Equipment Type</td>
<td>Inertial Profiler</td>
</tr>
<tr>
<td></td>
<td>Measurement Speed</td>
<td>80 km/h</td>
</tr>
<tr>
<td></td>
<td>Resolution</td>
<td>0,05 mm</td>
</tr>
<tr>
<td></td>
<td>Longitudinal Sample Interval</td>
<td>50 mm</td>
</tr>
<tr>
<td></td>
<td>Measuring Range</td>
<td>200 mm</td>
</tr>
<tr>
<td></td>
<td>Repeatability</td>
<td>0.1 mm</td>
</tr>
<tr>
<td></td>
<td>Operating Temperature Range</td>
<td>0°C to 50°C</td>
</tr>
<tr>
<td>Optional if high level control is exercised during validation or calibration procedures</td>
<td>Frequency Response</td>
<td>DC: -16 kHz</td>
</tr>
<tr>
<td></td>
<td>Long Term Drift</td>
<td>&lt; 0,3 per cent</td>
</tr>
<tr>
<td></td>
<td>Filtering</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>
Component calibration should specify the requirements for calibration of system components, and should address the following issues:

- Where relevant, the specifications may require that the contractor produce calibration certificates that are current, and that are preferably issued by an accredited body.
- If components are to be recalibrated during the course of the contract, the rules or conditions of recalibration should be specified.
- The components for which proof of calibration is required should be clearly specified.

System calibration for response type devices should be performed to ensure that the measurement device as well as the data acquisition system are working properly, and to adjust the device output so that it is adequately correlated to known values over a range of roughness values. Aspects to be covered in the specifications for system calibration include the following:

- The number and type of calibration sites should be specified. These sites should preferably be located and measured (using a Class 1 profiling device) by the network agency.
- The length of the calibration sections should be specified (see Section 3.4 for details).
- The calibration methodology and criteria should be specified (see Section 3.4 for details).
- Details of the calibration procedure, such as demarcation of sections, measurement speeds, and data to be gathered should be specified.

System validation for profiling devices should be performed to ensure that the measurement methodology (which includes device operation, data acquisition, operation and output) will provide roughness data in the correct format, and to the specified quality and consistency. Aspects to be covered in the specifications for system validation include the following:

- Pre-validation report: before validation procedures start, the contractor must provide a report to ensure that calibration requirements are met and that the equipment specifications are met.
- Aspects to be considered as part of the validation should be clearly specified. These should include roughness data, GPS equipment, distance measurement, etc. Details of these requirements are provided in Sections 4 and 5.
- Personnel: for profiling surveys, the training and experience of the operator can have a significant influence on the roughness results. Validations should ideally be performed for each vehicle operator.
- Multiple vehicles: the specifications should specify validation procedures if the survey is to use more than one vehicle.
- Validation procedures should be specified in case of vehicle breakdown.
- Statistical methods for processing validation data should be clearly specified, and a processing algorithm or spreadsheet should ideally be provided.
- Acceptance criteria should be specified to define the limits for a successful validation.
- The length of time over which a validation will be valid should be specified.
- If the contractor is to compile a validation report, then the reporting requirements should be specified.

### Table 3-3  Equipment Specification Considerations for Global Positioning Systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Example Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Type</td>
<td>Differentially Corrected Global Positioning System (DGPS)</td>
</tr>
<tr>
<td>Resolution (Static)</td>
<td>1 m (horizontal and vertical)</td>
</tr>
<tr>
<td>Sample Interval</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Repeatability (Static)</td>
<td>5 m (horizontal and vertical)</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>0°C to 50°C</td>
</tr>
</tbody>
</table>
It is important to note that the validation of profilers involves complex equipment and a variety of road conditions. Specifications for equipment validation and control should allow for the network manager to override or amend certain requirements under special conditions. Guidelines for tolerance limits for validation are provided in Section 5.

**Roughness Measurement: Version 1.0**

**Measurement Control**

The specifications for measurement control should include the checks and procedures to be followed on a daily basis, as well as control procedures to be undertaken from time to time. These control procedures will typically consist of a periodic remeasure of calibration sections to ensure that the device is still calibrated and valid, with no excessive drift in measurement. Guidelines for control procedures, including daily checks, are provided in Section 4 for response type devices and in Section 5 for profilers.

**Survey Procedures**

The specifications for survey procedures should cover aspects such as measurement speed and speed tolerances, survey start and end procedures, segment lengths and identification. The specifications should also note when a survey over a section should be repeated (e.g. when the vehicle is forced to stop, if adverse environmental conditions are encountered, etc.). The specifications for survey procedures may also be included as part of the measurement control specifications. Guidelines for survey procedures are provided in Section 4 for response type devices and in Section 5 for profilers.

**Contract Quality Plan**

The contractor should ideally submit a contract quality plan as part of the tender documentation. This plan should clearly define the procedures that will be followed to exercise quality control. The specifications should define the requirements for the quality plan, if such a plan is required from the contractor. Items to be addressed by the contract quality plan should include:

- A description of survey equipment, including data processing details, sampling intervals, anti-aliasing and other filters (only for profilers).
- Software to be used and methods for validating software accuracy.
- The procedures and details of the training of personnel to conduct the survey.
- Calibration procedures and examples of quality control checklists to be completed on a daily, weekly and monthly basis.
- Contingency plans to cover data backup, equipment breakdown, etc.
- Procedures and methods that will be followed during the survey, including start and end procedures on network segments.
- Ongoing checks to ensure distance measurement is accurate and valid.
- Data reporting formats (to match specifications).
- Control procedures to ensure accuracy of data processing (e.g. averaging over subsections) and reporting.

**Data Reporting Format**

The specifications should define the format in which the contractor should submit the data. The specifications should cover aspects such as:

- File format (e.g. ASCII file, comma delimited).
- Averaging procedures and segment length for reporting (e.g. data averages over 100 m segments).
- Required fields (columns), field length and number of decimals required.

The required fields would depend on the survey objectives but should include aspects such as section name, start km, end km, GPS coordinates, region, direction, survey date, IRI (for one or more wheelpaths) and measurement speed.

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**Further Reading: Calibration Sections and Calibration Procedures**

Guidelines for the selection of calibration sections are provided in Section 3.4.

Guidelines for the calibration of response type devices are provided in Section 4.

Guidelines for the validation of profilers are provided in Section 4.
Roughness Measurement: Version 1.0

Reporting
The specifications should list all reports that will be required from the contractor at different stages of the contract period. Report types that can be specified include:

- Pre-validation reports
- Calibration and validation reports
- Data summary reports
- Progress reports

For each report type, the specifications should state the submission deadlines, report formats, minimum requirements and general format. For calibration reports, it is important to ensure that vehicle configuration aspects (Section 6.1) be documented. Some of the aspects relating to the bulk roughness data and summary report are discussed in Section 6.3.

Other Aspects
The data delivery time and deadlines for all other deliverables should be specified. Where applicable, bonus and penalty schemes can be included. Most surveillance devices should be able to provide the data in a processed format immediately after, or within a short period after measurement. It is recommended that delays between the time of survey and data delivery be minimized to enable better monitoring of the measurement and processing tasks.

The contract specifications should also address other aspects which are part of the network agency’s directives and which may be affected by the surveillance contract. These aspects include:

- Required standards for traffic management and safety
- Aspects related to occupational health and safety for operators and the public
- Aspects related to environmental protection

For these aspects, it would often suffice to specify a requirement for the contractor to adhere to the relevant standards and codes of practice.

3.4. CALIBRATION SECTION REQUIREMENTS
The identification and survey of calibration sections should be done before any surveying is started on the network. Ideally, these sections should be selected and profiled by the network agency, or by a contractor other than the one responsible for the actual survey.

Key aspects related to calibration sections are the selection of the sections, profiling of the sections and processing of the calibration section profile data to facilitate calibration or validation. Each of these three aspects is discussed in the following paragraphs.

Selecting Calibration Sections
Sections to be used for calibration should be selected according to the following guidelines [Sayers et al., 1986]:

- Section lengths should be at least 200 m long, but should preferably be between 300 and 500 m long. All sections should have the same length.
- The calibration sections should be selected so that there is at least one section in each of the roughness ranges shown in Table 3.4. The sites should also be selected so that there are approximately an even proportion of sections in each roughness range.
- Each calibration section should have a relatively uniform roughness over its length as well as over the 50 m preceding the start of the section.
- The sections should preferably be on straight (tangent) sections of road. The sections do not need to be level, but there should be no significant change in grade within or before the section.
- The calibration sections should have different surfacing types, representing the types of surfacing frequently found on the network.

Important!
Since profiler components are calibrated in the factory, these devices are never calibrated as part of network survey operations, but only validated (i.e. correct operation is validated in the field). Response type devices, on the other hand, are calibrated as part of the survey process. For conciseness, however, the test sections on which such validation and calibration are performed will be referred to as calibration sections in these guidelines.

For practical reasons, it is also recommended that the calibration sites be located relatively close to the centre of operations, and that the sites selected sites are not subject to rapid deterioration. If a calibration site is rehabilitated, another site with a similar roughness range should be selected and profiled.
Table 3-4  Roughness Ranges for Calibration Section Selections

<table>
<thead>
<tr>
<th>IRI Range</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 to 3.0</td>
<td></td>
</tr>
<tr>
<td>3.0 to 4.5</td>
<td></td>
</tr>
<tr>
<td>4.5 to 6.0</td>
<td></td>
</tr>
<tr>
<td>6.0 to 8.0</td>
<td></td>
</tr>
<tr>
<td>8.0 to 16.0</td>
<td></td>
</tr>
</tbody>
</table>

Profiling Calibration Sections and Determining the Reference IRI

The reference device used to measure the profile of calibration sections should be able to match the criteria of a Class 1 device, as specified in ASTM E1365-95. This ASTM standard also defines the longitudinal sampling distance and vertical resolution of the device. The Precision Rod and Level, Dipstick™ and ARRB Walking Profiler devices (discussed in Section 2.4) are capable of meeting these criteria.

The following procedure is recommended for the measurement of reference profiles and IRI values on calibration sections:

- Each wheel path of each calibration section should be profiled four times, consisting of two runs in which the device returns along the same wheel path to form a closed return loop.

- The reference profiles should be stored and the IRI values calculated according to the calculation defined by ASTM E1926-98, which can be achieved using the public domain Road Ruf software.

- The IRI should be calculated for every 100 m segment of each measurement run over each wheelpath.

- The reference IRI for each wheelpath of the calibration section should be calculated as the mean of the four runs.

As a rough guideline, reference profiles can be considered acceptable if the variation in the IRI over each 100 m is less than 3 per cent or 0.2 IRI (whichever is greater). These criteria can be relaxed if special conditions prevail (like localized distress).

Further Reading: Determining the Reference IRI

ASTM Standard E1364-95 describes a standard test method for the measurement of profiles to determine the IRI using precision rod and level equipment. ProVal public domain software can be used to calculate the IRI and related parameters from a measured profile. The software can be downloaded from the following site:

http://www.roadprofile.com
### Checklist for Planning a Network Level Survey

<table>
<thead>
<tr>
<th>Item</th>
<th>Control or Decision Aspect</th>
<th>Guidelines in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Define budget and manpower constraints</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Define survey objectives and type or frequency of testing (Table 3.1)</td>
<td>Section 3.1</td>
</tr>
<tr>
<td>3</td>
<td>Obtain typical costs for surveying with recommended device types</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Determine equipment availability</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Decide on equipment type</td>
<td>Section 3.2</td>
</tr>
<tr>
<td>6</td>
<td>Determine contract period and compile project specifications</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Compile specifications for equipment</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Compile specifications for calibration and validation</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Compile specifications for measurement control</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Compile specifications for survey procedures</td>
<td>Section 3.3</td>
</tr>
<tr>
<td>11</td>
<td>Compile specifications for the contract quality plan</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Compile specifications for the data reporting format</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Compile specifications for reporting</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Identify calibration sections</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Obtain reference profile on calibration sections</td>
<td>Section 3.4</td>
</tr>
<tr>
<td>16</td>
<td>Process calibration section reference profiles as needed</td>
<td></td>
</tr>
</tbody>
</table>
4. CALIBRATION AND CONTROL TESTING FOR RESPONSE TYPE DEVICES

Since response type devices do not measure the actual road profile, the IRI cannot be calculated directly. Instead, the output of these devices is calibrated or adjusted to enable a relatively accurate assessment of the IRI to be made. This section deals primarily with the process for calibrating response type devices at the start of the network survey process, and also discusses measurement control procedures to be performed during the survey period.

It should be noted that a network manager can participate or control the calibration process, or can simply request that a calibration report be handed in before the measurement device is approved for use on the network. In the latter case, it is important for network managers to understand the key aspects related to calibration, and the preferred format of a calibration report. These aspects are covered in the paragraphs that follow.

4.1. CALIBRATION REQUIREMENTS

Guidelines for the location of calibration sites were provided in Section 3.4. Tables 4.1 and 4.2 shows guidelines for setting requirements for the calibration procedure.

As shown in Table 4.2, the calibration procedure requires a number of repeat measurements on each calibration section. Measurements should be made at the designated measurement speed, which should be 80 km/h for IRI measurement, unless special circumstances dictate another measurement speed.

It is recommended that the criteria shown in Table 4.2 be used as a guideline for accepting or rejecting a calibration for a response type device. The contractor should compile a calibration report in which the details of the calibration are clearly defined. The calibration report should show the following:

- Details of calibration sections used.
- Table showing average device count or measure for each run over each section, with the average and standard variation for of all runs over each section, versus the reference IRI.
- Evaluation summary sheet, showing compliance to the criterion shown in row 3 of Table 4.2 (repeatability per calibration section).
- Regression summary sheet showing compliance to regression criteria as shown in rows 4 and 5 of Table 4.1.
- Raw data for each calibration section, in electronic and hardcopy format, in Appendices.

Appendix B shows an example of summary sheets for calibration of a response type device in which the calibration does not satisfy the criteria in Table 4.1.

It is critical that the network manager accompany the contractor during the calibration testing, and note down values observed during repeat runs, as well as details of the vehicle configuration (e.g. driver used, number of occupants, tyre details, etc). Basic elements of the vehicle configuration should be checked and controlled during the survey. These aspects are discussed in more detail in Section 6.

4.2. VALIDATION OF POSITIONING EQUIPMENT

Validation of the distance measurement and location referencing equipment involves checking of the odometer and Global Positioning System (GPS). For the validation of the GPS, the following criteria are recommended:

GPS Validation

The GPS should be validated by comparing coordinates at several benchmark locations set out and maintained by a registered surveyor or surveying authority. It is recommended that this check be carried out at five to ten benchmark locations.

GPS benchmark locations should be roughly 1 km apart, and the dynamic accuracy of the GPS should be checked by completing several survey loops through the benchmark positions. These checks should preferably also be performed over more than one day, and at different times of the day.

The ability of the GPS inertial system to compensate for a loss in the GPS signal should preferably be demonstrated by the contractor.

The GPS coordinates should be within 5 m of the vertical and horizontal benchmark values, and for repeat dynamic measurements this accuracy should be achievable 90 per cent of the time.
Table 4-1 Guidelines for Calibration Acceptance Criteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recommended Criteria for Application Type:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Reliability</td>
</tr>
<tr>
<td>Scatter plot showing IRI (Y-axis) versus measured parameter</td>
<td>Examine scatter plot and ensure that the relationship is linear, and that the data range covers the range of expected IRI values on the network.</td>
</tr>
<tr>
<td>Coefficient of determination (R^2) for regression (Note 1)</td>
<td>Greater than 0.950</td>
</tr>
<tr>
<td>Standard error for regression</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Note 1: The regression refers to a simple regression analysis. For this regression, the dependent (Y) parameter is the reference IRI over each 100 m of the calibration section. The independent (X) parameter is the measured parameter over each 100 m segment, and for each repeat. Thus, there should be one data point for each repeat measurement on each 100 m segment of each calibration section.

Table 4-2 Calibration Requirements for Response Type Devices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recommended Requirements for Application Type (Note 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Reliability</td>
</tr>
<tr>
<td>Number of sites for each relevant roughness range (Note 2)</td>
<td>2</td>
</tr>
<tr>
<td>Minimum site length</td>
<td>200 m</td>
</tr>
<tr>
<td>Repeat runs per site</td>
<td>4</td>
</tr>
</tbody>
</table>

Note 1: Use the requirements for a lower reliability assessment if the objective of the survey is a once-off estimation of roughness to prioritize maintenance and rehabilitation work. Use the higher reliability requirements if the objective of the survey is to determine a relative indication of network deterioration over a period of time (See Section 3.1 for details).

Note 2: Relevant roughness range denotes the ranges shown in Table 3.4. The ranges to be covered include only those ranges which may be encountered on the network to be surveyed.

Distance Measuring System Validation

The validation of the distance measuring system should be checked on calibration sections that are located on a tangent section of road and are at least 1 km long. The length of the section should be measured beforehand using a high precision instrument.

The validation consists of driving the vehicle over the section at a specific speed. At the start of the section the distance measurement device is initiated and at the end of the section it is stopped again. The measured distance is then checked against the benchmark values. A run-in distance of at least 150 m should be used to bring the vehicle up to speed before the start of the section.

The distance validation should be performed at different measurement speeds. It is recommended that at least three different speeds be used, which should include the specified surveying speed (e.g. 60, 80 and 100 km/h).

For each measurement speed, three runs should be made. The reading of the distance measurement device should be recorded at each run. The output at each run should be within roughly 1 per cent of the benchmark value.

Further Reading: Response Type Devices and IRI

Definitions of response type devices and of the IRI are provided in Sections 1.3 and 1.4. The operational concepts of response type devices are discussed in Section 2.2. Guidelines for the selection of calibration sections and measurement of the IRI on calibration sections are provided in Section 3.4.
4.3. CONTROL TESTING

Control testing should be performed from time to time during the survey to ensure that the calibration is still relevant for the device. Control testing is specifically used to determine if there is a gradual shift in the measurements taken by the device, or if the repeatability of the device has changed.

Control testing can be performed on the calibration sections, or special control sections can be identified in different areas within the network. For the control tests, the reference IRI is not needed, since the control check is performed against the raw measurement of the response type device (typically counts per km or metre).

In either case, it is important that the reference values for control sections be determined as soon as possible after calibration, and that the control sections be representative of smooth and rough pavements (relative to the overall range of roughness expected on the network). There should thus be at least two control sections, but more if possible.

Control testing should be performed on a regular basis as part of the survey process (discussed in more detail below). If calibration sections are not used for control testing, then control sections can be identified at various locations within the network, which will minimize the travel time to control sections.

Control sections should be at least 400 m in length, and preferably more than 800 m. The general requirements for calibration sections, as discussed in Section 3.4, should be taken into account when identifying control sites.

The values measured for the control sections after calibration should be used as reference values for future testing. For each control section, the IRI values should be determined over each 100 m segment. These IRI values will then be used as control values.

Control testing performed during the survey should consist of a once-off remeasure of the IRI over each 100 m segment, and each 100 m IRI value should then be compared with the control IRI values. Each 100 m, IRI values should be within a specified percentage of the reference values on each control site. A maximum deviation of 5 to 10 per cent (using the reference values as a basis) can be considered as a guideline for control testing.

If control testing performed during the survey shows that the measured values had drifted by more than the specified percentage, then the measurement device should be checked for obvious defects. If a defect is found and corrected, and the control testing is acceptable, then the survey can proceed.

However, if an obvious defect is not found, then the device needs to be recalibrated and any data collected since the last successful control test should be discarded and remeasured. Under no circumstances should control test data be used to adjust the calibration equation for the device.

It should be obvious that the cost and time implications of a failed control test are severe. For this reason, control testing should be carried out as frequently as possible within the constraints of the network and the survey budget.

The frequency of testing is basically a compromise between the cost of control testing (which not only delays the survey, but requires additional time and travel), and the risk of remeasuring all data collected since the last control test.

As a rough guideline, control testing can be requested at five stages (equally spaced in terms of length surveyed) during the survey process.

Important!

The calibration of a response type device is valid only for the vehicle configuration used during calibration. Thus, all vehicle parameters that may impact on vehicle response should be noted down and should be checked when the calibration report is completed. The vehicle parameters that influence the measurement are discussed in more detail in Section 6.1.

Acceptance criteria for calibration of response type devices should not be enforced too rigidly. It is important that the network manager be involved in the calibration process to assess when special circumstances prevail; which may require a slight relaxation of the calibration criteria. The contract specifications should therefore make provision to allow certain requirements to be overridden by the client where needed.
Summary of Concepts: Section 4

- Response type devices do not measure the road profile directly. Because of this, the device output needs to be correlated to the known IRI values on several sections. The correlation is used to determine a calibration equation which can then be used to convert the device outputs to IRI estimates.

- Calibration sections should be profiled before calibration starts, and using a Class 1 measurement device such as precision rod and level or a walking profiler. These reference profiles should be stored together with their IRI values.

- The calibration of a response type device is only valid for a given vehicle configuration. If key components like the shock absorbers, tyres, mass distribution and driver are changed, the calibration should be redone.

- Table 4.1 provides guidelines for the number of calibration sites that should be used to calibrate response type devices, length of sites, etc.

- Table 4.2 provides guidelines on the criteria that can be used to determine if the correlation between the device output and the benchmark IRI value is acceptable.

- When the calibration is completed, a calibration report should be completed by the contractor. The report should include details of calibration sections, device outputs for each repeat run, summary sheet showing compliance to the calibration criteria, and raw data for each calibration section.

- It is critical that the network manager accompany the contractor during the calibration testing, and note down details of the test procedure, measured values, condition of measurement, etc. This information should be used to check the contractor's calibration report.

- Correct and accurate operation of the distance measurement equipment should be validated as part of the calibration process. This validation includes checking of the GPS system and odometer outputs.

- During the network survey process, control tests should be performed from time to time to ensure that the calibration equation is still valid for the device.

- During control testing, the measured outputs of the device are compared to benchmark outputs determined during or directly after calibration is completed, and before the survey starts. Control tests are used to determine if there is a gradual shift in the device output or if the repeatability of the device has changed.

- Control tests can be performed on the calibration sections, or on special control sections located across the network. In the latter case, reference average rectified slope (ARS) values should be obtained for control sections as soon as possible after calibration is complete.

- If a control test shows that the device output or its repeatability has changed significantly, then any survey data measured between the time of the last control test and the current test should be discarded and re-measured. For this reason control tests should be performed on regular intervals as part of the survey process.
5. VALIDATION AND CONTROL TESTING FOR PROFILERS

The objective of profiler validation is to determine if all of the components in the profiler system work correctly and to validate that all individual components are correctly calibrated. It is important to understand that the objective of profiler validation is not to adjust the profiler outputs to match a predetermined benchmark. A profiler is either accurate and calibrated (i.e. the profiler is “valid”) or it is not. If it is not, the profiler should be fixed by the manufacturer.

Another objective of profiler validation is to confirm that the measurement approach adopted by the contractor can provide consistent results in the required format. Validation is therefore carried out for a specific operator and measurement protocol adopted by the contractor.

5.1. VALIDATION REQUIREMENTS

If the specifications require a pre-validation report, then the first step in the validation process should be to obtain a pre-validation report from the contractor. The pre-validation report should contain calibration certificates for the main components including the GPS and any other reference devices used. Validation should only commence once the network manager is satisfied that the device calibration is up to date and that the device is capable of the required accuracy.

Since validation is a time consuming and costly exercise, it is important to determine the level of certainty and precision required from the roughness data. As explained in Section 3.1, the highest level of precision is needed for an annual survey in which network deterioration needs to be assessed and for which the outputs will drive planning models. On the other hand, a biennial survey which is used mainly to prioritize maintenance and rehabilitation and to assess relative network deterioration perhaps requires a lower level of precision.

Another aspect which impacts on the design of a validation exercise is the experience which a client has with a specific device or contractor on a network. If a validation had been done previously for a specific device and contractor (say within the last year), then the validation requirements can be relaxed considerably. However, even in such cases efforts should be made to ensure that the equipment is unchanged and that the earlier validation is still applicable.

Guidelines for determining validation requirements are shown in Table 5.1. These requirements are intended for validation at the start of a contract, and for devices and contractors that have been used before in the network region.

When a new device type or a new contractor is being used on the network for the first time, then a higher level validation in which a detailed spectral analysis of the profile wavelengths is performed can be considered. Such validation, however, requires specialist tools and experience and is not covered by these guidelines.

5.2. VALIDATION CRITERIA

A profiler can be accepted as being valid if the measured IRI values over different parts of each validation section have acceptable levels of bias (i.e. if the error between the reference and measured IRI is acceptable) and precision (i.e. if the variation amongst repeated measurements is acceptable). These two aspects should be validated over different speeds. Guidelines for setting validation criteria for profilers are shown in Table 5.2.
### Table 5-1 Validation Requirements for Profilers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recommended Requirements for Application Type (Note 1):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Reliability</td>
</tr>
<tr>
<td>Number of sites for each relevant roughness range (Note 2)</td>
<td>1 (minimum of 3 sites)</td>
</tr>
<tr>
<td>Minimum site length</td>
<td>200 m</td>
</tr>
<tr>
<td>Repeat runs per site</td>
<td>6 (3 runs each at 60 and 80 and 100 km/hr)</td>
</tr>
<tr>
<td>Repeated measurements (i.e. repeat of all runs) per site</td>
<td>2 repeats within a day of each other on 2 selected sites</td>
</tr>
<tr>
<td>Validate filtering of long wavelengths</td>
<td>1 site of 1 km length</td>
</tr>
</tbody>
</table>

**Note 1:** Use the requirements for a lower precision assessment if the objective of the survey is conducted every two years or more to prioritize maintenance and rehabilitation work. Use the higher precision requirements if the objective of the survey is to determine an absolute indication of network deterioration on an annual or biannual basis (See Section 3.1 for details).

**Note 2:** Relevant roughness range denotes the ranges shown in Table 6. The sections need only cover those ranges which may be encountered on the network to be surveyed.

### Table 5-2 Guidelines for Validation Acceptance Criteria

<table>
<thead>
<tr>
<th>Check For</th>
<th>Parameter</th>
<th>Suggested Acceptance Criterion</th>
<th>Scope of Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error of IRI over 100 m segments</td>
<td>Absolute difference between measured and benchmark IRI over 100 m for each repeat run</td>
<td>80% of values to be less than 8%</td>
<td>Check for each 100 m segment at each speed and on each validation section.</td>
</tr>
<tr>
<td>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)</td>
<td>$R^2$ of linear regression</td>
<td>&gt; 0.95</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>Standard Error of Linear Regression</td>
<td>&lt; 0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slope of linear regression</td>
<td>Between 0.9 and 1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intercept of linear regression</td>
<td>Between -0.1 and 0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% Confidence interval of Slope of linear regression</td>
<td>Should bracket 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95% Confidence interval of intercept of linear regression</td>
<td>Should bracket 0.0</td>
<td></td>
</tr>
<tr>
<td>Bias in measured IRI over 100 m segments</td>
<td>Difference in mean 100 m IRI value from repeat runs measured on different days</td>
<td>&lt; 3 %</td>
<td>Check for each speed and on individual validation sections</td>
</tr>
</tbody>
</table>
As shown in Table 5.1, the repeatability and bias of the profiler can be validated through the following checks and approaches:

- Checks should be run on the variability of measurements between different repeat runs. This can be done by evaluating the coefficient of variation of the measured IRI at each 100 m subsection for different repeat runs.

- Checks should be run on the level of correlation between the average measured IRI and the benchmark IRI for each 100 m segment within each individual validation section. A normal linear regression can be used and limits can be set on the confidence limits for the regression equation slope and intercept. Limits can also be set on the coefficient of determination ($R^2$). These checks should be performed for all validation sections and at all measurement speeds.

- Checks should be run on the level of correlation between the average measured IRI and the benchmark IRI for each 100 m segment over all validation sections. A normal linear regression can be used and limits can be set on the confidence limits for the regression equation slope and intercept. Limits can also be set on the coefficient of determination ($R^2$). These checks should be performed for all validation sections and at all measurement speeds.

- Checks should be run on the variability of measurements between different repeat runs. This can be done by evaluating the coefficient of variation of the measured IRI at each 100 m subsection for different repeat runs.

- Checks should be run on the level of correlation between the average measured IRI and the benchmark IRI for each 100 m segment within each individual validation section. A normal linear regression can be used and limits can be set on the confidence limits for the regression equation slope and intercept. Limits can also be set on the coefficient of determination ($R^2$). These checks should be performed for all validation sections and at all measurement speeds.

- Absolute limits (in units of the IRI) can be set on the errors between the measured and benchmark IRI values. These errors can then be monitored for each 100 m segment of each validation section. The limits should be achieved in each repeat run and for all measurement speeds.

- The mean IRI for each 100 m, recorded over several repeat runs, as recorded on a specific day should be checked against the mean IRI for each 100 m recorded on another day.

## 5.3. VALIDATION OF POSITIONING EQUIPMENT

The validation of the distance measurement and location referencing equipment involves checking of the odometer and Global Positioning System (GPS). For the validation of the GPS, the following criteria are recommended:

### GPS Validation

The GPS is validated by comparing coordinates at several benchmark locations set out and maintained by a registered surveyor or surveying authority. It is recommended that this check be carried out at five to ten benchmark locations. GPS benchmark locations should be roughly 1 km apart, and the dynamic accuracy of the GPS should be checked by completing several survey loops through the benchmark positions. These checks should preferably also be performed over more than one day, and at different times of the day.

The ability of the GPS inertial system to compensate for a loss in the GPS signal should preferably be demonstrated by the contactor.

The GPS coordinates should be within 5 m of the vertical and horizontal benchmark values, and for repeat dynamic measurements this accuracy should be achievable 90 per cent of the time.

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**Further Reading: Example Validation Calculations**

Appendix C shows some calculations for the validation of profiler data for a specific validation section and a specific measurement speed. It should be noted that the actual validation should include similar checks on all validation sections and at all measurement speeds.
Distance Measuring System Validation

The validation of the distance measuring system should be checked on calibration sections that are located on a tangent section of road and that are at least 1 km long. The length of the section should be measured beforehand using a high precision instrument.

The validation consists of driving the vehicle over the section at a specific speed. At the start of the section the distance measurement device is initiated and at the end of the section it is stopped again. The measured distance is then checked against the benchmark values. A run-in distance of at least 150 m should be used to bring the vehicle up to speed before the start of the section.

The distance validation should be performed at different measurement speeds. It is recommended that at least three different speeds be used, which should include the specified surveying speed (e.g. 60, 80 and 100 km/h).

For each measurement speed, three runs should be made. The reading of the distance measurement device should be recorded at each run. The output at each run should be roughly within 1 per cent of the benchmark value.

5.4. CONTROL TESTING

Control testing should be performed from time to time during the survey to ensure that the profiler output is still valid and that the accuracy and precision of the device is still within specification.

It is recommended that control testing be performed on the validation sections, and that the same criteria as used for validation (Table 5.1), be used for control testing. However, control testing need not be performed on all validation sections, and normally control testing on two or three sites would suffice.

Control testing should be performed on a regular basis as part of the survey process (discussed in more detail below). If control testing performed during the survey shows that the measured values are no longer within the specified limits, then any data collected since the last successful control test should be discarded and remeasured. Under no circumstances should control test data be used to adjust or calibrate the profiler outputs. It should be obvious that the cost and time implications of a failed control test are severe. For this reason, control testing should be carried out as frequently as possible within the constraints of the network and the survey budget.

The frequency of testing is basically a compromise between the cost of control testing (which not only delays the survey, but requires additional time and travel), and the risk of remeasuring all data collected since the last control test.

As a rough guideline, control testing can be requested on a monthly basis or at five stages (equally spaced in terms of length surveyed) during the survey process.

Further Reading: Validation through Spectral Analysis

Appendix A contains a basic outline of Spectral Analysis of Profiles. For another basic outline, the Little Book of Profiling [Sayers and Karamias, 1998] can be consulted. For more information on the use of Spectral Analysis for profiler validation, the following references can be consulted:

- Prem (1998a) and Prem (1998b)
- Robertson (1998)
- Cenek and Fong (1998)

For full reference details on the above noted documentation, consult the reference list in Section 7.
Summary of Concepts: Section 5

- Profiler validation is performed to ensure that all components of a profiler are working properly, and that the measured profile is of the specified precision and accuracy. Profiler validation is not used to adjust or calibrate profiler output, but to check that the profiler meets specifications. If the profiler does not meet specifications, the device needs to be repaired by the manufacturer.

- During validation, the output of a profiler is compared to the known profiles and IRI values on several validation sections. These sections need to be profiled beforehand using a Class 1 measurement device (typically an ARRB Walking Profiler or Face Dipstick™). The benchmark IRI values are then calculated for each validation section using the standard methodology.

- Table 5.1 provides guidelines for validation requirements (number of sites, site length, required repeat runs, etc.).

- Table 5.1 provides guidelines for determining whether a profiler has been successfully validated or not. The guideline criteria include several parameters which jointly or individually assess the repeatability and accuracy of the profiler.

- Validation criteria include checks on the variation between outputs from repeat runs. Different measurement speeds should be assessed, and several repeat runs should be performed at each speed.

- Checks should be run on the correlation between the IRI measured with the profiler and the benchmark IRI values. The errors between IRI values should be evaluated over 100 m segments for each run and each measurement speed.

- Appendix C shows calculations for the validation of profiler data for a specific validation section and a specific measurement speed.

- Correct and accurate operation of the distance measurement equipment should be validated as part of the validation process. This validation includes checking of the GPS system and odometer outputs.

- Control tests should be performed at frequent intervals during the survey to confirm whether the profiler measurements are still valid. Control testing is typically performed on validation sections for which the profile and IRI is precisely known.
6. OPERATIONAL AND QUALITY CONTROL PROCEDURES

This section of the guidelines deals with the daily checks and procedures that need to be carried out during the course of a roughness survey. It should be noted that, while the guidelines cover the basic operational aspects and their influence on measurement, the guidelines are intended mainly for network managers, and not for contractors.

The network manager is not responsible for performing daily checks or following of proper operational procedures. However, a proper understanding of the elements that influence measurement and of the procedures that a contractor should perform each day, will allow a network manager to exercise better control over the measurement process. The guidelines in this section thus focus on how operational procedures can be controlled.

The operators of measurement devices should – in addition to the elements covered in this section – have an in-depth understanding of the influence of all operational elements on the measurement process. Detailed guidelines for device operators can be found in Sayers et al. (1986), and in NCHRP Research Digest 244 (1999). Additional information can be obtained in the relevant standards for specific device types.

6.1. OPERATIONAL PROCEDURES FOR RESPONSE TYPE DEVICES

Response type devices directly measure the response of the vehicle suspension to the travelled profile (as discussed in Section 2.2). For this reason, the characteristics of the vehicle, and specifically the tyres and suspension are critical to the accuracy and repeatability of the measurements.

Some of these elements, such as shock absorber selection and installation of the measurement device in the vehicle, are not within the control of the network manager, but are implicitly controlled by ensuring that the device calibration meets a minimum specification (as suggested in Table 4.2). Apart from these elements, there are several operational aspects that should be checked on a daily basis, and which may impact significantly on measurements taken with response type devices. These are [Sayers et al., 1986]:

- **Vehicle Loading**: an increase in vehicle weight typically results in an increase in measured roughness. Care should therefore be exercised to ensure that the loading configuration (number of occupants, cargo load and load distribution) is approximately the same as that which was used during calibration. Since the amount of fuel in the vehicle also impacts on loading, a minimum fuel content should be maintained (one third tank is suggested).

- **Tyre Pressure**: roughness increases with increasing tyre pressure, and the tyre pressure should therefore be checked every morning before the vehicle is started.

- **Linkages**: all mechanical linkages should be inspected on a daily basis. If some linkages are loose, then the measured roughness may be inaccurate.
6.2. OPERATIONAL PROCEDURES FOR PROFILERS

Before profiling operations start each day, system checks should be performed to ensure all inertial and distance measurement components are working correctly. The checks should also monitor vehicle parameters such as tyres.

As part of the Quality Control Plan (Section 3.3), the contractor should submit a detailed checklist which should outline daily checks that will be performed. The contractor’s checklist will depend on the vehicle type and the recommendations from the manufacturer. However, as a minimum, inertial profilers should be subjected to the following daily checks [NCHRP Research Digest 244, 1999]:

- **Warm-Up Time:** Adequate time should be allowed for all electronic components to warm up before measurement starts. For the profile measurement components, the manufacturer’s recommended warm-up time should be used. The vehicle should be driven for 10 to 30 minutes (longer when operating temperatures are low), to allow the tyres to warm up.

- **Check Electronic Components:** The measurement components should be checked to ensure cleanliness and correct configuration. Specifically, height sensors should be wiped clean (this may also be necessary several times during the day). If height sensors are covered when not in operation, the covers should be removed.

- **Output and Data Collection:** The profile output display should be checked (preferably in graphical format) to ensure the system is working correctly. Manufacturer’s warm-up times should be adhered to.

- **Bounce Test:** This test is performed with the profiler stationary on a flat surface. An up-down and sideways rocking motion is induced in the vehicle while the resulting “profile” is recorded. The measured profile should be flat (within 1 per cent of the bounce amplitude).

As part of the Quality Plan (see Section 3.3), the contractor should submit a checklist of items which should be completed and signed off each morning by the operator. This checklist should at least contain checks on all of the elements noted above, with additional vehicle-specific elements as needed.

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Table 6-1 Checklist for Operational Control Checks on Response Type Devices

<table>
<thead>
<tr>
<th>Control or Decision Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Check vehicle to ensure it is the same as used in the calibration exercise.</td>
</tr>
<tr>
<td>2. Ensure that the driver is the same as the one who conducted the calibration exercise.</td>
</tr>
<tr>
<td>3. Request and inspect the daily checklist. Ensure it meets the Quality Control plan format.</td>
</tr>
<tr>
<td>4. Check the number of occupants and cargo configuration to ensure it matches the calibration setup.</td>
</tr>
<tr>
<td>5. Check the fuel gauge and ensure that the minimum fuel level is maintained.</td>
</tr>
<tr>
<td>6. Check the type of tyres and ensure there is not excessive wear or damage. Confirm the correspondence to the calibration setup.</td>
</tr>
<tr>
<td>7. Check the type and condition of the shock absorbers and confirm correspondence to the calibration setup.</td>
</tr>
<tr>
<td>8. Check all linkages on the roughness measurement equipment (measurement device and odometer).</td>
</tr>
<tr>
<td>9. Confirm the correct operation of the GPS.</td>
</tr>
</tbody>
</table>

- Height Sensor Accuracy Check: this check involves the placement of a stepped block, of which the height of each step is known precisely, under the height measurement sensor. The height to the top of each step is measured and the differences in height are checked against the known heights.

As with response type devices, the network manager cannot ensure that all of the checks are rigorously performed each day. However, as a minimum form of control over operating procedures, spot checks should be performed from time to time. These checks should be performed randomly on a weekly or two-weekly basis. During each check, the contractor should be asked to stop the vehicle and a control check should be performed by the network manager. Table 6.1 provides guidelines for items to monitor during random control checks on profilers.

6.3. DATA CAPTURE AND DOCUMENTING

The contract specifications should provide details on the format required for the captured roughness data. As a minimum, the specifications should state the format of the required files (e.g. Comma Delimited ASCII file, Spreadsheet format) and the required columns. For roughness data, the required columns would typically include at least the following:

- Operator name;
- Section details (separate columns for Section name, lane, direction, region, etc.);
- GPS latitude, longitude and height;
- Km Position;
- Left and right wheelpath IRI, and
- Measurement speed.

The contractor should also provide a definition sheet to define any codes or abbreviations used in the file and column naming. Details of the format in which the output will be provided should ideally be submitted with the contractor's quality control plan.

The specifications (see Section 3.3) should stipulate the deadline for delivery of data files on completion of the survey. It is important to minimize delays between the time of survey and data analysis, in order for errors to be identified as soon as possible. Ideally, some data files should be given to the network manager while the survey is in progress, so that the data can be checked and any inconsistencies identified at an early stage.

The contractor should flag any data files or parts thereof for which measurements are regarded as unusual or in which excessive variations may occur because of environmental effects. Operators should therefore be trained not only in the vehicle operation aspects, but also in the interpretation of IRI and perceived roughness. Also, operators should be aware of the impact of certain pavement and environmental parameters on the precision of measurement, so that files recorded under non-optimal conditions can be clearly flagged for detailed analysis.
6.4. DATA CHECKING AND TROUBLESHOOTING

When the roughness data has been received, the network manager should perform some control checks on a few data files. The objective of these checks should be to ensure the measured roughness corresponds with basic engineering judgement, and that the data are consistent with that of earlier surveys.

For these control checks, the network manager should select a few sections for which the manager is familiar with the roughness properties (e.g. sections with poor riding quality or newly reconstructed sections with good riding quality).

The control check should look at the detailed plotted profile (over 10 or 100 m intervals, depending on the reporting frequency) as well as the segment averages for IRI. If surveys were undertaken in preceding years, then the roughness data can be graphically compared to the data collected in previous years.

Table 6-2 Checklist for Operational Control Checks on Profilers

<table>
<thead>
<tr>
<th>Control or Decision Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Check the vehicle and ensure it is the same as used in the validation exercise.</td>
</tr>
<tr>
<td>2. Ensure that the driver is the same as the one who conducted the validation exercise.</td>
</tr>
<tr>
<td>3. Request and inspect the daily checklist. Ensure it meets the Quality Control plan format.</td>
</tr>
<tr>
<td>4. Inspect the vehicle and ensure that the height sensors are free of excessive dirt, mud, etc.</td>
</tr>
<tr>
<td>Request the operator(s) to perform a height check using a height calibration block. Check to ensure that the measured heights are within limits and ensure that the operator is capable of performing the test consistently.</td>
</tr>
<tr>
<td>Request the operator(s) to perform the bounce check. Check the output to ensure the measured profile is flat, and ensure that the operator is capable of performing the check consistently.</td>
</tr>
<tr>
<td>7. Confirm the correct operation of the GPS.</td>
</tr>
</tbody>
</table>

6.5. PAVEMENT AND ENVIRONMENTAL INFLUENCES

There are several parameters related to the pavement condition and the measurement environment that can significantly affect measured roughness. Operators and network managers should ensure that they are familiar with key effects, and data files should be flagged if conditions are observed that could impact negatively on the precision and accuracy of measurement. In the event that inconsistencies in roughness data are suspected, the data file should first be checked to determine if the file was flagged and for what reason. The paragraphs below summarize the key parameters that can impact on the repeatability of roughness measurements [NCHRP Research Digest 244, 1999].

Pavement Related Influences

The condition and type of the pavement surface has an effect on the repeatability of measurements. This effect is to a large extent caused by the transverse variation of distress within the wheelpaths, and by the inability of the driver to maintain the exact measurement line at all times. Factors that have the greatest impact on measured roughness are:

- Crocodile cracking: if crocodile cracking is present, then the measured IRI from one run to the next may differ by 0.2 to 0.5 m/km. The impact of crocodile cracking on measured IRI is greatest on roads with a low IRI (roughly below 2.0).
- **Transverse cracking**: this type of cracking also increases the variability of measured roughness for profilers. The significance depends on whether or not a crack is detected by the profiler. Differences in IRI with repeat runs may differ by 0.1 to 0.2 m/km.

- **Coarse Texture**: the surface texture of the pavement can significantly affect the roughness measured with profilers. Coarse surfaces like single or double seals sometimes lead to anomalies in the measured profile, and ultrasonic sensors should not be used at all on course textured surfacings. Laser profilers also sometimes measure false increases in roughness. The significance of such errors is greatest when the IRI value is relatively low (say, below 2.0 m/km) and texture is high (mean texture depth greater than 1 mm). The magnitude of these errors can be reduced through proper anti-aliasing filter techniques, but some anomalies may persist. Texture does not have a significant impact on roughness measured with response type devices.

- **Potholes and Patching**: potholes and rough patches are an obvious source of roughness, and as expected the measured roughness will determine whether or not the pothole or patch was hit by one of the wheels. Variation in the travelled line, or change in the severity of potholes from one year to the next may cause significant differences in measured roughness.

- **Daily Profile Variations**: on concrete pavements, and because of temperature effects, the time of measurement may significantly impact on the measured roughness. Roughness will generally be higher in the early morning hours than in the afternoon, and the difference in IRI measured in the morning and afternoon can vary by roughly 0.1 to 0.3 m/km, depending on the times of measurement. It is thus important to ensure that roughness measurements on concrete pavements are made at the same time of the day, as far as possible.

- **Seasonal Variations**: movement in the pavement subgrade may impact on measured roughness. These movements will be most severe where there are significant moisture sensitivity or frost heave effects present in the subgrade. To minimize the impact of seasonal variations, roughness surveys should be conducted as far as possible in the same season, and preferably in the same month.

The impact of pavement texture and distress can be minimized if the operator consistently maintains the same tracking line (i.e. if the wheels maintain the same distance from the yellow line). A monitor system or windshield target can assist in consistently positioning the vehicle in the travelled lane.

The impact of seasonal and daily variations on roughness values measured in different years can be minimized by ensuring that the survey is executed in the same season (or month, if possible), each year. For concrete pavements, roughness should preferably be measured consistently in the mid-morning or mid-afternoon periods.

**Measurement Environment**

The environment in which measurements are performed may impact on the repeatability of measured roughness. Operators and network managers should be able to identify conditions that may impact on roughness.

In severe cases, operations should be stopped while the conditions persist. In less severe cases, the operator should flag the data file to indicate that the measurements were taken under non-optimal conditions, and should specify the nature of the problem. Environmental factors that may impact on roughness measurements are:

- **Wind**: Heavy wind and gusts may affect measured roughness. This effect is more severe for profilers that use ultrasonic height measurement. The effect will also be more severe if there is sand, snow or other contaminants (e.g. leaves or grass) present.

- **High Temperature and Humidity**: in extreme temperature or humidity situations, the operator should check to ensure that the conditions are still within the operating range for components as specified by the manufacturer.

- **Surface Moisture**: operations should not be undertaken if there is water standing or flowing on the pavement surface.

- **Contaminants**: a data file should be flagged if the operator observes contaminants over large parts of the measurement section. Such contaminants may include spilled sand, cement or loose gravel.
### Table 6-3 Troubleshooting Procedure for Inconsistent Data

<table>
<thead>
<tr>
<th>Possible Causes of Data Inconsistency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Check to see if the data file was flagged by the operator.</td>
</tr>
<tr>
<td>2. Check to see that distance markers were not changed between surveys.</td>
</tr>
<tr>
<td>3. Check absolute difference error between the IRI of this and the previous survey. If the difference is less than 0.5 m/km, the cause may be inconsistent tracking or normal deterioration.</td>
</tr>
<tr>
<td>4. Check the pavement condition as reported in the previous survey year and in the current year. Pavement condition: does the pavement have a coarse texture? This could cause accuracy problems, especially if the IRI is low.</td>
</tr>
<tr>
<td>5. Pavement condition: does the section have severe crocodile cracking? Pavement condition: does the section have potholes or patching? Pavement condition: if the pavement is jointed concrete, was the time of measurement roughly the same? Pavement condition: was the pavement possibly flooded, or is the drainage inadequate? Moisture effects will be worse if the subgrade contains active clay. Pavement condition: were the measurements taken in the same season or month (if comparing the results from two surveys)?</td>
</tr>
<tr>
<td>6. Environment: were wind conditions severe at the time of measurement? Check for comments or flags in the data file. Environment: was there construction in the measurement area that could have contaminated the pavement surface (spilled sand, loose gravel, etc.)? Environment: check rainfall records in the area of measurement. Was there rainfall during the time of measurement or a possibility of standing water? Environment: check the temperature and humidity records. Were these perhaps outside the operating range of the equipment?</td>
</tr>
</tbody>
</table>
7. REFERENCES


Relevant Standards:


8. GLOSSARY

Calibration: The process of determining the relationship between the output of a measuring device (e.g. the ARS measured by a Response Type device) and the value of the input quantity (e.g. the IRI). Calibration is often regarded as including the process of adjusting the output of a measurement instrument to agree with the value of the applied standard (definition after Wikipedia, 2007).

DGPS: Differential Global Positioning System. A system that uses a network of fixed ground based reference stations to broadcast the difference between the positions indicated by the GPS satellite systems and the known fixed positions (definition after Wikipedia, 2007).

Dipstick: Commonly used term for the slow moving profiling device named the Face Dipstick™ (patented, manufactured and sold by the FACE Corporation).

Filter: A mathematical function used to process a measured profile, normally with the objective of removing certain wavelengths from the profile. The moving average is an example of a simple filter.

GPS: Global Positioning System.

HRI: Half Car Index. A roughness index calculated by means of the IRI transform, but using the point-by-point average of the two profiles measured in both wheelpaths (as opposed to the IRI, which uses the profile of only a single wheelpath). The HRI is always lower than the IRI.

IRI: International Roughness Index. A roughness parameter determined from a measured road profile in a single wheelpath. In the IRI calculation, the measured profile is processed using a mathematical transform which filters and cumulates the wavelengths encountered in the profile.

LDI: Linear Displacement Integrator. A response type device manufactured and sold by the CSIR in South Africa.

Profilometer: A mobile device used for measuring the longitudinal profile of a road. The measured profile may or may not be the true road profile, depending on the wavelengths that have been filtered out of the measured profile. High speed profilometers are capable of measuring at normal road speeds. Static profilometers operate at walking speeds or slower (definition after Sayers et al., 1996).

Repeatability: The expected standard deviation of measures obtained in repeated tests, when using the same instrument and measurement team on a single, randomly selected test section (definition after Sayers et al., 1996).

Reproducibility: A measure of the ability to reproduce a measured result (such as the IRI measured over a 100 m segment of road) by another measurement device or measurement team working independently (definition after Wikipedia, 2007).

Resolution: The resolution of a device specifies the smallest measurement increment that the device is capable of.

Riding Quality: Term used to describe the relative degree of comfort or discomfort a road user experiences when using a road. The terms riding quality and roughness are often used interchangeably. In these guidelines, the term roughness is preferred.

Roughness: Term used to describe the relative degree of comfort or discomfort a road user experiences when using a road.

True Profile: The actual profile of the road, relative to a fixed reference point, without any filtering out of certain wavelengths.

Validation: The process of determining if a measurement device, when operated according to a established procedure and within established operating ranges, can operate effectively and reproducibly (definition after Wikipedia, 2007).

Verification: The process of proving or disproving the correctness of a system or measurement device with respect to a certain formal specification.
Appendix A
Analysis of Road Profiles: Basic Concepts
Defining a Sinusoid

For planning and condition assessment purposes, the roughness of a road can be adequately summarized by means of a summary parameter such as the IRI. However, to understand how the IRI is derived, and for a more in-depth analysis of road profile data, a basic understanding of sinusoid curves and the basic terminology associated with frequency analysis is essential. Figure A1 shows an idealized road surface that varies in a sinusoidal manner. The idealized profile of Figure A1 could represent a road surface on which speed bumps are placed very close together.

This figure also shows the basic terminology associated with a sinusoid, which has the following mathematical equation:

\[ Y = A \sin \left( \frac{2\pi}{\lambda} (X - X_0) \right) \]

Where:
- \( Y \) = Elevation
- \( A \) = Amplitude
- \( \lambda \) = Wavelength
- \( X \) = Distance
- \( X_0 \) = Phase Shift

As can be seen from Figure A1, the sinusoid, which describes the road roughness completely in this idealized case, consists of three main components. These are:

Amplitude: The amplitude is the absolute deviation from the neutral line. In this case, the road roughness varies about 200 mm up and down from the neutral axis.

Wavelength: The wavelength determines the length of a full cycle, or wave. In other words, the wavelength determines the distance from one crest on the profile to another crest a full cycle further on. For the example shown in Figure A1, the wavelength is 20 m.

Phase Shift: The phase shift determines the point where the first full cycle starts. It is basically determined by the reference point of our distance measurement, relative to the value of the sinusoid.

It should be obvious that the roughness a road user will experience will depend mainly on the amplitude and the wavelength. If the amplitude is very small (say 1 or 2 mm), the tyres will absorb the roughness completely and it would not be transmitted to the suspension system. However, if the amplitude is larger (say 200 mm as shown in Figure A1), then the effect would be similar to driving over speed bumps placed at fixed intervals.

The wavelength determines how far apart the bumps in the road are spaced. If the wavelength is very long (say 70 m or more), then a car driving at 80 km/h would experience the bumps as slight undulations, since the vehicle would float over the bumps. In such a case the suspension system would absorb (or “filter out”) the long wavelengths almost completely. However, if the wavelength is much shorter (say 5 to 10 m), then the crests of the bumps would be much closer together and although the vehicle would dampen some of the roughness, much of it would be transmitted to the road user.

The influence of the wavelength can also be expressed by dividing the wavelength by a unit length (typically a metre). This parameter \((1/\lambda)\) is known as the wave number. The higher the wave number, the more waves per unit length and thus the shorter the wavelength.
Profile Analysis Using Power Spectral Density

The example shown in Figure A1 is highly idealized and no road surface would have such a profile. However, an interesting aspect of road profiles (or any type of curve which varies with distance, time or angle), is that the profile can be constructed by adding sinusoids like that shown in Figure A1, for which the properties of each sinusoid varies in a specific manner.

Figure A2 shows four sinusoids, each with a different wave number and amplitude. For this example, the sinusoid with the highest wave number (i.e. the blue line with the shortest wave length) has the smallest amplitude.

By contrast, the green line which has the lowest wave number, has a much larger amplitude (about 2 m) (For the X-axis scale chosen in Figure A2, only part of this sinusoid is shown).

If we now “sample”, at different locations along the X-axis, the elevation (i.e. Y-value) of each of the four sinusoids, and add up these four Y-values at each point, we get the profile shown in Figure A3. This profile is a more realistic representation of a road profile. It looks almost “random” and any cyclic sinusoidal pattern is hard to discern.
Four sinusoids, each with different wavelength and amplitude.

Figure A2: Four Different Sinusoids

Profile resulting from a sum of four sinusoids, each with different wavelength and amplitude.

Figure A3: Profile Resulting from Sum of Four Sinusoids
In Figures A2 and A3, we saw how a profile can be constructed by adding only four sinusoids. If we use a much larger number of sinusoids, a virtually random profile could be obtained. The opposite approach can also be adopted, in which we start off with a random profile (as measured on a road), and then split the profile into separate sinusoids, each with a different wave number and amplitude, as in Figure A2.

The information gleaned from this splitting up of the profile into sinusoids can be very useful. A road profile which consists mainly of sinusoids with high wave numbers (i.e. short wavelengths) and large amplitudes will result in a bone jarring ride. On the other hand, a profile that consists mainly of low wave numbers (i.e. longer wavelengths) would perhaps result in a more nauseating wave-like motion of the vehicle.

The process of splitting up the road profile into different sinusoids, and the analysis of the resulting data, is generally called Power Spectral Density (PSD) analysis. The term power originated from the first use of the technique in electronics, which was concerned with voltages and their variations. Spectral Density refers to the analysis of the density or composition of the spectrum of sinusoids which make up the measured profile.

The analysis of the sinusoids that constitute a profile is summarized through a PSD plot. An example of a PSD plot is shown in Figure A4. For road profiles, a characteristic of a PSD plot is that the curve slopes down toward the right. That is, the amplitude decreases as the wave number increases.

This occurs because shorter bumps (i.e. higher wave numbers) generally have lower amplitude than that of longer undulation-type roughness.

It should be noted that the splitting up of a random road profile into its constituent sinusoids (i.e. into the sinusoids that make up the profile), is not a straightforward exercise, since there can be an almost infinite number of sinusoids that make up a profile, and the wave number and amplitudes of these are not known (in fact, this is what the PSD analysis will determine). PSD analyses are typically done by means of Fourier Transforms or similar techniques. As noted in the previous paragraph, power spectral density analysis is an important method of understanding the cause of roughness at a fundamental level.

Another important use of the power spectral density is to troubleshoot and analyze the accuracy of profilers. Some profilers, because of the way in which they sample elevations, effectively “lose” or filter out some wavelengths. The characteristics of a specific profiler could thus be evaluated at a fundamental level by comparing the power spectral density of a profile measured with one device with the power spectral density measured with another benchmark device. This technique has advanced to the point where some network managers are using power spectral density as part of the validation of a profiler before a network survey [Prem, 1998; Fong and Brown, 1997].

Figure A5 shows how a PSD analysis can be used to understand a roughness profile. In this figure, Curve A (red curve) denotes a profile made up of many short, low bumps (i.e. low amplitude, high wave number). Curve B (blue curve), on the other hand, consists of only a few high bumps, spaced further apart (i.e. low wave number, higher amplitude). The PSD plot clearly separates the two profiles and shows that Curve B has higher amplitudes for low wave numbers. By contrast, Curve A has a higher amplitude for higher wave numbers.
Filtering of Road Profile Data

A filter is a transform that is applied to a measured series of data to filter out or remove some of the information. The filter, or transform, can be a mathematical function (as in the IRI calculation) or it can be a physical filter, such as the suspension of a road profile, which filters the profile elevation into a series of counts. Engineers often think of a filter as a way to hide some information in a negative way. However, in profile analysis, filtering is rather used (or should be used) to remove unwanted information.

As an example, consider the simulated profile in Figure A6. The formulation of this profile is identical to that shown in Figure A3, only the data series was extended over a longer length of road. As shown before, this profile is actually constituted of the four sinusoids shown in Figure A2.

Suppose now that, for a detailed analysis of the roughness profile, we are not interested in the sinusoids with the shorter wave numbers (e.g. the green curve in Figure A2). We can then filter out the influence of this sinusoid (and others with similar wave numbers). There are several filters that can be used to achieve this. One simple way to achieve such filtering is by taking the moving average over a length that is roughly equal to the wavelengths we are trying to filter out. Figure A7 shows the original profile (as in Figure A6), with a filtered profile consisting of the moving average over 6 metres. This moving average is called a smoothing, or low-pass filter. It is denoted by the smoothed red line in Figure A7.

If we compare the moving average line in Figure A7 to the original, we can see that the smoothed profile mainly gives us an indication of slope changes (large elevation changes). It is thus not very useful for roughness purposes.

Further Reading: SINUSOIDS and FILTERS

A comprehensive discussion of sinusoids and different filter types can be found in the “Little Book of Profiling” [Sayers and Karamihas, 1998].

For a more-in depth discussion of the use of PSD functions to validate profilers, see Prem (1998) and Fong and Brown (1997).
Figure A5: PDS Analysis of Two Profiles

Figure A6: Profile as shown in Figure A3, Extended Over a Longer Length of Road
Appendix A: Analysis of Road Profiles: Basic Concepts

Roughness Measurement: Version 1.0

Figure A7: Filtered Profiles

Original Profile
First filter, consisting of a moving average over 6 metres. This is a smoothing filter

Final filtered profile, consisting of moving average minus original profile. This is an "Anti-Smoothing" filter.
Appendix B

Calibration Report Details

(Response Type Devices Only)
The figure on the next page shows an example of a calibration dataset as it should be summarized in a Calibration Report. The figure shows the section summary data as prepared for determining the calibration equation. As can be seen from the figure, the data has been ordered to systematically show data in the following columns:

- Calibration section name (shown here as A,B,C, etc)
- Repeat run number
- Measurement speed (shown only for confirmation, since calibration should always be done at the IRI reference speed of 80 km/h)
- Start position for each 100 m segment of the calibration section (note that in this case each calibration section is 200 m long)
- The measured value (ARS) from the response type device
- The reference IRI over each 100 m segment of each calibration section

The graph shows the relation between the measured values (on the X-axis) and the reference IRI values. The clusters of data that are visible on the graph generally represent the measurements of different repeat runs on each 100 m segment of different calibration sections. It should be noted that, for two calibration sections with a similar roughness, the data clusters can overlap significantly and may appear as a single cluster in such a case.

The graph should first be checked to ensure that the relation between the measured ARS and benchmark IRI values is generally of a linear form. If it seems that the relationship is curved or logarithmic, then the calibration data and equation are not valid, and the equipment and data should be checked.

The linear regression data shown below the graph can be obtained with a spreadsheet program. The acceptance criteria for the calibration data are highlighted in green. In this case, the two parameters of interest are:

- The Coefficient of Determination ($R^2$) which has a value of 0.965;
- The Standard Error which has a value of 0.37.

The acceptance criteria guidelines shown in Table 8 of Section 4.1 are essentially as follows:

**Lower Reliability Applications:**
- Minimum Coefficient of Determination ($R^2$) of 0.950
- Maximum Standard Error of 0.45

**Higher Reliability Applications:**
- Minimum Coefficient of Determination ($R^2$) of 0.975
- Maximum Standard Error of 0.35

Thus this example calibration data set would satisfy the requirements for a lower reliability application (e.g. required only for prioritization or a once-off survey), but not for an application that requires a higher reliability (e.g. annual survey to be used for long term planning).
### SUMMARY OUTPUT

**Regression Statistics**

- Multiple R: 0.977
- R Square: 0.956
- Adjusted R Square: 0.955
- Standard Error: 0.44
- Observations: 70

**ANOVA**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Significance F</th>
</tr>
</thead>
<tbody>
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**Coefficients**

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Check graph for non-linear trends (there should be none). Also, ensure data covers expected IRI range.

Acceptance Criteria
Appendix C
Validation Calculation Details
(Profilers Only)
The figure on the next page shows an example of a validation dataset as it should be summarized in a Calibration Report. It should be noted that the dataset shown on the next page has been abbreviated for conciseness. In an actual validation, there will be more rows of data representing more repeat runs and/or more measurement speeds.

The figure shows the section summary data as prepared for validation. As can be seen from the figure, the data has been ordered to systematically show data in the following columns:

- Repeat run number and validation section number
- Start and end positions for each 100 m segment of the calibration section (note that in this case each calibration section is 200 m long)
- Measurement speed (shown only for confirmation, since calibration should always be done at the IRI reference speed of 80 km/h)
- The benchmark and measured IRI values for each 100 m segment of each calibration section
- The calculated absolute percentage difference between the measured and benchmark IRI values, using the benchmark IRI as base value

The graph shows the relation between the measured IRI values (on the Y-axis) and the benchmark IRI values (on the X-axis).

It should be noted that, for two calibration sections with a similar roughness, the data clusters can overlap significantly and may appear as a single cluster in such a case.

The graph should first be checked to ensure that the relation between the measured and benchmark IRI values is generally of a linear form. A line of equality should be plotted on the graph, and a check should be done to ensure the data lies randomly distributed around the line of equality.

If it seems that the relationship is curved or logarithmic, then the calibration data and equation are not valid, and the equipment and data should be checked. Similarly, if the data consistently lies above or below the line of equality, or if the data moves away from the line of equality for higher or lower IRI values, then this indicates a systematic measurement error, and the equipment should be checked.

The linear regression data shown below the graph can be obtained with a spreadsheet program. The acceptance criteria for the calibration data are highlighted in green. For easy reference, the recommended validation criteria shown in Table 10 of Section 5.2 are partially reproduced here as Table C1.

It will be noted from the data on the next page that, for this abbreviated example data set, the validation data pass all of the recommended criteria shown in Table C1.

### Table C1: Guidelines for Validation Acceptance Criteria

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<th>Check For</th>
<th>Parameter</th>
<th>Suggested Acceptance Criterion</th>
<th>Scope of Calculations</th>
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<td>Error of IRI over 100 m segments</td>
<td>Absolute difference between measured and benchmark IRI over 100 m for each repeat run</td>
<td>80% of values to be less than 8%</td>
<td>Check for each 100 m segment at each speed and on each validation section</td>
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<tr>
<td>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)</td>
<td>R² of linear regression</td>
<td>&gt; 0.95</td>
<td>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.</td>
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<td>Standard Error of Linear Regression</td>
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### Roughness Measurement: Version 1.0

#### Appendix C: Validation Calculation Details (Profilers Only)

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#### Summary Output

**Regression Statistics**

- Multiple R: 0.992
- R Square: 0.984
- Adjusted R Square: 0.984
- Standard Error: 0.188
- Observations: 40

**ANOVA**

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**Coefficients**

- Intercept: 0.002, Standard Error: 0.068, t Stat: 0.030, P-value: 0.976, Lower 95%: -0.137, Upper 95%: 0.141
- X Variable 1: 1.968, Standard Error: 0.021, t Stat: 49.067, P-value: 0.000, Lower 95%: 0.967, Upper 95%: 1.968

---

Data Set Continues (abbreviated here because of space constraints).

**Percentage Absolute Errors Greater Than 8% = 18%**

Check graph to ensure the trend is linear and that points are located randomly around the line of equality.

**Green Cells denote acceptance criteria**
Appendix D
Guidelines for Checking of Data Consistency
Appendix D: Guidelines for Checking of Data Consistency

Roughness Measurement: Version 1.0

The following paragraphs illustrate typical scenarios that may arise when roughness data from different years are compared. Each situation is illustrated graphically and a description of the general trend is provided. Guidelines for interpretation, including possible causes of problem situations, are then provided.

Situation D1

![Graph showing roughness measurements]

**Description:** The new data follows the same trend as that of the previous survey. The average IRI value for the section is roughly the same.

**Interpretation:** Roughness on the section deteriorated little or not at all. The data can be accepted into the database.

Situation D2

![Graph showing roughness measurements]

**Description:** The new data follows the same trend as that of the previous survey, but the average IRI value for the new survey is slightly higher.

**Interpretation:** Roughness deteriorated within acceptable limits. Data can be accepted into the database.
**Situation D3**

![Graph](image1)

**Description:** The new data follows the same trend as that of the previous survey, and the average IRI is the same. However, the IRI at specific distance readings differs significantly.

**Interpretation:** There is a phase difference in the trend of the data. This is most likely caused by inaccurate distance measurement or triggering at the start of the section. The cause of the phase change should be investigated and the problem should be corrected before the data is accepted into the database.

---

**Situation D4**

![Graph](image2)

**Description:** The average IRI for the section is visibly higher and the trend in the IRI data is not the same for the two surveys.

**Interpretation:** First ensure that the correct section was measured. It may be possible that the section name or starting distance is incorrect. If it is confirmed that the section location and number is correct, perform a visual assessment to determine the cause of the deviation in the data. Possible causes may include severe water infiltration, severe cracking or extensive failures. If the visual condition or road history does not suggest severe deterioration, faulty measurements should be suspected.
### Situation D5

**Description:** The average IRI for the latest survey is lower than that of the previous survey, but the data trend is the same.

**Interpretation:** If the data for the previous survey is assumed to be correct, then possible explanations could be that the section received a surface seal or other light maintenance treatment. It could also be that the device is not properly calibrated, or an operational error occurred during measurement. The data can be accepted into the database after a small adjustment is made, provided that the cause of the inconsistency is determined with confidence.

### Situation D6

**Description:** The average IRI for the two surveys is similar, but the data trend is significantly different.

**Interpretation:** An adjustment to the distance measurement would not address this situation. Since the average roughness for the latest survey is similar to that of the earlier survey, likely causes may include: incorrect section name or starting position; lateral wander; significant variations in measurement speed or a coarse textured surface. Data should not be accepted into the database unless the cause of the inconsistency can be determined with confidence.