

TMH 13

**AUTOMATED ROAD CONDITION
ASSESSMENTS
PART A: GENERAL**

**Committee Draft Final
May 2016**

Committee of Transport Officials

**TECHNICAL METHODS
FOR HIGHWAYS**

TMH 13

**AUTOMATED ROAD CONDITION
ASSESSMENTS
Part A: General**

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May 2016**

Committee of Transport Officials

Compiled under auspices of the:

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Synopsis

TMH13 provides the guidelines and procedures to assist road authorities to plan, execute and control automated road conditions assessments for: roughness, skid resistance, texture, rutting, deflections and distress imaging. Automated measurement concepts as well as background to different devices are provided. TMH 13 is a companion document to TMH 22 on Road Asset Management Systems and as such includes aspects of data capturing, analysis and documentation.

Withdrawal of previous publication:

This publication is new publication.

Technical Methods for Highways:

The Technical Methods for Highways consists of a series of publications in which methods are prescribed for use on various aspects related to highway engineering. The documents are primarily aimed at ensuring the use of uniform methods throughout South Africa, and use thereof is compulsory.

Part A: General

Users of the documents must ensure that the latest editions or versions of the document are used. When a document is referred to in other documents, the reference should be to the latest edition or version of the document.

Any comments on the document will be welcomed and should be forwarded to coto@nra.co.za for consideration in future revisions.

Document Versions

Working Draft (WD). When a COTO subcommittee identifies the need for the revision of existing, or the drafting of new Technical Recommendations for Highways (TRH) or Technical Methods for Highways (TMH) documents, a workgroup of experts is appointed by the COTO subcommittee to develop the document. This document is referred to as a Working Draft (WD). Successive working drafts may be generated, with the last being referred to as Working Draft Final (WDF). Working Drafts (WD) have no legal standing.

Committee Draft (CD). The Working Draft Final (WDF) document is converted to a Committee Draft (CD) and is submitted to the COTO subcommittee for consensus building and comments. Successive committee drafts may be generated during the process. When approved by the subcommittee, the document is submitted to the Roads Coordinating Body (RCB) members for further consensus building and comments. Additional committee drafts may be generated, with the last being referred to as Committee Draft Final (CDF). Committee Drafts (CD) have no legal standing.

Draft Standard (DS). The Committee Draft Final (CDF) document is converted to a Draft Standard (DS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a draft standard. This Draft Standard is implemented in Industry for a period of two (2) years, during which written comments may be submitted to the COTO subcommittee. Draft Standards (DS) have full legal standing.

Final Standard (FS). After the two-year period, comments received are reviewed and where appropriate, incorporated by the COTO subcommittee. The document is converted to a Final Standard (FS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a final standard. This Final Standard is implemented in industry for a period of five (5) years, after which it may again be reviewed. Final Standards (FS) have full legal standing.

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A.1. Introduction

A.1.1 Context and Scope

TMH 13 *Part A: General* is the first of seven parts on automated road condition assessments. Part A discusses basic measurement concepts limited to the most essential and frequently used aspects of automated road condition assessments. In addition, this part introduces aspects related to the planning of such automated condition assessments.

Automated road condition assessments are typically intended for use in the network's Pavement Management System (PMS) to assess the network condition and prioritize maintenance and rehabilitation actions. The guidelines refer to related documents within the TMH series along with appropriate standards and other associated sources.

TMH 13 is primarily concerned with the needs of road agencies or managers of road networks. These documents focus on providing a framework to promote consistency in pavement surveillance measurement practice and do not serve as a complete specification. Although some details of measurement procedures are discussed, the emphasis remains on the needs of the network manager, and not on the requirements for the contractor in charge of the actual measurement.

A.1.2 Objectives

The primary objective of TMH 13 is to assist road network management personnel to plan, execute and control automated road condition assessments over a road network. In this regard, Part A:

- Provides definitions and clarification of key measurement concepts and methodologies.
- Introduces key aspects of planning surveillance measurement surveys.

A.1.3 TMH 13 Structure and Layout

TMH 13 comprises seven parts:

- **Part A:** General
- **Part B:** Positioning
- **Part C:** Roughness
- **Part D:** Rutting
- **Part E:** Skid and texture
- **Part F:** Deflection

- **Part G:** Imaging

The level of technical detail adopted for these guidelines was selected to suit network managers that are relatively new to the field of automated road condition assessments. 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 these documents firstly as a practical guide, and only secondly as a source of general information.

Extensive use is made of concept summaries and checklists, which are clearly highlighted. 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.

This document, **Part A**, is structured as follows:

Section A2 provides a brief overview of the main concepts related to positioning, roughness, rutting, skid and texture, deflection, and imaging.

Section A3 covers aspects related to the planning of automated road condition 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 including specifications, calibration, validation and control are also discussed.

The introductory Part A is elaborated on in Parts B through G that constitute measurement specific aspects with the following general structure:

- Measurement devices;
- Calibration, validation and control testing;
- Operational and quality control procedures;
- References;
- Glossary, and
- Appendices

A.2. Automated Road Condition Measurement Concepts

A.2.1 Positioning

The process to figure out where you are is probably one of man's oldest pastimes. Positioning is crucial to so many activities and yet the process has always been quite cumbersome. Over the years all kinds of technologies have tried to simplify the task but all has had some disadvantage. Finally, the U.S. Department of Defence decided that the military had to have a super precise form of worldwide positioning.

The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. GPS uses these satellites as reference points to calculate global positions. State of the art systems can make measurements to better than a centimetre! In a sense it's like giving every point on the planet a unique address in terms of a geographic co-ordinate (Latitude, Longitude, Height). This means we are not bound by physical or man-made landmarks to define reference points. Once we have surveyed a road we obtain a series of GPS co-ordinates that defines that road's unique position on earth. We can now reference any point on that road without any ambiguity. The reference is also absolute as opposed to traditional linear references being relative to some starting point.

The term: "GPS" has been adopted referring to Global Navigation Satellite Systems (GNSS) in general. GPS is in fact the US implementation of GNSS. Other GNSS exist and more is in development.

A.2.1.1 GPS co-ordinates

GPS Receivers report co-ordinates using the World Geodetic System (WGS84) format. For a discussion see **Appendix A-1: Geographic Co-ordinate System**.

GPS co-ordinates are used in:

- Spatial Pavement Management Systems as the basis for Location Referencing;
- Geographical Information Systems (GIS);
- Survey Validation;
- Cross referencing between PMS and GIS and vice versa, and

- Asset Management Software

Although the increased availability of accurate GPS positioning on hand held devices has resulted in the more traditional referencing methodology, of using linear distance travelled to provide relative location data, now becoming technologically obsolete from data referencing point of view, the linear reference is still easiest method of communicating between humans.

Using GPS co-ordinates as an absolute reference means that accurate and continuous GPS data are required. The best accuracy one can expect with autonomous data (uncorrected data) for any commercial GPS receiver is within 15 meters horizontally and 25 meters vertically. In addition, data may be lost due to the effects of tunnels, woods and structures. For these reasons, the GPS system needs augmentation to achieve higher accuracy and continuous data supplements. Two of the main augmentation systems in use are:

- Differential Correction
- Inertial Augmentation

A.2.1.2 Differential Correction

As alluded to above, the GPS in its standalone mode is of limited accuracy. Differential Correction or Differential GPS (DGPS) refers to techniques and technology to "correct" current limitations, issues and effects to enhance or increase the location accuracy of GPS data.

Errors in GPS data may be caused by satellite orbit and clock errors as well as atmospheric refraction errors. By differencing data observed simultaneously at two different sites (base and rover) systematic errors can be spatially correlated and their effects completely or partially eliminated. The relative positions of these two sites can therefore be determined with much greater accuracy by differencing. (See: More Information: How GPS works). Differential GPS can improve positioning accuracy to around 1 meter or sub-meter accuracy depending on the measurement mode, single or multiple bases, and data processing used (Merry, 2007).

Augmentation systems provide the infrastructure to determine and model GPS errors and to transmit correction and integrity information in near real-time to users.

- **Ground-based Augmentation Systems (GBAS)**

Differential GPS can refer to any type of GBAS. In these systems, permanent base stations are installed to transmit correction and integrity information from ground-based transmitters using both real-time and post-processing correction. These systems can make use of a single base or larger multiple base/ networks. TrigNet (www.trignet.co.za) is an example of a larger network of continuously operating GNSS base stations covering South Africa all managed and controlled by a single control centre situated in the offices of the Chief Directorate National Geospatial Information (CDNGI). Various methods are used to communicate corrected data to rover stations, including radio links or the internet making use of Network Transport of the Radio Technical Commission for Maritime Services (RTCM) via Internet Protocol (NTRIP).

- **Satellite-based Augmentation Systems (SBAS)**

These systems are synonymous with wide-area differential GPS (WADGPS). Correction and integrity information are transmitted via geostationary satellite. SBAS services are commercially available in South Africa. The two main global SBAS service providers are: Omnistar (www.omnistar.co.za) and Starfire (www.navcomtech.com/StarFire).



Important!

It is important to note that Differential Correction technology “Correct” or enhance existing GPS data but cannot create GPS data. GPS data that is missing (i.e. through a tunnel, woods and in certain urban areas) cannot be created by this technology.

A.2.1.3 Inertial Augmentation

GPS reception under certain practical conditions is erroneous or not possible. To “create” accurate “missing” GPS data, inertial augmentation is used. Inertial augmentation systems consist of accelerometers (motion sensors), gyroscopes (rotation sensors), distance measuring instruments (DMI) and a processor. The GPS data is combined with inertial data to create a continuous stream of GPS co-ordinates. These systems are referred to as inertial navigation systems (INS), inertial measurement units (IMU), inertial reference platform and other variations.

A.2.1.4 Pavement Surveillance Context

GPS receivers usually form part of the pavement surveillance equipment configuration as discussed in Parts B through G of TMH 13.

Apart from differential correction techniques, some of the factors that influence GPS can be mitigated during planning, quality control and data interpretation stages of a surveillance survey. These aspects are addressed in Part B.

Summary of Concepts: Positioning

- The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations.
- The term “GPS” has been adopted in this document referring to Global Navigation Satellite Systems (GNSS).
- GPS Receivers report co-ordinates using the World Geodetic System (WGS84) format.
 - Many factors influence GPS accuracy. Two of the main augmentation systems in use are: Differential correction or differential GPS (DGPS), and inertial augmentation systems.
- DGPS can refer to any type of Ground-based Augmentation System (GBAS).
- Satellite-based Augmentation Systems (SBAS) refer to wide-area DGPS (WADGPS).
- To “create” accurate “missing” GPS data, inertial augmentation is used. Synonymous terms are inertial navigation system (INS) and inertial measurement unit (IMU).



More Information: How GPS Works

The basis of the GPS technology is currently a set of 24 satellites, orbiting the earth with a period of 12 hours at an altitude of about 26,600km. The satellites are being constantly tracked by a globally monitored network; the control centre is located at the Falcon Air Force Station at Colorado Springs. The satellites carry an atomic frequency standard to generate a stable signal. They transmit at the frequencies L1 = 1575.42 MHz and L2 = 1227.6 MHz. These carriers are modulated with two codes generally referred to as the coarse acquisition (C/A) code and the precision (P) code. In addition, a navigation message is transmitted that allows the user to compute the position of the satellite as a function of time. Once the GPS receiver locks on to four or more of these satellites, it can triangulate its location from the known positions of the satellites.

Here's how GPS works in five logical steps:

1. The basis of GPS is triangulation from satellites.
2. To "triangulate," a GPS receiver measures distance using the travel time of radio signals.
3. To measure travel time, GPS needs very accurate timing which it achieves with some technology.
4. Along with distance, you need to know exactly where the satellites are in space. High orbits and careful monitoring are the secret.
5. Finally you must correct for any delays the signal experiences as it travels through the atmosphere.

1. Triangulation

Position is calculated from distance measurements (ranges) to satellites. Mathematically we need four satellite ranges to determine exact position. Three ranges are enough if we reject ridiculous answers or use other techniques. Another range is required to calculate a common correction factor.

2. Measuring Distance

Distance to a satellite is determined by measuring how long a radio signal takes to reach us from that satellite. To make the measurement we assume that both the satellite and our receiver are generating the same pseudo-random codes at exactly the same time. By comparing how late the satellite's pseudo-random code appears compared to our receiver's code, we determine how long it took to reach us. Multiply that travel time by the speed of light and you've got distance.

3. Timing

Accurate timing is the key to measuring distance to satellites. Satellites are accurate because they have atomic clocks on board. Receiver clocks don't have to be too accurate because an extra satellite range measurement can remove errors.

4. Satellite positions

To use the satellites as references for range measurements we need to know exactly where they are. GPS satellites are so high up their orbits are very predictable. Minor variations in their orbits are measured by the Department of Defence. The error information is sent to the satellites, to be transmitted along with the timing signals.

5. Corrections

| Typical Error in Meters | Standard GPS | Differential GPS |
|-------------------------|--------------|------------------|
| Satellite Clocks | 1.5 | 0 |
| Orbit Errors | 2.5 | 0 |
| Ionosphere | 5.0 | 0.4 |
| Troposphere | 0.5 | 0.2 |
| Receiver Noise | 0.3 | 0.3 |
| Multipath | 0.6 | 0.6 |

A.2.2 Road Profile Wavelength

The road surface is made up of various longitudinal profile wavelengths as seen in Figure A.2-1, which has various effects on vehicle-pavement interactions.

In TMH13 the automated measurement of these various profiles wavelengths are discussed in more detail.

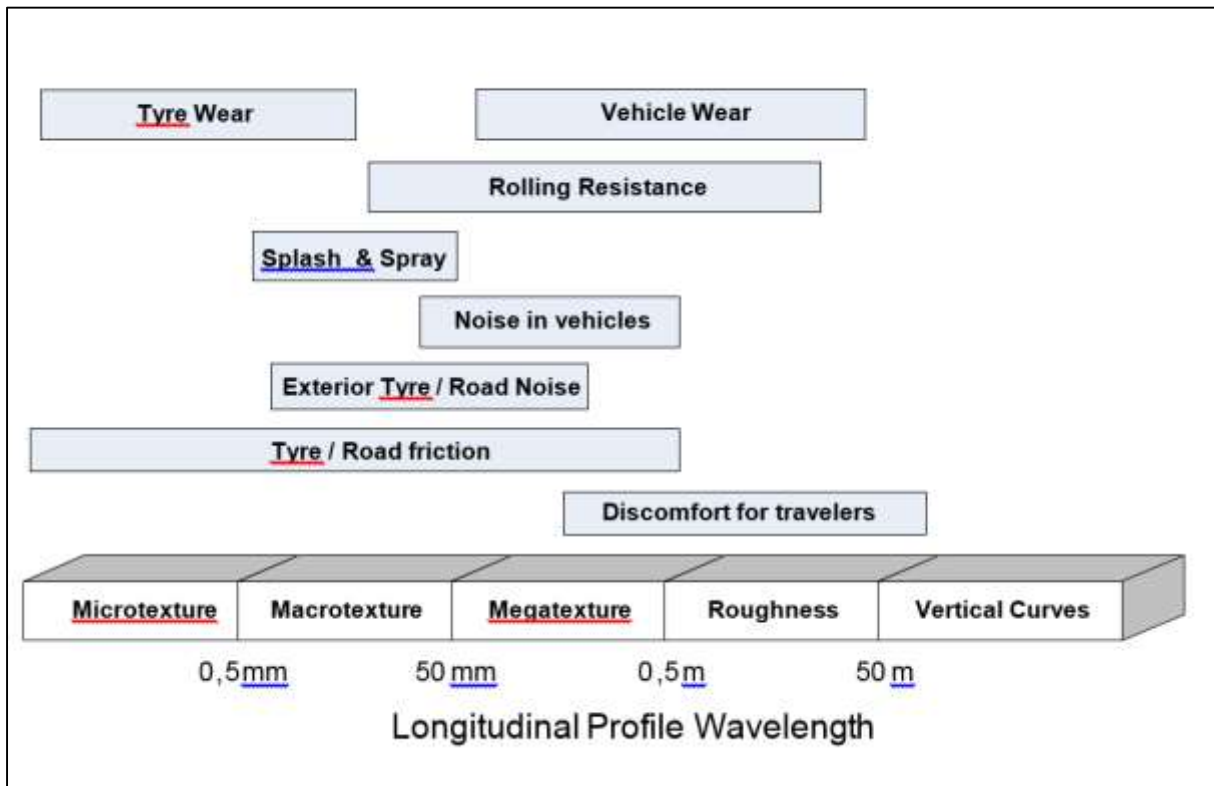


Figure A.2-1: Longitudinal profile wavelength ranges and their effects on vehicle-pavement interactions (ISO 13473)

A.2.2.1 Road Roughness

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, 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.

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 A.1. This figure also shows the difference between the lateral profile and the longitudinal profile.

Part A: General

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 Figure A.1 and Figure A.2):

- Along any line on the road, there exists a “true profile” (top graph in Figure A.2). The true profile is approximated by the measured profile, which is a profile measured at a predetermined sampling interval (middle graph in Figure A.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.

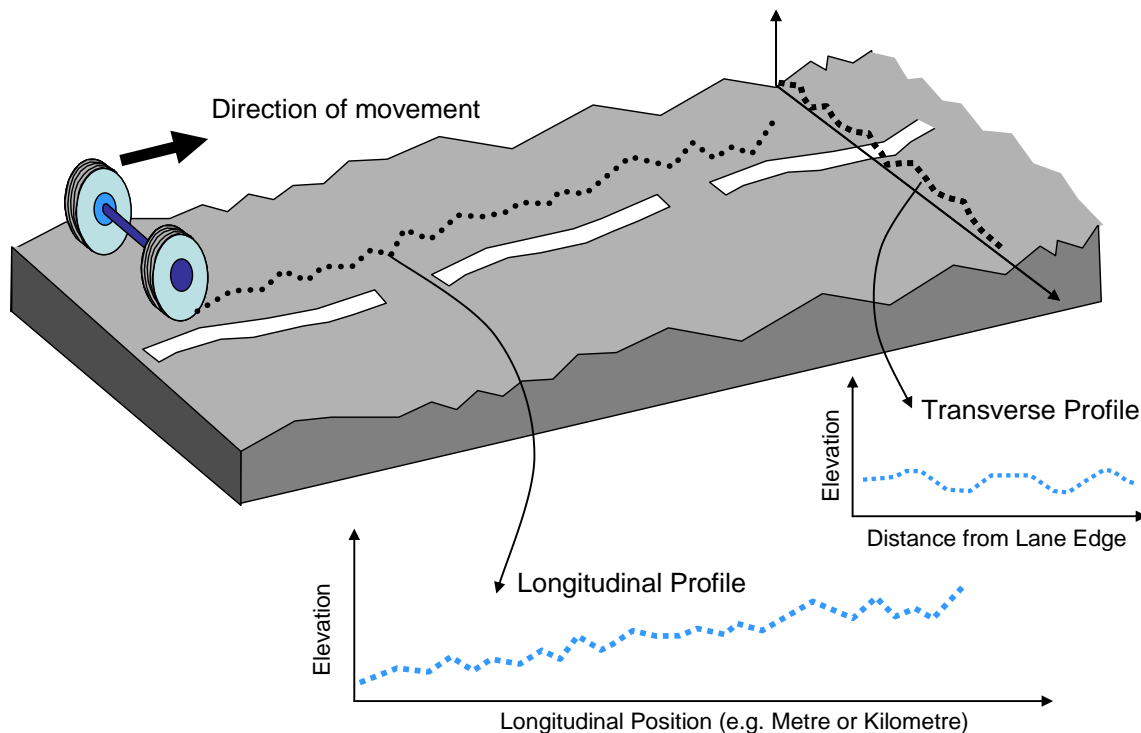


Figure A.1 Road Profile Measurement

- A profile can be subdivided into a number of sinusoidal curves, each with a different wavelength. The top graph in Figure A.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 A.2 shows the measured profile after the very short wavelengths and grades have been filtered out.

A.2.2.2 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.

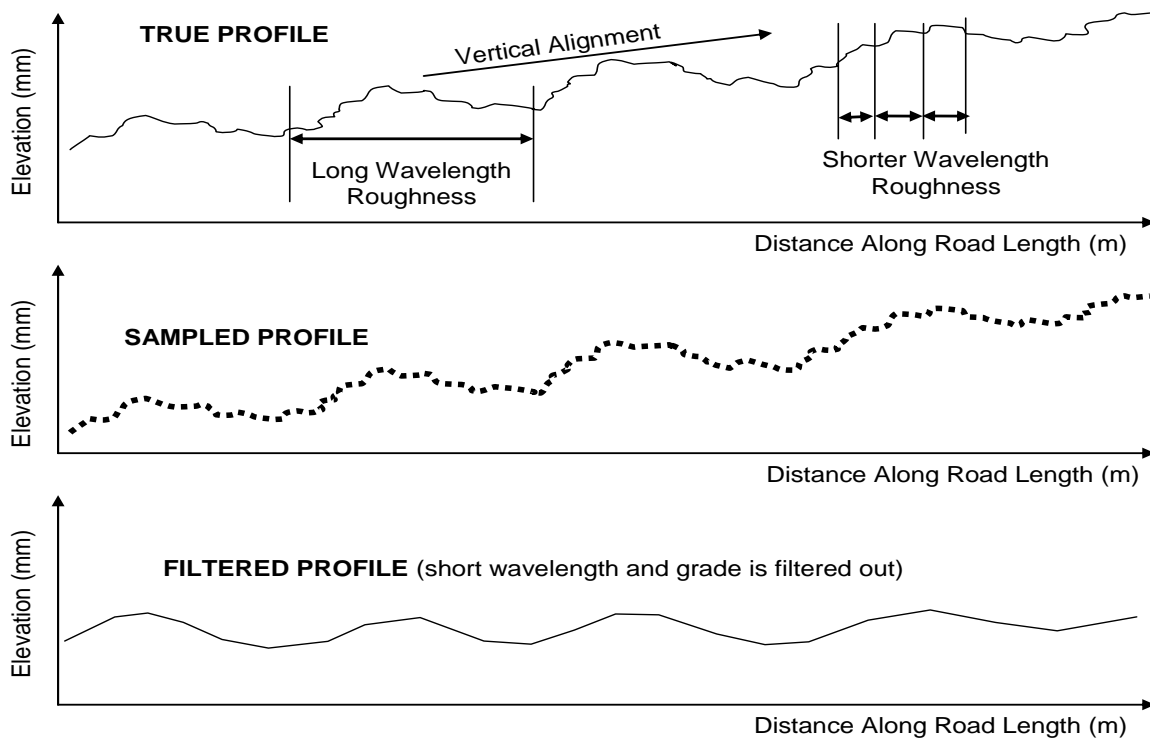


Figure A.2 Profile Measurement Concepts

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 A.2.2.4.

A.2.2.3 Measurement Approaches

The measurement of road roughness can be classified into two basic types (also illustrated in Figure A.3):



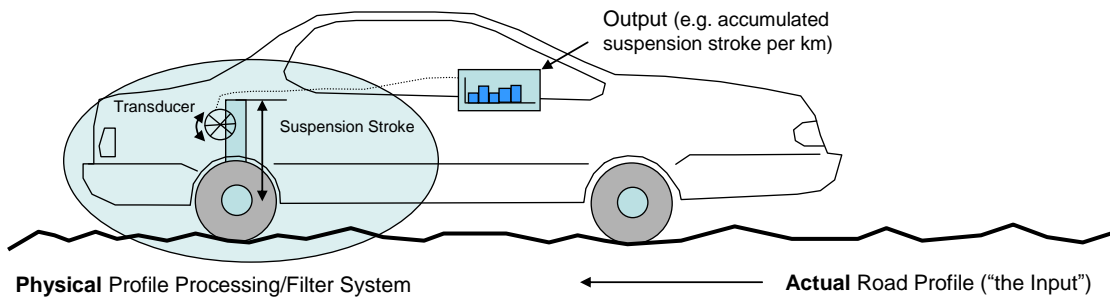
Further Reading: SINUSOIDS and FILTERS

For a more in-depth discussion of the basic aspects of sinusoid curves (e.g. wavelength, amplitude, frequency), see **Appendix A-2**.

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

- 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 A.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.

RESPONSE TYPE MEASUREMENT



PROFILOMETRIC METHODS

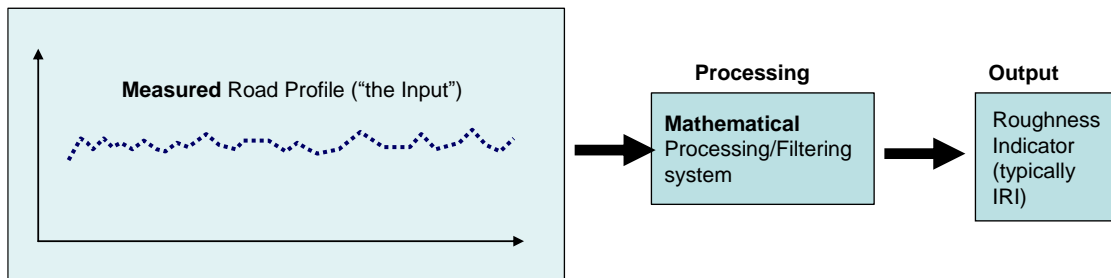


Figure A.3 Measurement Types (Response and Profilometric Types)

- Profilometric Type Measurement** involves the measurement of the road profile after which the profile is filtered (as shown in Figure A.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 has distinct advantages and disadvantages, which are discussed in more detail in Part C. 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.

Part A: General

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.

A.2.2.4 International Roughness Index (IRI)

The IRI is a roughness parameter 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 A.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 A.4.

Thus, in essence, the IRI is calculated through 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 A.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 A.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, 1986).

The IRI interpretation scale is illustrated in Figure A.5. More detailed scales for IRI interpretation for paved and unpaved roads can be found in ASTM E1926-98. As shown in Figure A.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.

Part A: General

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.



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>

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].

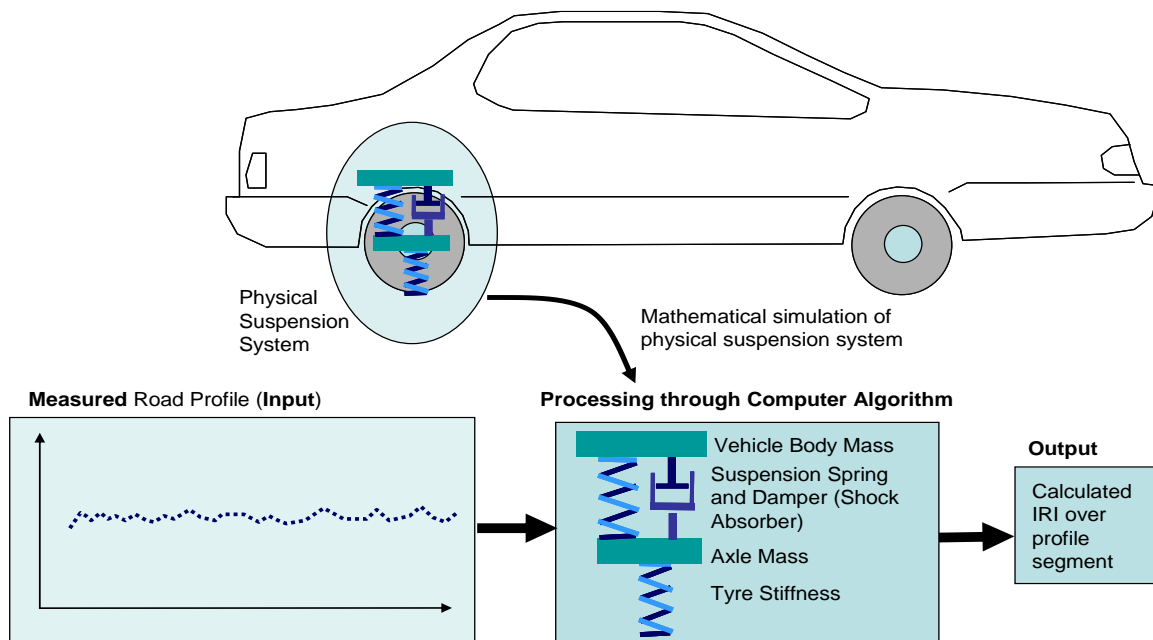


Figure A.4 Aspects of the IRI Calculation (after Sayers and Karamihas, 1989)

IRI Scale (m/km)

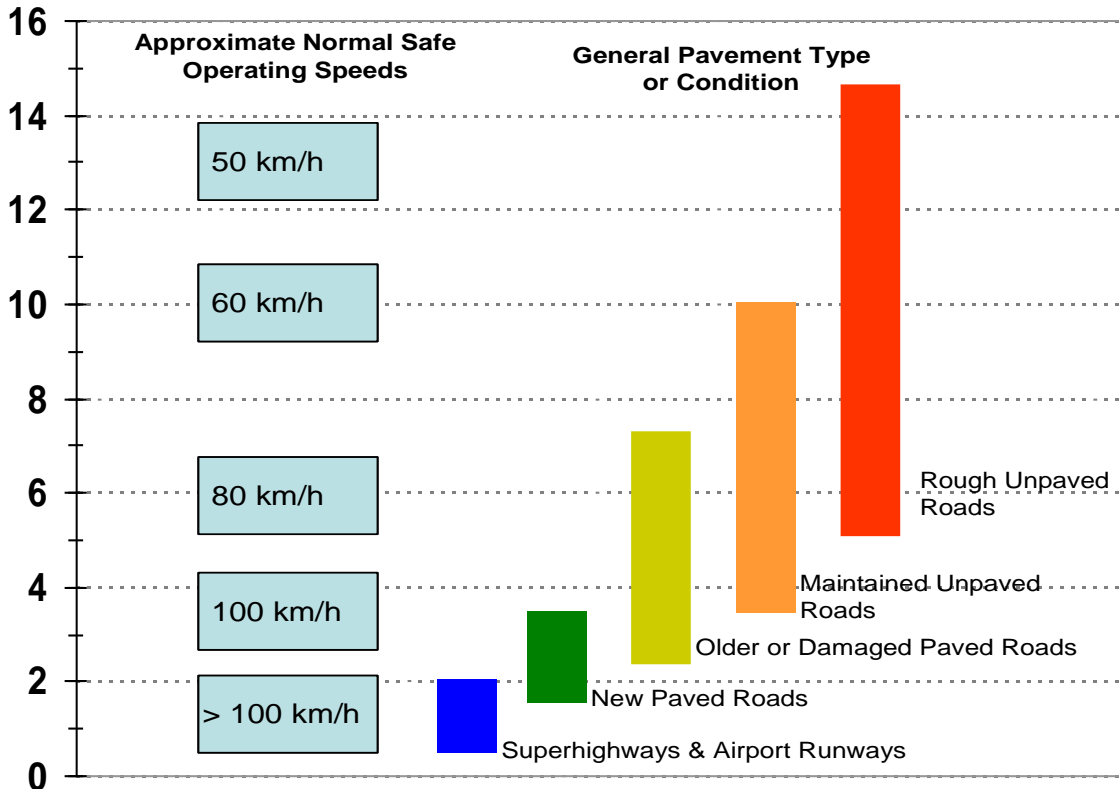


Figure A.5 The IRI Interpretation Scale

A.2.2.5 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 traditional response type devices with a single centre axle mounted sensor measured 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.

Studies have shown that, for roads without paved shoulders, the HRI is typically equal to 80 percent of the average IRI in both wheelpaths [Sayers, 1989]. For roads with wide paved shoulders, or multi-lane freeways (which have less roll-impact on roughness), the HRI is typically equal to 90 percent of the average IRI in both wheelpaths.

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Although both the IRI and HRI are good indicators of pavement roughness, the IRI is more widely used and is recommended for network level reporting. If the IRI is measured in both wheelpaths, the HRI can always be estimated from the two IRI values. However, the HRI generally provides little information additional to the IRI.

Summary of Concepts: Roughness

- 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.

A.2.3 Rutting

Rutting is the longitudinal permanent deformation that occurs in the wheel paths of flexible pavements. As shown in Figure A.6, In South Africa, rut depth is commonly measured and defined as the maximum permanent deformation measured under a two meter straight edge placed transversally over the rut.

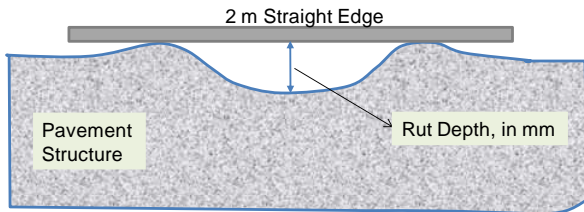


Figure A.6 Rut Depth Measurement

Rut depth is generally used on the network level along with other parameters to estimate the timing, type and cost of maintenance needs. This parameter relates to the riding experience and safety of the road user and provides information on the structural condition and deterioration of pavement structures.

This section explains the functional and structural significance of rutting, discusses interpretation criteria, and explores characteristics of the surface transverse profile.

A.2.3.1 Functional Significance

Rutting is one of several pavement defects that collectively result in **road roughness**. Road roughness directly relates to the degree of comfort or discomfort experienced by the road user as discussed in the preceding section and in Part C.

Well defined deep ruts pose a safety risk to road users as it may cause loss of vehicle control when travelling at high speeds under both dry and wet conditions.

Under wet conditions, **aquaplaning** (also known as hydroplaning) may occur when water ponds in ruts. In such an event, a vehicle's tyre is separated from the road surface when water builds up under high pressure and forms a continuous film between the surface and the tyre. Under these conditions, steering ability of the vehicle is completely lost and braking ability substantially reduced.

Aquaplaning is a complex phenomenon influenced by a number of road surface and vehicle related factors as well as the amount of water present. However, the possibility of a hazardous condition existing mainly increases

with an increase in water depth and length of the flooded area (Stocker and Lewis, 1972). Table A.1 classifies the risk of a hazardous pond based on water depth and pond length.

Table A.1 Risk Pond Classification (Nygårdhs, 2003)

| Risk | Depth (D, mm) | Length (L, m) |
|--------|-------------------------------|-------------------------------|
| Low | $D < 8$ | $L < 8$ |
| Medium | $8 \leq D < 10$ or $D \geq 8$ | $L \geq 8$ or $8 \leq D < 10$ |
| High | $D \geq 10$ | $L \geq 10$ |

The Draft TRH12 (2006) guideline document also highlights the risk of standing water and states that at a common cross-fall of 2 per cent, water ponding can be expected when the rut depth exceeds 10 mm. Table A.2 indicates the effect of cross-fall on water ponding.

Table A.2 Water Ponding Potential (Draft TRH12, 2006)

| Road Cross-fall (%) | Rut Depth |
|---------------------|-----------|
| 2 | > 10 |
| 2½ | > 12 |
| 3 | > 14 |



More about Aquaplaning

When a water wedge builds up between the surface and the tyre, friction between the tyre and surface diminishes and spin-down (reduction in wheel speed) occurs.



A more detailed discussion of aquaplaning, including the two types of aquaplaning, can be found in Austroads (2005).

A.2.3.2 Structural Significance and Causes

In the context of pavement design and network management rutting is one of the primary indicators of structural performance. That is, rutting develops with an increase in the number of wheel load applications and the objective is to keep rut levels below a specified threshold. Experience shows that once rut levels reach magnitudes in the order of 15 mm there is an increased probability of cracking in the wheel paths with subsequent water intrusion and accumulation of failure (Croney and Croney, 1998).

Increasing truck tyre pressures, axle loads and traffic volumes place high demands on design engineers and network managers. Rutting – which contributes to road roughness – further induces dynamic loads (axle bounce) which increase the effective magnitude of loading experienced by pavements.

Rutting is caused by a combination of shear-related deformation and densification which may develop in any of the pavement layers. The loading characteristics and relative strength of pavement layers determine the origin of rutting in the pavement structure. The way in which rutting manifests at the surface provides clues to the origin of the distress. For example, pavement engineers know that narrow, sharply defined ruts point to problems in the upper pavement layers, whilst wide, even-shaped ruts generally relate to problems in the lower layers. Figures A.7 to A.9 illustrate classical rut manifestations. The visual assessment of rutting is described in TMH 9.



Figure A.7 Rutting originating from thick asphalt surface layer



Figure A.8 Rutting originating from the upper pavement layers



Figure A.9 Rutting originating from the lower pavement layers

A.2.3.3 Evaluation Criteria

The preceding subsections introduced important aspects that should be considered when deriving criteria for interpreting rut depth data. In pavement management systems, rut depth thresholds are used together with other performance indicators to trigger pre-defined remedial or rehabilitation measures. The discussions in these guidelines are limited to benchmarking of pavement condition using three broad categories, namely Sound, Warning, and Severe.

Pavement evaluation standards in South Africa have long used rut depths of 10 mm and 20 mm as thresholds for Warning and Severe conditions, respectively. A review of these criteria based on risks associated with aquaplaning, as well as

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typical rut depth distributions encountered on South African roads suggest that characteristic rut depth distributions also be calculated from transverse profiles. Table

Summary of Concepts: Rutting

- Rutting is the longitudinal permanent deformation that occurs in the wheelpaths of flexible pavements.
- In South Africa, rut depth is commonly defined as the maximum permanent deformation measured under a 2 meter straight edge placed transversally over the rut.
- Rut measurements are used to monitor the functional condition of roads (or road networks). In this regard, rutting relates to riding quality and road safety.
- Aquaplaning is a phenomenon where vehicle control is lost due to build-up of water under the tyre. Aquaplaning may occur when water ponds in a rut. The risk of a hazardous pond situation is defined by pond depth and length of the pond area.
- Rutting develops as a result of accumulated wheel load repetitions throughout the service life of the pavement. Rutting is therefore an important measure of structural performance.
- Proposed rut depth criteria suggest that characteristic rut depths > 8 mm should be regarded as “Warning”, whilst rut depths > 12 mm should be regarded as “Severe”.
- Rut depth is only one of several characteristics of the surface transverse profile. Other parameters include rut width, area of the rutting profile, pond depth, pond width, and pond area.

depths greater than or equal to 12 mm should be regarded as severe (Draft TRH12, 2006).

In light of functional and structural considerations presented thus far, Table A.3 offers general criteria for the evaluation of rut depth.

Table A.3 Rut Depth Evaluation Criteria

| Safety Risk | Condition | Rut Depth (RD) |
|-------------|-----------|--|
| Low | Sound | $RD < 8 \text{ mm}$ |
| Medium | Warning | $8 \text{ mm} \leq RD < 12 \text{ mm}$ |
| High | Severe | $RD \geq 12 \text{ mm}$ |

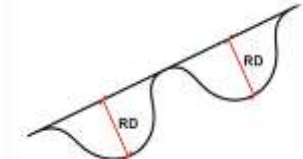
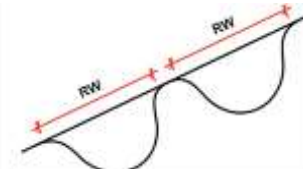
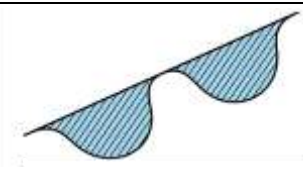
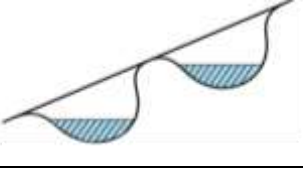
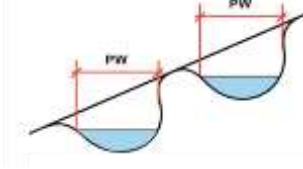
A.2.3.4 Characteristics of the Surface Transverse Profile

Modern measurement devices measure both the longitudinal and transverse (or lateral) road profiles as previously illustrated in Figure A.1. These devices – referred to as profilers – use various sensor technologies to capture the road profile details (See Part D). The longitudinal profile is measured in the direction of movement and is primarily used to assess road roughness (Part C). Transverse profile data is mainly used to determine:

- Mean transverse profile;
- Maximum rut depth, and
- Cross-fall

A.4 conceptually defines different rutting parameters that can be determined from surface transverse profiles.

Table A.4 Typical Rutting Parameters

| | |
|-----------------|---|
| Rut Depth (RD) |  |
| Rut Width (RW) |  |
| Rut Area |  |
| Pond Area |  |
| Pond Width (PW) |  |

A.2.4 Skid Resistance and Texture

Skid resistance is a measure of the ability of a road surface to prevent a vehicle’s tyres from sliding whilst the vehicle performs typical manoeuvres such as turning or braking (Visser and Marais, 1984). Since skid resistance plays a role in determining how a vehicle will respond to sudden braking or turning at speed, it is related to road safety and accident frequency. As such, it is one of the most important features to monitor as part of road network surveillance operations.

Road accidents are caused by many factors such as driver behaviour, vehicle and tyre characteristics, vehicle speed and roadway characteristics (which includes skid resistance properties).

Because of the complex causes of road accidents, links between accident frequency and skid resistance are not always clear and easy to understand. However, there is little doubt that poor skid resistance is often a contributory factor in road accidents, and that the likelihood of accidents increases significantly on roads where the skid resistance is below certain thresholds.

Many studies have shown a clear link between the skid resistance of roads and the likelihood of road accidents. A recent documentation of such studies showed the following key findings (Austroads, 2005; Noyce et al., 2007):

- There is a significant relationship between the rate at which road accidents occur and the skid resistance of road segments.
- Sections of road with a high proportion of crashes have a lower skid resistance, on average, than sites with a low proportion of crashes.

The relationship between accident frequency and skid resistance follows directly from the influence that skid resistance has on stopping distance. Figure A.10 shows the nature of the relationship between the friction coefficient (a measure of skid resistance) and stopping distance. Some studies have shown a similar non-linear relationship between accident rate and measured skid resistance indicators.

Skid resistance reduces significantly on wet road surfaces, and this has a significant impact on accident risk. For example, Visser (1976) reported that roads in the Tswane region are wet for only two per cent of the year, and yet the mean wet road injury and fatality rates for the region was nearly 12 per cent. Similar statistics have been reported in countries such as New Zealand (Clissold, 1977).

Since skid resistance is most critical under wet conditions, most measurement devices are designed to measure skid resistance when the road surface is wet. This guideline is thus concerned mainly with the measurement of skid resistance under wet conditions.

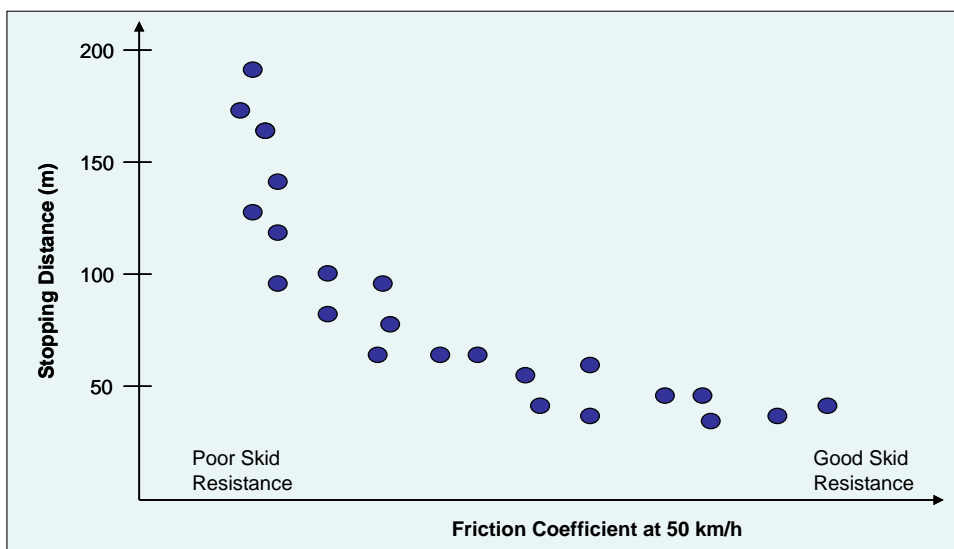


Figure A.10 Generalized Relationship between Stopping Distance and Skid Resistance (after data in Noyce et al., 2007)

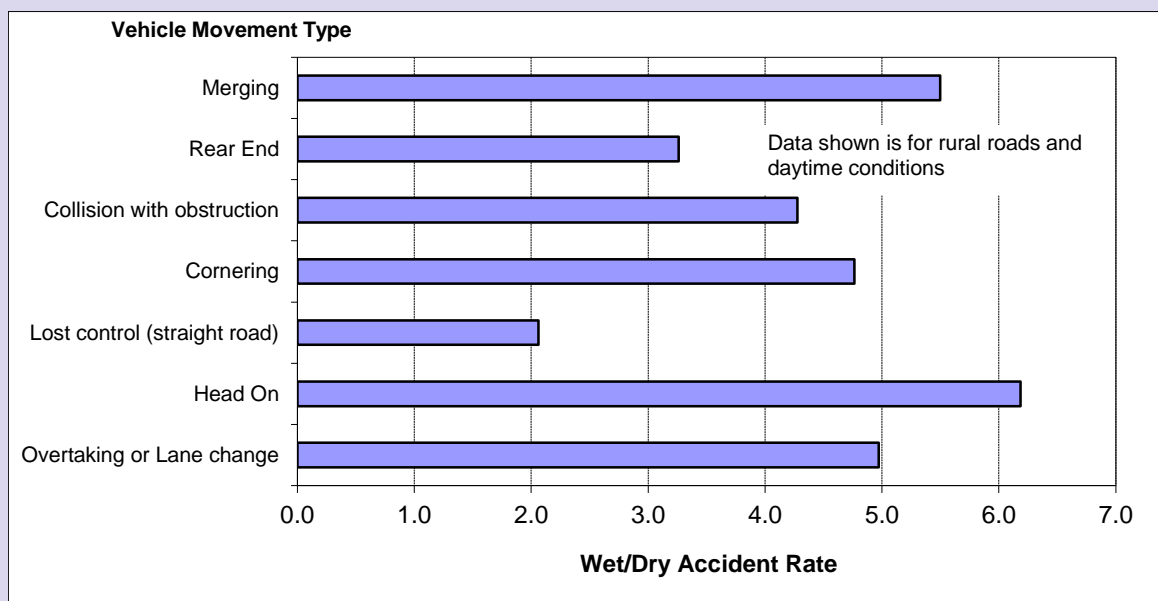


More Information: Skid Resistance, Accident Risk and Wet to Dry Accident Ratios

Skid Resistance and Accident Risk: Several studies have compiled in-depth literature reviews on the relationships between road accident risk and skid resistance. One such study is a recent and comprehensive literature survey documented by Noyce et al (2007). Austroads (2005) also contains a brief summary of studies related to skid resistance and accident risk. Some of the findings documented by Noyce et al. (2007) and in Austroads (2005) include the following:

- Studies show that road sections with a high skid resistance generally have a lower proportion of crashes than sections with low skid resistance;
- Some studies found a significant (up to 45 per cent) decrease in the number of accidents before and after road rehabilitation in which a road with poor skid resistance was improved.
- Some studies have found a threshold in measured skid resistance parameters below which the risk of accidents increase significantly.
- Not all studies are consistent in establishing links between skid resistance and accident rates. In general, researchers experience difficulty in predicting accident frequency using only skid resistance data.
- Despite the clear links between accident rates and skid resistance there is no simple method for determining when a road changes from “safe” to “hazardous” based solely on skid resistance properties. This is because of the many factors involved in road accidents, and to the complex nature of skid resistance,

Wet versus Dry Accident Risk: Analyses of the number of road accidents in wet and dry conditions combined with the percentage of time that the roads are wet or dry, are generally used to establish the wet/dry accident rate. Most wet/dry accident data show a significant increase in accident risk under wet conditions. The figure below shows data reported by Clissold (1977) for accidents on rural roads in New Zealand. The data show that, for all vehicle movement types, the risk of accidents under wet conditions is at least twice as high as that under dry conditions. It should be noted, however, that this risk is only partly caused by reduced skid resistance, and other factors such as sight distance are also primary causes of wet weather accidents.



A.2.4.1 Factors Defining and Influencing Skid Resistance

As with many other measures of road characteristics, skid resistance is a complex phenomenon, and the measured skid resistance can vary significantly depending on the speed of measurement, tyre characteristics, the volume of water used during measurement etc. To ensure pragmatic and consistent interpretation of skid resistance data, it is essential that persons charged with management and interpretation of skid resistance surveys be familiar with the fundamental aspects that define and influence skid resistance. An overview of these factors is therefore given in the following paragraphs.

A graphical overview of the factors that define and influence skid resistance is shown in Figure A.11. Aspects shown in this figure are elaborated on in the following paragraphs.

a) The Coefficient of Friction

A wheel moving over a road surfaces loses energy as a result of the friction that resists movement. If there is no engine torque applied to the wheel the energy loss will cause the forward movement of the wheel to slow and eventually stop.

The Coefficient of Friction is a measure of the magnitude of friction present between the tyre and road surface. The Coefficient of friction is calculated by dividing the friction force (working along the road surface and resisting forward movement) by the force (weight) on the tyre.

For any situation, the coefficient of friction is determined by (a) the characteristics of the area of contact between the tyre and the road surface; (b) the speed of the vehicle; and (c) the degree of free rotation, which is zero when full brake force is applied (also see the sidebar on Friction and Degree of Slip).

b) Water Dispersion from the Contact Area

For friction resistance in wet weather, the coefficient of friction is highly dependent on the thickness of the water film between the tyre and road surface, and by the ability of the tyre and the road to rapidly disperse water from the tyre and road surface interface, thereby establishing a semi-dry contact area.

Road-related factors that will influence the degree of water dispersion include the following:

- The texture depth of the surface;
- The geometric crossfall;
- The Porosity of pavement (i.e. open graded asphalt)

Vehicle-and-Tyre-related factors that will influence the degree of water dispersion include the following:

- The vehicle speed (the faster the vehicle is moving, the less time there is to effectively disperse the water film);
- The tread depth of the tyre, which provides channels in which water can escape from the contact area. Worn or smooth tyres will dramatically reduce the dispersion capabilities of a tyre.

The intensity of the rainfall will naturally influence the thickness of the water film that needs to be dispersed between the road and tyre interface. The thickness of the water film also reduces sight distance, thereby further increasing the accident risk.

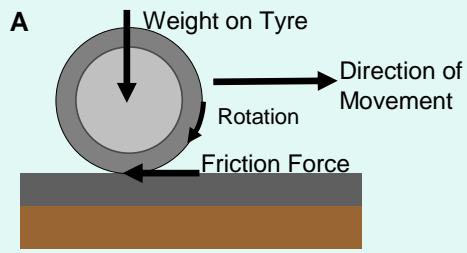
For roads with adequate drainage, geometric design and surface texture, and for vehicles operating at suitable speeds for wet weather, there should be enough time for water dispersion to take place so that a partially dry contact area with high friction can be achieved. If the water film cannot be dispersed, aquaplaning is likely to occur.

As described in Section 2.3, aquaplaning (also know as hydroplaning) occurs when a relatively thick water film is present between the tyre and the road surface. In this situation, high water pressures build up which cause the tyre and road surfaces to separate, causing an almost complete reduction in friction and a resulting loss in control over the vehicle.

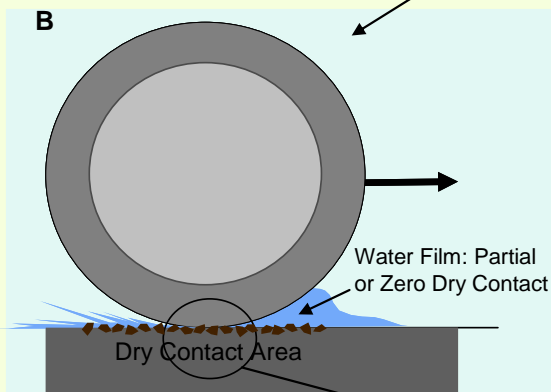
Aquaplaning should not be confused with skidding. In aquaplaning, there is complete separation of the tyre and road surface, and the friction potential of the road is not brought into play. Skidding, on the other hand, deals with the friction potential when between road and tyre surfaces where the water film can be partially or totally dispersed. These guidelines are primarily concerned with skidding.

A: Friction that Resists Skid is caused by energy loss taking place between the road surface and the tyre. This energy loss causes reduction in speed until the tyre or vehicle comes to a stop.

Friction is measured by the coefficient of friction, which is determined by the quality and size of the contact area, the vehicle speed, and the degree of free rotation (zero when full brake force is applied)

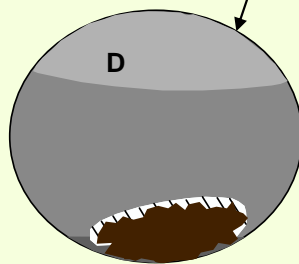
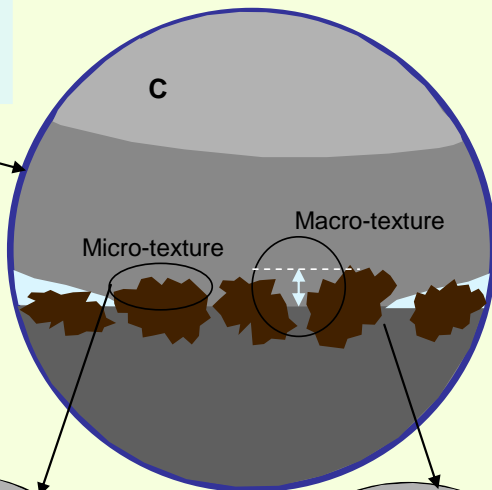


$$\text{Coefficient of Friction} = \frac{\text{Friction Force}}{\text{Weight on Tyre}}$$

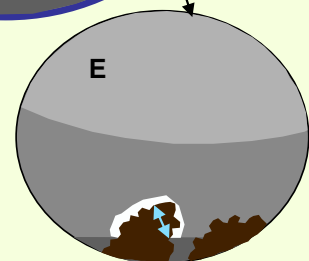


B: Quality and Size of Contact Area is determined by (a) the ability of the tyre and the road to drain water from the contact area, (b) on the time available to do this; and (c) the texture characteristics of the dry contact area

C: Surface Texture Characteristics determine the strength of the grip or bond between aggregate and tyre surfaces, and the degree of elastic deformation in the tyre, caused by protrusions in the surface texture. These protrusions also determine the speed at which water can be drained from the contact area.



D: Microtexture causes momentary, small scale bonding between the tyre and the road surface aggregate. The rapid forming and breaking of the bonds cause frictional resistance.



E: Macrotexture develops friction resistance because it deforms the tyre, causing energy loss through heat, resulting in increased friction resistance. Macro texture also helps to disperse the water film, thereby establishing a partially dry contact area.

Figure A.11 Factors Affecting Skid Resistance

c) Elements of Surface Texture

The texture of the road surface significantly influences the friction (i.e. energy loss) that develops between tyre and road surface and which can prevent skidding or can rapidly slow down a vehicle when needed.

As shown in Figure A.11, skid resistance is influenced by two key components of surface texture: microtexture and macrotexture. These definitions are :

Microtexture is provided by the irregularities on the surfaces of road surface aggregate. Microtexture increases friction by creating momentary molecular bonding (known as adhesion) between the tyre and aggregate surfaces. The smoothness or harshness of aggregate and sand in the road surface are the key elements that cause and influence microtexture.

Microtexture is important at most vehicle speeds, and in wet and dry weather. At low speeds, microtexture is the primary contributor to skid resistance. However, microtexture will reduce significantly as the water film between the tyre and road surface increases, and the role that microtexture plays in skid resistance thus depends on how much water can be dispersed by the tyre tread and macrotexture.

Over time, microtexture of a road surface may reduce because aggregate become smooth and polished by traffic. Microtexture can also be influenced by the presence of dust, contaminants and excess binder (often found on recently constructed road surfaces).

A direct measurement of microtexture is very difficult to make. For this reason, measurements of friction on a small scale are mostly used to characterise microtexture. Larger scale skid resistance measurements measure the combined contribution of micro-and-macro texture.

Macrotexture is caused by protruding aggregate (in the case of surface seals and asphalt) and by grooves or textures (in the case of concrete) in the road surface. Macrotexture is thus primarily influenced by design and construction aspects of seals, asphalt and concrete surfacings.

Macrotexture contributes to skid resistance in two ways: (a) it deforms the tyre, thereby leading to energy loss (known as hysteresis); and (b) it provides the grooves and unevenness needed to

rapidly disperse surface water at higher speeds. Because of its influence on water dispersion, macrotexture becomes more important at high vehicle speeds. At vehicle speeds of more than 100 km/h, macrotexture is the dominant factor in determining skid resistance.

Macrotexture is often referred to simply as texture depth, and tests such as the sand patch test (see Part E) are designed to quantify macrotexture.



More about Texture Classes

The Permanent International Association of Road Congresses (PIARC, now known as the World Road Association, or WRS) has defined four ranges of texture, with the following wave characteristics (PIARC, 1987):

- Microtexture: those surface irregularities that have amplitudes of less than 0.2 mm, and wavelengths of less than 0.5 mm.
- Macrotexture: covers irregularities that have amplitudes of 0.1 to 20 mm, and wavelengths of 0.5 to 50 mm.
- Megatexture covers irregularities with amplitudes of 0.1 to 50 mm, and wavelengths of 50 to 500 mm.
- Roughness covers unevenness which has wavelengths of 0.5 to 50 m.

Researchers are generally in agreement that skid resistance is primarily influenced by microtexture and macrotexture, with mega-texture playing a lesser role and roughness not being significant.

d) Interaction of Micro and Macrotexture

Under dry conditions, microtexture is the most important aspect of skid resistance. However, in wet conditions, the influence of microtexture depends on how much water can be dispersed to ensure the small scale asperities can break the remaining water film, thereby establishing the momentary bonds that contribute to friction.

Since the ability to disperse water depends on macrotexture and vehicle speed, the manner in which micro-and-macro texture contributes to skid resistance is rather complex and depends significantly on vehicle speed and water film depth. Figure A.12 shows a generalized graphical illustration of the interaction between macrotexture, microtexture and vehicle speed.

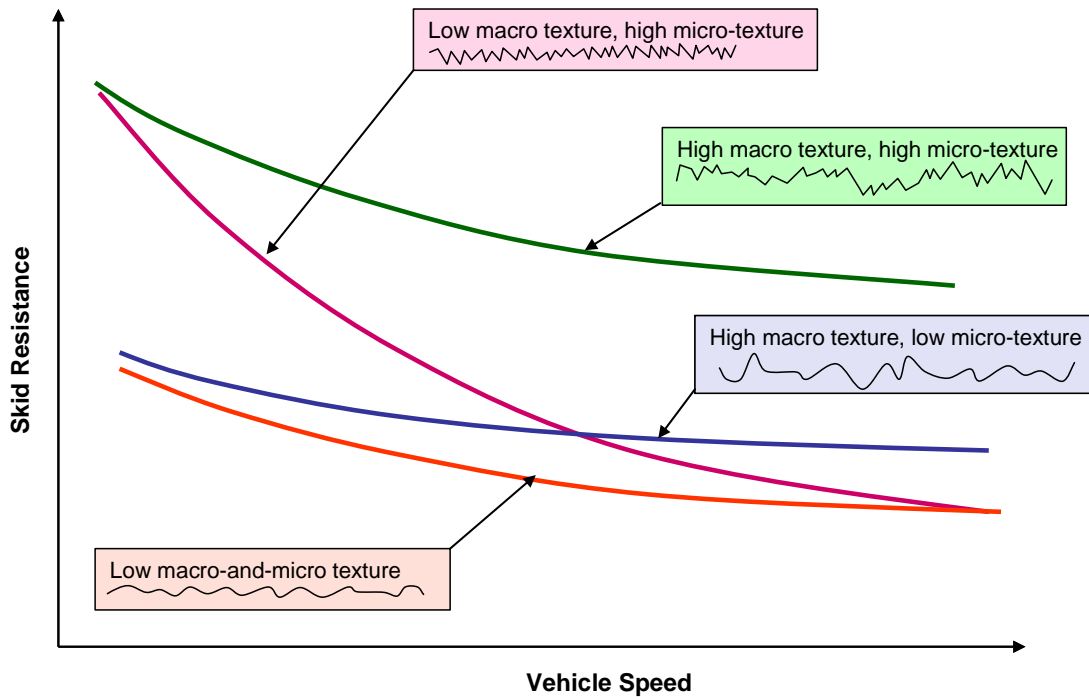


Figure A.12 The Interaction between Texture Type and Vehicle Speed
(after Visser and Marais, 1984; and Sabey, 1966)

It can be seen from Figure A.12 that the following interactions and skid resistance effects exist between texture type and vehicle speed:

- **When microtexture and macrotexture is low** the skid resistance is relatively low at all vehicle speeds. Speed does not have a significant influence on skid resistance.
- **When microtexture is high but macrotexture is low** there is a significant drop in skid resistance with increasing speed. This is because, at higher speeds, the low macrotexture is not capable of dissipating water effectively. Thus the benefit of the good microtexture is rapidly diminished with speed.
- **When microtexture is low and macro texture is high** there is a fair overall skid resistance and the influence of speed again diminishes. At high speeds, this texture provides a better skid resistance than the preceding one. However, at low speeds, the
- lack of good microtexture results in lower skid resistance than for surfaces with higher microtexture.
- **When microtexture and macrotexture is high** there is a good overall skid resistance. The influence of speed is relatively high, but the skid resistance remains high at all speeds.

It should be clear from the above discussion that surfaces where a good microtexture and a good macro texture exist are the most desirable from a safety viewpoint.

A.2.4.2 Interaction of Factors that Influence Skid Resistance

There are clearly many factors that determine the skid resistance for a specific vehicle-road situation at a particular time. From a road manager's viewpoint, the texture of the road surface is clearly the most relevant and is the only factor that can be controlled to some extent through proper planning, measurement and network maintenance.

However, engineers involved with skid resistance measurement should understand that skid resistance measurements can normally be made for a specific speed, water film thickness and vehicle-tyre combination.

Skid resistance measurements therefore provide only an approximate indication of the skid resistance potential of a road at a specific point in time. Even when measurement parameters are fixed (i.e. same speed and test device is used), the measured skid resistance can vary from one measurement to the next at the same location (random variation in measurement).

Part A: General

The degree of wear on the tyre, for example, will greatly influence how sensitive the measurement is to vehicle speed. Other factors such as the amount of dust on the road can also greatly influence skid resistance measurement.

It is thus essential that skid resistance data be interpreted by careful consideration of the test parameters and of the pavement and seasonal parameters that can influence test results.

Table A.5 summarizes the most important factors that influence skid resistance, with emphasis on the factors not already introduced in Figure A.11 and discussed in the preceding sections.

Of particular importance in Table A.5 are the environmental influences. Since temperature and dust influence skid resistance, the measured skid resistance will depend on the time of year, and

this should be taken into account when planning skid resistance surveys. More detail on this aspect is provided in Part E.

Another factor that can significantly influence skid resistance is contaminants on the surface. Spilled diesel, excessive dust, loose gravel etc) can lead to decreases in measured skid resistance which do not provide a true reflection of the average long term skid resistance of a road. For some surface types, the binder coating on surfacing aggregate when the surfacing is newly placed can also lead to decreased skid resistance (Austroads, 2005).

These aspects require attention during quality control and data interpretation stages of a survey (more detail on this aspect is provided in TMH 13 Part E, which deals with operational issues related to surveys).

Table A.5 Summary of Factors Influencing Skid Resistance

| Category | Factor | Influence on Skid Resistance | Comments |
|-----------------------------|----------------------|---|--|
| Road Related Aspects | Surface microtexture | Higher microtexture increases skid resistance | Important at all vehicle speeds |
| | Surface macrotexture | Higher macrotexture increases skid resistance | Important mainly at higher vehicle speeds (speeds greater than 50 km/h). |
| | Crossfall | Higher crossfall improves skid resistance in wet weather | Crossfall influences the water film thickness on the road surface during rainfall. Thicker water films lead to reduced skid resistance. |
| Vehicle and Tyre Parameters | Tyre tread depth | Greater tread depth improves skid resistance in wet weather. | The influence of tread depth depends on the vehicle speed and the macrotexture of the surface. Tread depth becomes more important on surfaces where macrotexture is insufficient to effectively disperse water from the contact area at high speeds. |
| | Applied Brake Force | Variable | Skid resistance varies depending on the brake force applied. The greatest friction is generated when the brake force slows down wheel movement significantly, but not so much that locking of the wheel occurs (see sidebar on Influence of Applied Brake Force) |
| | Tyre Temperature | Lower tyre temperature causes improved skid resistance. | At low temperature, the tyre rubber is stiffer, providing more resistance to deformation of rubber which leads to improved skid resistance. |
| | Tyre design | Better tread design and rubber composition improves skid resistance | Tyres with modern tread design are able to better disperse water from the contact area. However, this effect is likely to be significant mainly at high speeds and on surfaces with low macrotexture. |
| Environment | Temperature | Lower water and air temperature causes improved skid resistance | Temperature influences the stiffness of the tyre (see also Section 5.5 for more information on seasonal effects on skid resistance measurement). |
| | Surface Contaminants | Contaminated surfaces have lower skid resistance. | Dust, spilled diesel, oil and excessive bitumen can significantly decrease skid resistance (see also Section 5.5 for more details on influence of surface condition on skid resistance measurement).. |



More Information: The Influence of Braking Force

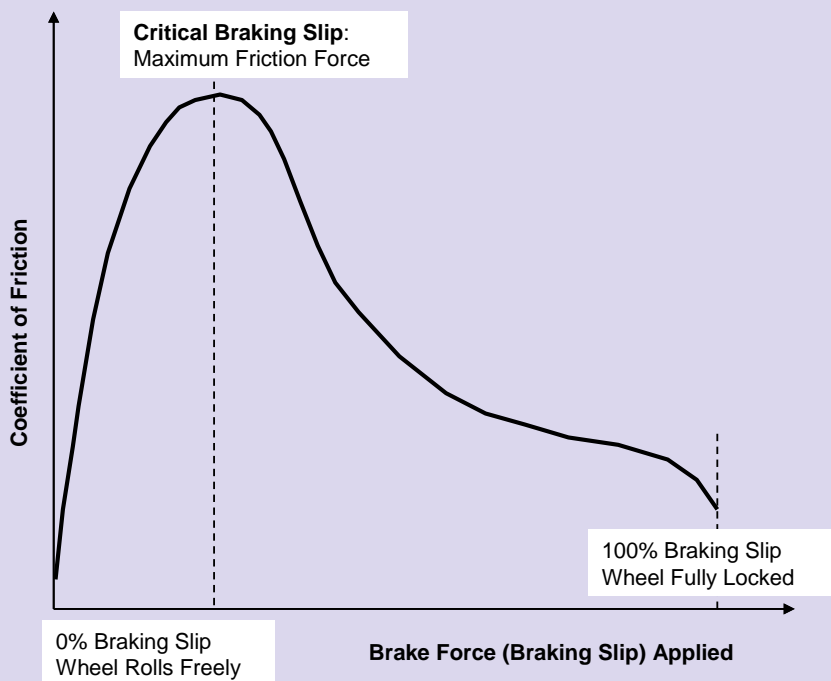
The applied braking force has a significant influence on the friction coefficient that can be obtained on any surface. The braking slip is a parameter that quantifies the applied brake force and its effect on preventing the rolling movement of the wheels.

As shown in the figure below, when no brakes are applied the wheels roll freely and the coefficient of friction between the rolling wheel and the surface is very low. As more brake force is applied, the braking slips increases and friction increases rapidly. However, beyond a certain braking slip (known as critical slip), the friction decreases and becomes very low at the point when the wheels become fully locked (100 per cent braking slip).

Vehicles with anti-locking brakes are designed to maintain a brake force that is close to that needed to effect maximum friction throughout the braking movement.

The concept of braking slip is also important in the measurement of skid resistance, and some measurement devices are designed to create a fixed or variable degree of braking slip. Fixed slip devices apply a fixed braking slip (typically 10 to 20 per cent) to measure friction close to the critical slip, whereas variable slip devices apply a range of braking slips to detect the friction across the complete brake force spectrum (ACPA, 2007). These devices are discussed in more detail in Part E.

A relatively detailed guide on the influence of brake force on friction, and the aspects involved in the measurement of this effect, can be downloaded from the Norsemeter ROAR web site at "<http://www.norsemeter.no/Downloads/Files/Runway%20Primer.pdf>"



Summary of Concepts: Skid Resistance and Texture

- Skid resistance is a measure of the ability of a road surface to prevent a vehicle's tyres from sliding under typical turning and braking actions.
- Since skid resistance is a determining factor in a vehicle's response to sudden braking, it is related to road safety and accident frequency. Skid resistance is therefore a key aspect to monitor in network surveys.
- Friction that resists skid is caused by energy loss taking place between the tyre and road surface. The coefficient of friction is a measure of the magnitude of friction present between the tyre and the road surface and is determined by:
 - The quality and size of the contact area (ability to drain water and texture characteristics);
 - Vehicle speed, and
 - Degree of free rotation (zero under application of full braking force)
- Skid resistance reduces significantly under wet road conditions. For this reason, most measurement devices are designed to measure skid resistance when the road surface is wet.
- Skidding, other than aquaplaning, deals with the friction potential between road and tyre surfaces where the water film can be partially or totally dispersed, i.e. a semi-dry surface. Surface texture, geometric cross-fall, vehicle speed, and tyre tread depth are factors that control water dispersment efficiency.
- Skid resistance is influenced by two key components of surface texture, namely micro-texture and macro-texture.
- Microtexture is defined as surface irregularities with amplitudes less than 0.2 mm and wavelengths less than 0.5 mm. Momentary bonding between the tyre and small-scale surface asperities cause friction resistance.
- Macrottexture comprises irregularities with amplitudes 0.1 to 20 mm and wavelengths of 0.5 to 50 mm. Aggregate that protrudes from the surface cause energy loss when it deforms the tyre and also help to disperse the water film.
- The influence of micro-texture is especially sensitive to water dispersment efficiency. Generally, micro-texture is the primary contributor to skid resistance at low vehicle speeds. Macrottexture, in turn, becomes more important at high vehicle speeds.
- Skid resistance measurements are influenced by road-related aspects, vehicle-tyre aspects, and environmental factors. These measurements therefore only provide an approximate indication of the skid resistance potential of a road at a specific point in time. It is essential that these factors be considered during the quality control process and interpretation of test results.

A.2.5 Pavement Deflection

Measurement of deflections has been used since the 1950s to monitor the structural condition of road pavements (HRB, 1953). A good knowledge base also exists in South Africa and this technology has become an integral part of structural evaluation of pavements in this country. Whilst data such as rut depth, roughness, and skid resistance have direct implications on user safety and comfort, measurement of deflection – related to pavement structural capacity – is mainly of interest for the road owner with respect to maintaining the investment in the road network.

This section introduces technical concepts related to pavement deflection and briefly discusses factors influencing deflection measurements. The use of deflections within the context of condition assessment and estimation of pavement structural capacity or residual life is also addressed.

A.2.5.1 Pavement Response

Pavement surface deflection differs from other measures of pavement condition such as rutting and roughness, in that deflection is an instantaneous response of a pavement structure under a vehicle wheel load. It follows that this response, namely elastic deflection, is fundamentally related to the mechanical behaviour of the structure. Other pavement mechanical responses include, for example, stresses and strains. Figure A.13 illustrates the concept of pavement deflection.

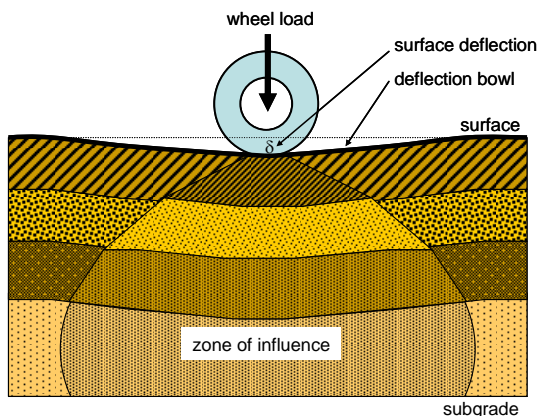


Figure A.13 Concept of Pavement Deflection

The pavement layers elastically deform primarily within the zone of influence, or stress bowl, which result in a physically measurable deflection at the surface.

The deflection indicated in Figure A.13 is the maximum deflection which is located directly under the load. When the load is applied, the instantaneously deformed surface takes on the shape of a bowl, known as a deflection bowl, or deflection basin. Most modern deflection measuring devices determine the deflections at various offsets with respect to the centre of the load, and as such, measure the maximum deflection as well as the shape of the deflection bowl.

The size, depth, and shape of the surface deflection bowl depend on several variables including the thickness and stiffness of the pavement, the underlying materials, and magnitude of the load.

A.2.5.2 Characteristics of the Surface Deflection Bowl

Pavement maximum deflection is a representation of pavement stiffness, i.e. the load spreading ability of the composite structure. Consider the two deflection bowls presented in Figure A.14.

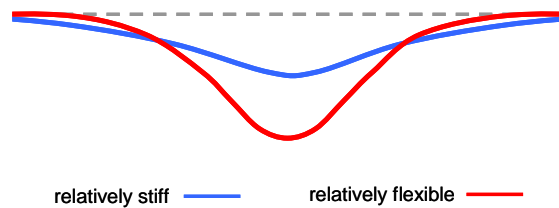


Figure A.14 Deflection Represents Stiffness

Assume that the same load was applied in both cases. The shallow bowl (low deflection case) represents a pavement where the load is effectively distributed by a relatively stiff structure. The deeper bowl (high deflection case) represents a pavement where the load is less effectively distributed by a relatively flexible structure. Consequently, the subgrade is subjected to higher stress levels in the second case.

Several parameters, such as maximum deflection, have been defined to describe various characteristics of the deflection bowl (Horak, 1988). The most common deflection bowl parameters are indicators of relative stiffness or load spreading ability of prominent zones in the pavement structure. The magnitudes of these parameters are dictated by the stiffness properties (known as elastic moduli) of the layers of the pavement. Table A.6 provides a summary of the most common deflection bowl parameters.

Table A.6 Basic Deflection Bowl Parameters

Part A: General

| Bowl Parameter | Acronym | Definition* |
|--------------------|---------|---------------------|
| Maximum Deflection | YMax | D_0 |
| Base Layer Index | BLI | $D_0 - D_{300}$ |
| Middle Layer Index | MLI | $D_{300} - D_{600}$ |
| Lower Layer Index | LLI | $D_{600} - D_{900}$ |

Note: * D_i denotes the deflection at a radial offset of i mm from the centre of the load

The parameters or indices defined in Table A.6 are named relative to the horizontal zones within the pavement structure that they most likely represent. The boundaries of these zones cannot be clearly defined and will differ depending on the composition and condition of the pavement under consideration. Figure A.15 defines the parameters graphically and conceptually illustrates the respective zones.

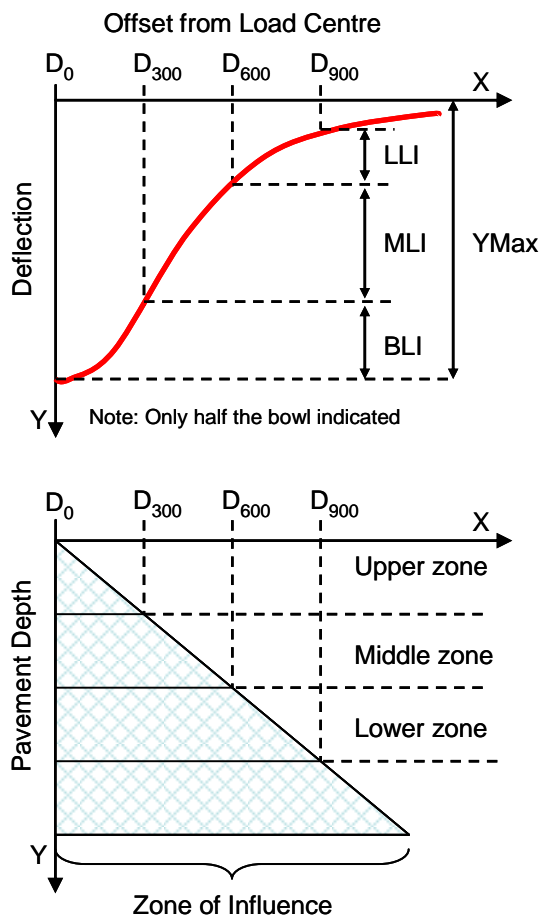


Figure A.15 Deflection Bowl Parameters and Zones they Represent

An important concept illustrated in Figure A.15 is that deflections at different offsets away from the load relate to a response deeper down in the structure. This idea stems from the assumption that elastic deflections originate within the boundaries of the zone of influence (also see Figure A.13 and related text). It follows that the outer deflections primarily represent the response of the subgrade, while the inner deflections represent the response of the pavement layers and the subgrade. The maximum deflection, therefore, represents the response of the total pavement. The difference between deflections at selected offsets therefore relate to the response of a certain zone within the pavement structure, i.e. the definition of BLI, MLI, and LLI.

Figure A.15 further shows that the parameters defined in Table 1-1 are indicative of the slope of the deflection bowl between predefined offsets. The slope of the bowl in a given zone relates to the stiffness of that zone. A steeper slope represents higher flexibility, while a flatter slope represents higher stiffness. Therefore, the higher the deflection bowl parameter under consideration, the lower the relative stiffness of the associated zone, and vice versa.



Important!

The outer deflections are inherently smaller than the inner deflections due to dissipation of the applied energy away from the load. For this reason, LLI will always be smaller than the MLI, MLI always smaller than BLI, and BLI always smaller than YMax. Each parameter should therefore be evaluated on its own basis. Empirically developed interpretation categories and relationships are generally used which enable interpretation and comparison of different parameters. Table A.7 provides examples of interpretation categories developed by Horak (1988) for different pavement types in South Africa. It is important to note that the categories shown in Table A.7 are based on impulse deflection measurements (see Part F for information on different devices).

Part A: General

**Table A.7 Typical Interpretation Categories for Deflection Bowl Parameters
(Adapted from Horak, 1988)**

| Behaviour State | Maximum Deflection | Base Layer Index | Middle Layer Index | Lower Layer Index |
|---|--------------------|------------------|--------------------|-------------------|
| Granular Base Pavements | | | | |
| Very Stiff | < 300 | < 80 | < 50 | < 40 |
| Stiff | 300 to 500 | 80 to 250 | 50 to 150 | 40 to 80 |
| Flexible | 500 to 750 | 250 to 500 | 150 to 200 | 80 to 100 |
| Very Flexible | > 750 | > 500 | > 200 | > 100 |
| Asphalt Base Pavements | | | | |
| Very Stiff | < 250 | < 50 | < 30 | < 30 |
| Stiff | 250 to 400 | 50 to 200 | 30 to 100 | 30 to 50 |
| Flexible | 400 to 600 | 200 to 400 | 100 to 150 | 50 to 80 |
| Very Flexible | > 600 | > 400 | > 150 | > 80 |
| Cemented Crushed Stone Base Pavements | | | | |
| Pre-cracked phase | < 150 | < 40 | < 30 | < 30 |
| Initial fatigue | 150 to 250 | 40 to 100 | 30 to 60 | 30 to 50 |
| Substantial fatigue | 250 to 400 | 100 to 300 | 60 to 100 | 50 to 80 |
| Flexible phase | > 400 | > 300 | > 100 | > 80 |
| Notes: 1. Deflection in microns (μm) | | | | |
| 2. These categories are based on measurements with an impulse deflection device | | | | |

A.2.5.3 Factors Influencing Deflections

Measurement and interpretation of deflections require consideration of various factors that may affect the data. The major factors influencing deflections include loading, climate, and pavement type and condition (Huang, 2004).

a) Loading

The magnitude and loading time, or duration, have a great influence on pavement deflections. The type of deflection measurement device dictates the loading characteristics. Deflection devices can be divided into three categories based on type of loading, namely static or slow moving, steady-state vibratory, and impulse loads.

Part F describes different measurement devices in some detail. Naturally, it is ideal to measure deflections under actual design loads. However, few devices can accurately simulate design loads. First generation devices typically apply static or slow moving loads which are close to the design load magnitude but at a different loading frequency. Third generation impulse load devices, on the other hand, can apply loads similar to the actual design load in magnitude as well as loading frequency.

Pavement deflections are not proportional to load due to the nonlinear behaviour of most road building materials. For this reason, measurements obtained under light loads should not be extrapolated to represent those under

heavy loads, and vice versa. Most devices can test at different load levels. Small corrections to the deflections to account for variations from the target load are allowed, and this is known as 'normalization' of deflections.

b) Climate

Temperature and moisture can affect deflections significantly. Thick asphalt layers are especially prone to temperature effects, because bitumen binder softens at higher temperatures and thus causes deflections to increase. Temperature also has a great effect on concrete pavements. Thermal gradients cause curling in concrete slabs and the time of testing during the day therefore becomes a critical consideration.

Seasonal changes generally cause deflections to follow a sine curve with the peak deflection occurring in the wet season. In dry areas, however, peak deflections may occur in the summer when thick asphalt layers are soften.

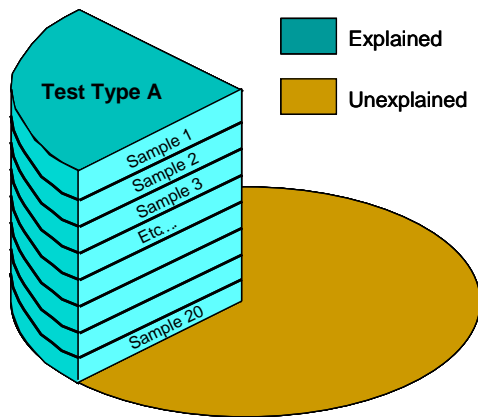
c) Pavement type and condition

Apart from the fact that more rigid structures will produce lower deflections, modes of deterioration associated with different pavement types should also be considered. For thick asphalt base pavements, and pavements with cemented layers, cracking is the dominant mode of deterioration. Cracking of these layers normally cause higher pavement deflections. For granular pavements, moulding by traffic may result in densification and lower pavement deflections over time.

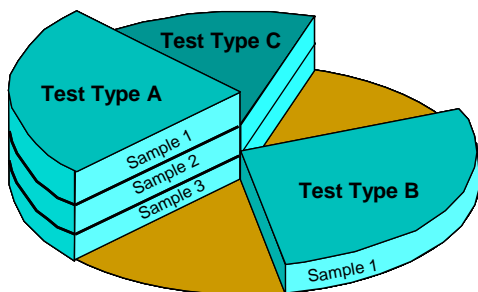
A.2.5.4 Structural Condition Assessment

Although these guidelines focus on measurement and application at the network level, it is important to appreciate the role of deflection measurements within the general process of pavement structural condition assessment.

A holistic approach is typically recommended in which various tests and methods are used to obtain an overall picture of a pavement's condition, expected bearing capacity, and alternative remedial strategies, i.e. the so-called multi-criteria approach. The approach suggests that no single test or method provides a complete description of the information needed to determine the structural condition with confidence. All tests are regarded as indicators and each indicator contributes to an understanding of pavement behaviour. Jooste et al (2007) argue that in a holistic evaluation approach, a balance needs to be struck between a more reliable assessment of a small part of the behaviour to be explained, and less reliable assessment of a large part of the behaviour to be explained. This concept is illustrated in Figure A.16.



Situation 1 Reliable estimation of one indicator



Situation 2 Three indicators, but less reliable estimation each

Figure A.16 Reliability versus Completeness of Assessment

Within the context of this document, therefore, deflection measurements used in isolation cannot be expected to produce a reliable estimate of a pavement's structural condition.

A.2.5.5 Aspects of Relations with Structural Performance

The primary objective of collecting deflection data is to provide an indication of the structural condition and associated residual pavement structural capacity or life. A number of approaches exist to relate deflections or deflection derived parameters to performance. These approaches vary from simple empirical correlations to more complex mechanistic-empirical approaches. This subsection categorizes and briefly discusses different approaches available for use on a network level.

a) Deflection Bowl Parameters

The deflection bowl concept and most commonly used bowl parameters were previously introduced. Since the development of the Benkelman Beam deflection test device, numerous studies were undertaken to directly relate *maximum deflection* to structural capacity of flexible pavements. The most commonly applied methods were those developed by the Transport and Road Research Laboratory (Kennedy and Lister, 1978) and the Asphalt Institute (AI, 1969). Because maximum deflection strongly correlates with subgrade conditions, however, these methods only apply where the behaviour of the pavement is dominated by the subgrade (Jordaan, 1994).

In addition to maximum deflection, performance relations with other bowl parameters (BLI, MLI, and LLI) were developed to improve the representation of the total pavement structure (Horak, 1988, Maree and Bellekens, 1991, Maree and Jooste, 1992). Basic relations and tolerances for different types of South African pavement structures are included in the 1997 TRH12 document. It is well accepted that structural capacity estimates based on deflection bowl parameters can lead to oversimplification of a complex structural response and often to embarrassing inaccuracies. It is therefore recommended that these parameters be used in a benchmarking approach, together with other condition data, to determine the relative structural condition (e.g. sound, warning, or severe) of the pavement in respect to its structural capacity and behaviour state (Horak, 2008).

b) Pavement Strength Indices

Pavement strength indices, correlated with pavement performance, are often used to provide estimates of structural capacity. Techniques have been proposed to determine strength indices from deflection testing which is convenient for characterizing pavement strength at the network level. The **Structural Number (SN)** approach received much attention and has been adopted by organizations such as the World Bank. A wealth of experience also exists with the application of this approach in South Africa.

The concept of structural number was first defined in the AASHTO road test (HRB, 1962). The original index only represents the structure above the subgrade and a separate term in the correlation with structural capacity was added to reflect the effect of the subgrade. The modified structural number (SNC) was subsequently developed to incorporate the variation in subgrade strength as part of a single index (Rohde, 1994). Rohde's approach - adopted in the World Bank's Highway Design and Maintenance Standards Model (HDM) - utilizes the full deflection bowl to calculate the modified structural number. These relationships are recommended for structural capacity estimates at the network level. Details of this approach are appended to Part F.



More about Structural Number

- AASHTO Guide for the Design of Pavement Structures (1993) describes the traditional SN approach;
- TMH 13 Part F contains Rohde's approach to calculate the deflection-based modified structural number.

c) Mechanistic-Based Approaches

The use of mechanistic-empirical methods to determine the structural capacity of pavements is traditionally associated with project level applications. Nevertheless, this approach has also been applied in network level applications.

In this approach mechanics of materials (such as the theory of elasticity) is used to simulate the effect of a wheel load on a theoretical pavement structure. Various software packages are available for this purpose. A summary of the traditional mechanistic-based approach follows:

- 1) Through an iterative process, the measured deflection bowl is matched by a simulated bowl by progressively changing the elastic modulus of each layer in a trial pavement structure. This is known as the backcalculation process. The derived elastic modulus, together with known thickness and Poisson's ratio (defaults assumed for typical materials) for each layer provide a model structure for further analysis.
- 2) The model structure is subjected to a standard load to generate stresses and strains, i.e. response parameters. The critical response parameter (typically the highest value) for each layer is recorded.
- 3) For each layer, the critical response is entered into a criterion to determine the structural capacity. These criteria or 'transfer functions' are empirically developed, and generic for typical materials. The pavement structural capacity is dictated by the critical layer in the structure, i.e. the layer associated with the lowest bearing capacity.

The information box on the next page "Pavement structural modelling" contains a more detailed description of the techniques outlined above.

Although the mechanistic-based approach is considered more fundamental than others described so far, it is still a rather poor approximation of the extremely complex conditions encountered in real pavement structures (Ullidtz, 1987). In addition, different backcalculation software packages are based on different assumptions. Successful implementation of this approach also involves a large experience component. In-depth knowledge of pavement materials and their behaviour is needed. Expert system approaches to backcalculation has been developed and proposed for years (Chou et al, 1989). In such an approach domain knowledge (specialist or private knowledge) is incorporated into the software through predefined sets of production rules.

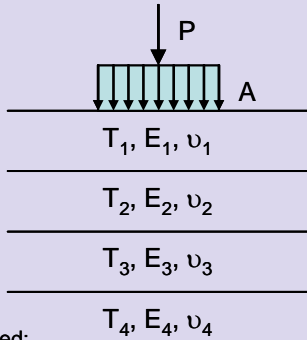
d) Knowledge-Based Approaches

As indicated in the preceding section, expert systems have been developed and promoted to improve the credibility of backcalculation procedures. The approaches discussed above are all examples of deterministic methods.



More Information: Pavement Structural Modelling (Irwin et al, 1994)

Structural deterioration in pavements results from stresses and strains in the individual materials when wheel loads are distributed by the layered pavement system. Every material type behaves differently, e.g. asphalt exhibits cracking when subjected to tensile strains, and tend to rut under repeated shear stresses above tolerable limits. Although stresses, strains, and deflections are all response parameters, surface deflection is a poor substitute for strain and the use of deflection as a direct measure of structural capacity or pavement life should be avoided.

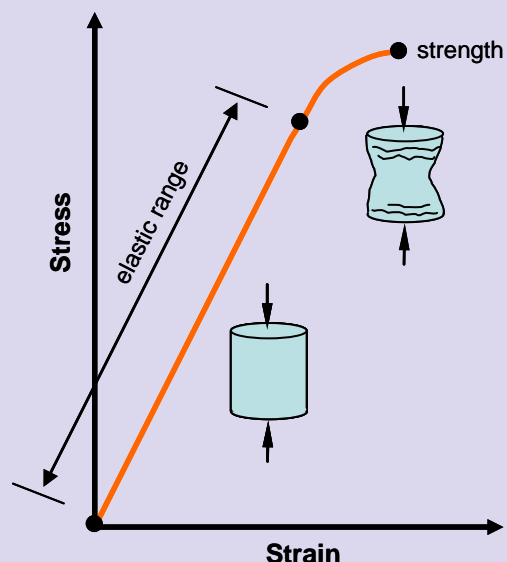


- Legged:
- P: Load
- A: Contact Area
- ν_i : Poisson's Ratio, Layer $i = 1$ to 4
- T_i : Thickness, Layer i
- E_i : Elastic Modulus, Layer i

Pavement engineers typically build pavement models to investigate the behaviour of real pavement structures during the design process. Layered elastic response models, or other more sophisticated mechanistic models, simulate a load and calculate the resulting pavement response parameters. The calculated responses are then typically used as inputs to empirical relationships ('transfer functions') between tolerable stresses or strains and pavement performance to determine the structural capacity or pavement life. This process is generally known as the Mechanistic-Empirical approach to pavement analysis and design. A typical pavement model is shown on the left. An important input to any pavement model is the *modulus of elasticity*. While discussions thus far focused on indicators of relative stiffness, the modulus of elasticity can be regarded as an indicator of absolute stiffness.

A material is elastic if it is able to return to its original shape and size immediately after being elongated, or compressed. The modulus of elasticity is simply the stiffness of the material within its elastic range and is quantified as the constant ratio between the applied stress and resulting strain. Most materials are elastic to some extent as long as the material does not deform permanently under the load placed on it. Modulus of elasticity is not a measure of strength – the stress needed to break or rupture a material. These concepts are illustrated in the figure below. Although not a measure of strength, the *modulus of elasticity as a measure of stiffness may provide an indication of material condition or quality*.

In pavement condition assessments, characteristics of the measured deflection bowl are used to determine the elastic modulus value of each layer in the pavement. This process involves calculation of the theoretical deflections under the applied load using assumed pavement layer moduli. Knowledge of the layer thicknesses and material types are required. The theoretical deflections are compared to the measured deflections and the assumed moduli are adjusted until theoretical and measured deflection bowls match within a specified tolerance. The measured responses are therefore used in a reversed fashion to derive elastic moduli, which are model characteristics. This iterative process is known as backcalculation of elastic moduli. The moduli derived in this way are considered representative of the pavement response to load and can be used to calculate stresses and strains in the pavement structure for analysis purposes.



Note: See Glossary for definitions of technical terms not explained in this information box

Part A: General

These methods are based on specific assumptions and contain little knowledge other than the equations or algorithms with the necessary boundary conditions to solve specific problems. Knowledge-based systems, or expert systems, represent the expert knowledge, experience or judgement as data or rules within a software program. These systems capture the fragments of human know-how which is used to reason through a problem, compensating for the weaknesses of purely deterministic methods.

Knowledge-based systems may vary from simple checks and interventions to complex systems incorporating sophisticated inference procedures

that make provision for uncertainty. As an example, the UK Highways Agency uses the TRRL relationships to interpret deflections measured with deflectograph devices. In recognition of the limitations of structural capacity/residual life produced by this method, a “UKPMS Rule Set” was developed in consultation with practising maintenance engineers. In this way the residual life alone is constrained to generating a structural treatment within the pavement management system. A low residual life value requires coincident cracking in the wheel tracks and/or rutting from visual surveys to trigger a treatment using the national default rule set (UKPMS, 2005).

Summary of Concepts: Pavement Deflections

- Surface deflection is an instantaneous, non-destructive response of a pavement structure under the application of a vehicle wheel load. The instantaneous deformed surface takes on the shape of a bowl, known as a deflection bowl or deflection basin.
- Deflection bowl parameters describe the size and shape of the deflection bowl which reflect the load spreading ability of the pavement, or zones within the pavement structure, i.e. they are indicators of relative stiffness.
- The most common deflection bowl parameters and zones they represent within the pavement structure are listed below. The higher the magnitude of the deflection bowl parameter, the lower the relative stiffness of the zone it represents.
 - Maximum deflection (YMax): represents the total pavement structure;
 - Base Layer Index (BLI): represents the upper zone in the vicinity of base and surfacing;
 - Middle Layer Index (MLI): represents the middle zone in the vicinity of the subbase;
 - Lower Layer Index (LLI): represents the lower pavement layers such as the selected layer and upper subgrade.
- Measured deflections are primarily influenced by: (1) Load – magnitude and duration; (2) Climate – temperature and moisture, and (3) Pavement type and condition.
- The main objective of collecting deflection data is to provide an indication of the pavement structural condition, residual structural capacity or residual life. Several approaches have been developed to utilize deflections in this regard:
 - Deflection bowl parameters: Performance related directly to YMax, BLI, MLI, and LLI;
 - Pavement Strength Indices such as Structural Number (SN);
 - Mechanistic-based approaches including backcalculation of layer elastic moduli, and
 - Knowledge-based approaches.
- A holistic approach is recommended to obtain an overall picture of a pavement’s condition, expected residual life, and remedial strategies. No single test – including deflections – or analysis method used alone can provide a complete description of the information needed to determine a pavement’s structural condition with confidence.

A.3. Imaging

TMH13 Part A introduces concepts of imaging and imaging systems as a basis for content included in Part G. Digital Imaging is the technology of electronically capturing, recording, processing, storing, transmitting, and reconstructing images. Digital Imaging started to evolve in the 1960s and 1970s, largely to avoid the operational weaknesses of film cameras, initially for scientific and military applications. As digital technology became cheaper in later decades it replaced the old film methods for many purposes.

A digital image may be created directly from a physical scene by a camera or similar device. The most basic elements of imaging systems include:

- Camera
- Lens
- Capturing hard- and software
- Reference system

Imaging systems widely used in the road industry include:

- Frame imaging or two-dimensional area scanning, and
- Line imaging or one-dimensional scanning.

The technology and system to be used for applications are dictated by various factors including:

- The intended use of the images
- Cost (system and operation)
- Availability

In this Part, frame and line scan imaging as well as advanced laser enhanced and laser based imaging technologies are introduced. The seventh part of TMH13, Part G, describes different imaging systems in detail and provides guidelines on the selection and use of these systems.

A.3.1 Imaging Basics

Whilst imaging encompasses many technologies, the use of optical instruments remains the reference for capturing visual scenes. The camera houses the imaging device (or imaging sensor) electronics and internal storage medium.

In road and pavement surveillance big data applications, external bulk storage mediums such as hard drives are commonly used.

Some commercial cameras include the lens as an integral part of the camera but the lens will be discussed as a separate element of the imaging system.

Although most functions of modern cameras are electronic, terminology from the film camera era is preserved.

A.3.1.1 Camera Concepts

a) Image Sensor

An image sensor converts an optical image into an electronic signal. Modern cameras use an array of light sensitive elements (or photo sites) to capture light intensity levels. The image sensor is traditionally called a charge-coupled device (CCD) but nowadays nearly all commercial cameras use active pixel sensors in complementary metal-oxide-semiconductor (CMOS) devices. The term “CCD” is often used to refer to CCD or CMOS devices.

b) Monochrome or Colour

Although this distinction may seem unimportant, it is actually one of the most fundamental points to consider. For industrial applications, colour is often selected because a monochrome image is perceived as inferior. The fact is that the most advanced and expensive cameras are monochrome.

Monochrome cameras have a single sensor that outputs gray scale images. Effectively each pixel on the sensor is assigned a numerical value based on the amount of incident light. The smallest number (0) represents black, the largest number white and all the other numbers shades of gray. Therefore, each pixel generates information only about intensity and not colour.

A mosaic filter is required to detect colour using a single sensor. As a result monochrome cameras have higher pixel counts, better signal-to-noise ratio, increased light sensitivity, and greater contrast than similarly priced colour cameras. In addition, industrial applications requiring a computer interface typically operate with a black and white camera, since a colour image requires more processing time and does not yield significantly more information about the object.

Although colour imaging may be preferable, the eye perceives spatial differences more clearly in gradients of black and white.

For these reasons, monochrome cameras are generally better for measurement and machine vision applications where resolution is more important. When a high resolution colour image is necessary then it is beneficial to use a 3-CCD or RGB camera (delivering the primary colour components red, green, and blue). These cameras use three sensors, one for each primary visual light colour and thus offer the best of both worlds, yielding greater spatial resolution and dynamic range than single sensor colour cameras.

e) Physical Size of Sensor

Since an image sensor consists of millions of light sensitive spots (photo sites) used to record information about what is seen through the lens, the sensor size ultimately determines how much light it uses to create an image.

Sensor size is usually quoted as the diagonal size in inches and the aspect ratio (ratio of horizontal to vertical number of pixels). Figure A.17 shows the popular sensor sizes (with an aspect ratio of 4:3) relative to the 35mm standard full frame (36mm x 24mm).

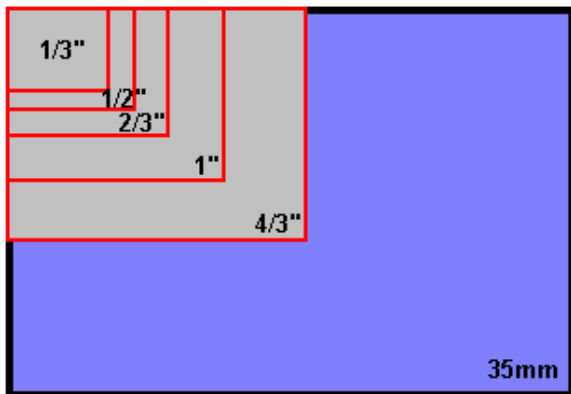


Figure A.17 Popular Sensor Sizes

f) Number of Pixel Elements (Pixels)

The number of pixel elements or photo sites of an image sensor is quoted as a pixel dimension or a number in mega-pixels (i.e. 1280x1024 or 1.3MP). In this case the sensor has 1280 columns and 1024 rows of pixels giving a total of 1.3 mega-pixels or 1.3MP. A general misconception is that the pixel count determines the resolution.

Resolution is defined as the smallest quantity that a sensor can detect or resolve. The resolution of a camera is determined by many factors of which the pixel count of the sensor is only one.

g) Dynamic Range

The dynamic range of an image sensor characterizes the ability of the device to image



Important!

It is a general misconception that the pixel count of an image sensor determines the image quality or resolution. The quality or resolution of an image is determined by many factors, including the pixel count. For example, a larger sensor size would be able to accommodate bigger pixels (compared to smaller sensor size with the same pixel count). The larger photo sites would be capable of producing photos with better dynamic range, less noise and improved low light performance.

light/dark differences. The dynamic range is defined as the ratio between the maximum and minimum measurable light intensities, i.e. white and black, respectively.

h) Bit Depth

Once photo sites have collected and stored photons during exposure, the relative quantity of photons at each site or pixel are sorted into various intensity levels. Bit depth quantifies how many unique shades or colours are available in a single pixel, represented by 0's or 1's, i.e "bits". Bit depth therefore indicates the level of precision with which colours can be specified. Images with higher bit depths can accommodate more shades or colour since there are more combinations of 0's and 1's available. The total number of colours available for any x-bit image is 2^x where x refers to the bits per pixel. Therefore, for 8 bits per pixel, 256 colours are available.

i) Gain or ISO

The sensor pixels convert light photons into a charge; the charge is converted to a digital reading by an analog-to-digital converter (ADC).

The ADC gain can be set and is denoted by an ISO number, i.e. the amount of gain applied to the sensor output that adjusts the sensitivity. The higher the ISO number the higher the gain. Smaller ISO settings require more light but create better images, whilst larger ISO numbers require less light (results in lighter images) but produce grainy images (i.e. more noise sensitive).

j) Iris

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The iris or iris diaphragm with an adjustable opening (or aperture) controls the amount of light coming through the lens and reaching the sensor. In modern systems the iris constitutes a set of overlapping blades in a fan-like arrangement around the aperture. The Iris setting is denoted by an f-number (focal ratio, f-ratio, f-stop or relative aperture), and is preceded by “f”. The f-number is the ratio of the lens’s focal length to the effective aperture. A smaller f-number (larger aperture) results in a lighter image but produces a shallower depth of field (the region that appears sharp in focus).

k) Electronic Shutter Speed

The electronic shutter speed is the time allowed for exposure. For moving scenes the exposure time must be as short as possible (high shutter speed) to avoid “blur” or “smearing”. There is a trade-off between shutter speed, ISO, and the iris setting. For example, a faster shutter speed would mean a darker image and the ISO or iris must be adjusted to obtain a lighter image.

l) Frame Rate or Readout Speed

This is the time needed to get all the information out of the imaging sensor. A faster readout speed would mean a faster frame rate (i.e. the system can deliver more frames per second).

Two types of readout methods are used:

- Frame transfer where the sensor data is transferred frame by frame.
- Interline transfer where the sensor data is transferred line by line.

A.3.1.2 Lens Concepts

The function of a lens is to collect reflected light from a scene and form a focussed image of the scene on the camera’s sensor plane. The lens could be an integral part of the camera or detachable. Cameras with detachable lenses offer flexibility over a range of lens properties such as focal length and aperture size.

The lenses attach to the camera using a lens mount. The lens mount design becomes an important consideration for compatibility between cameras and lenses.

Figure A.18 shows some lens terminology and an introduction of basic concepts follows. Since the iris is a partition of the camera lens some of the lens parameters were introduced previously.

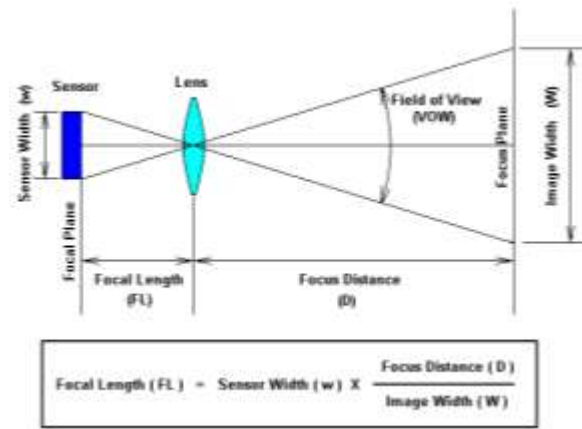


Figure A.18 Lens Terminology

a) Focal Length and Aperture

Focal length is the distance between the lens and the focal plane as defined in Figure A.18. The aperture and f-number concept were introduced previously. The focal length determines the magnification of the image projected onto the focal plane and the aperture determines the light intensity. Focal lengths are normally specified in millimetres. The focal length determines the angle of view for a given sensor size, lenses may be classified as follows:

- Normal: focal length approximately equal to sensor size (length of diagonal as previously defined);
- Wide-angle: focal length shorter than sensor size;
- Long-focus (or telephoto lens): focal length longer than the sensor size.

b) Field of View (FOV)

The field of view (FOV) determines the area one can see in the image and is expressed as the angular size of the view. This aspect relates directly to the lens focal length as discussed above. A bigger FOV means a wider area. Lenses could have a fixed field of view or variable. In the latter case, or for zoom lenses, the focal length is adjustable by mechanical or automatic means.

c) Depth of Field (DOF)

The depth of field (DOF) is the region where an image is sharp. DOF is determined by aperture, object distance from the lens, and focal length. DOF is commonly described as shallow or deep. Shallow represents a narrow region of focus, whilst deep is when the region is wide to infinity.

A.3.2 Imaging System Considerations

In the context of pavement surveillance, imaging systems can be used to capture:

- Right of Way (ROW) images, and
- Pavement distress images.

Each application requires its own special considerations. For example, for ROW imaging the FOV needs to be sufficiently wide to capture all features along a road, taking into account geometry. Dedicated pavement distress imaging units are normally faced downward and aspects such as minimum resolution and lighting becomes critical to capture relevant details. Considering the basics of imaging introduced above, these mobile systems are generally faced with a number of challenges:

- Vast amounts of image data are to be captured, transferred and managed and infrastructure must be capable of managing such amounts of data;
- Shadowing by clouds, trees, bridges etc.;
- Reflection of sunlight at certain times during the day or certain types of surfaces such as flushed surfaces, light surfaces or black new asphalt;
- Over exposure on light coloured surfaces, and
- Correct referencing of captured images.

Whilst these aspects are addressed in detail in Part G, the following subsections illustrate concepts and challenges of image capturing using traditional frame imaging.

A.3.3.1 Capturing at Discrete Intervals

Frame images captured at discrete distance intervals need to be captured correctly at a predetermined interval. Figure A.19 shows an example of such a process. If a survey is done at 80 km/h and an image needs to be captured within one metre of a certain position then the time window for this action is 90 milliseconds.

All cameras must be triggered at the same time and the capturing process must be finished in time for the next trigger. If the interval is set to 10 metres the operation must be completed within 450 milliseconds.

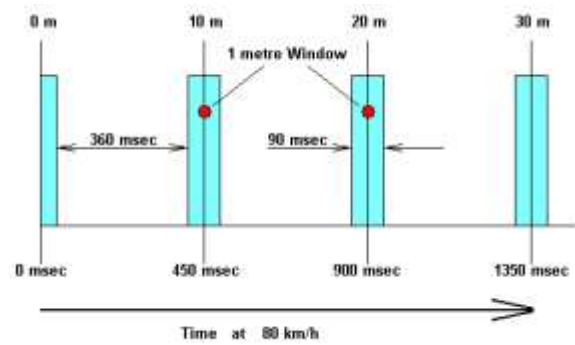


Figure A.19 Image Capturing Times

A.3.3.2 Continuous Frame Imaging

Another method is to capture a stream of images at a fixed frame rate and keep an index or reference of frame versus distance. The correct frame is located using the index. Some advantages include:

- Capturing of the data stream can continue independently of the other survey systems and even on digital tape.
- A complete video is available and if more images (or at different locations) are needed, it can be extracted from the stream of images.

Disadvantages include more storage space and in some cases post processing. Figure A.20 shows the method.

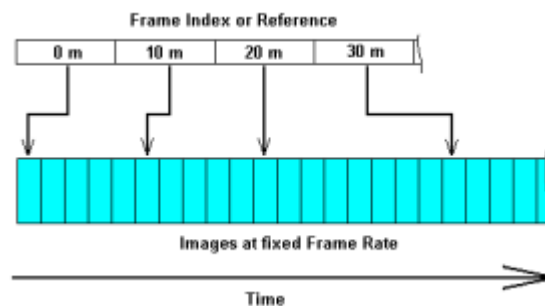


Figure A.20 Reference to Images

A.3.3.3 Synchronization Systems

Nowadays geographical location information can be assigned to images using GPS. For high speed applications, automatic methods are usually employed. For this purpose either cameras (with GPS interface) connected to an external GPS receiver, or cameras with built-in GPS receivers are used. In some cases synchronizing is done by post-processing GPS and image timestamps.

Before routine use of GPS, high speed surveillance systems were dependent on the distance measuring instruments (DMI) to synchronize all sub-systems. For this reason, DMI was considered as the most critical sub-system of any surveillance system. DMI is still conveniently employed as a supplementary linear location reference in many surveillance systems.

The DMI is usually a rotary distance encoder attached to the back wheel of the survey vehicle. The device is, however, constantly exposed to the elements, close to danger and therefore the most vulnerable component of any system. High resolution encoders are used (>1,800 pulses per revolution) to provide a linear resolution of less than 1 mm.

The pulses are used by all the sub-systems of a profiler to index or synchronize data and events. If, for instance images are captured at 10m intervals and the DMI is calibrated for 1mm per pulse then an image will be captured every 10,000 pulses. Figure A.21 shows the pulse train from the DMI at various speeds. The time scale is stretched to illustrate the concept.

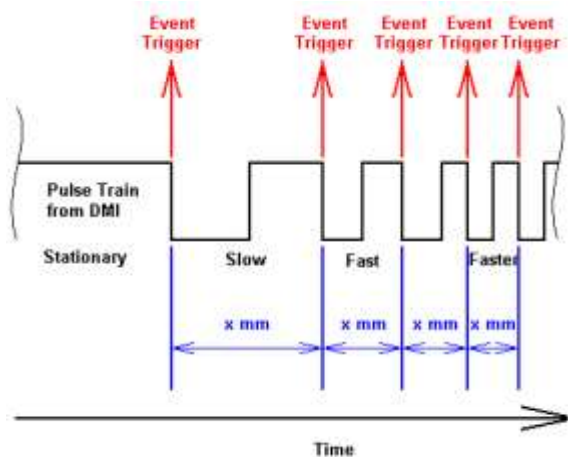


Figure A.21 Pulse Train from DMI

A.3.3 Imaging Technologies

This section introduced frame imaging, which can be described as a two-dimensional array of pixels captured in a conventional sequence of snapshots. Frame or area scan cameras may be regarded as first generation technology widely used in both ROW and pavement distress imaging systems. Other technologies, such as line scan cameras have also been used in pavement distress imaging applications. Whilst photogrammetry is not a new concept, systems designed to utilise these principles offer the ability to extract measurements from images and to do 3D mapping. Many new generation systems incorporate laser enhanced imaging features, whilst others are entirely laser based employing high resolution laser scanning technologies.

A.3.3.1 Line Scan Cameras

The basic concepts of a line scan camera and frame camera are virtually the same. The difference is that the line scan camera uses a line of sensors that has a width of only a single pixel (one-dimensional). As the object or camera moves perpendicular to the line of pixels, successive line scans are generated and linked to produce a continuous two-dimensional image.

Collecting images with line scan cameras have many advantages, including (Wang, 2011):

- Very high spatial resolution;
- High dynamic range compared to alternative area scan systems;
- Very high light sensitivity, and
- Blur-free images at high speed without shuttering.

Figure A.22 shows the implementation of a line scan camera in a pavement distress detection system enhanced with a high power laser line projector. The camera and projector are aligned in the same plane. The line projector illuminates the line to be imaged. The laser projector, optics and filtering ensure that these systems can operate in full sunlight and in darkness and is immune to ambient light variations i.e. shadows cast by roadside objects, viaducts, the survey vehicle itself, and surface features such as cracks.

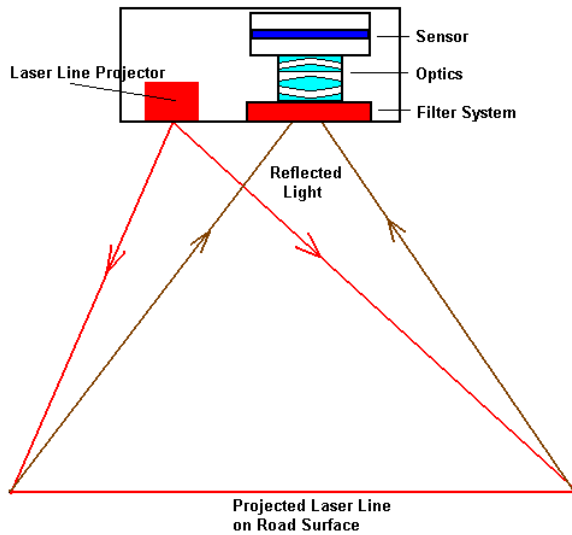


Figure A.22 Laser Road Imaging System (Pavemetrics, 2010)

A.3.3.2 Photogrammetry

Photogrammetry is the science of obtaining measurements from photographs. Whilst photography essentially transforms a 3D scene into a 2D image, photogrammetry may be regarded as the reversed process. As illustrated in Figure A.23, at least two locations are needed to develop lines of sights from the cameras to the object under consideration. The principle of triangulation is used to determine the location of a point in 3 dimensions by mathematically intersecting the converging lines in space. To triangulate a set of points, the relative camera positions (baseline) and orientation of the cameras in relation to the object should be known.

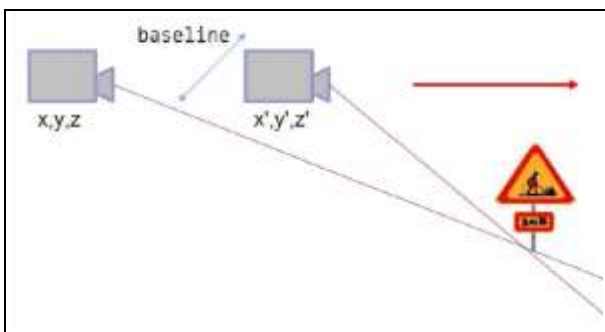


Figure A.23 Photogrammetric Principle (Faber et al, 2014)

In order to scale a photogrammetric measurement, at least one known distance is required. This can be determined if the actual coordinates of target point are known, or if a scale bar fixture is attached to the target before imaging.

Photogrammetry can be used to measure multiple points at a time since the number of points triangulated simultaneously is virtually unlimited. For this reason, a point cloud of 3D coordinates can be generated.

A.3.3.3 Range Imaging

Range images are a special class of digital images. Range Imaging (RIM) integrates distance measurement and imaging technologies. The imaging array (e.g. CMOS sensor) enables each pixel to store distance towards the corresponding object. A range image therefore reproduces the 3D structure of a scene. These images are also known as depth images, depth maps, xyz maps, surface profiles, and 2.5D images (Cantzler, 2014).

This technology has been employed in computer vision, implemented in factories, e.g. at conveyer belts for inspection of products. Figure A.24 illustrates the concept. The system uses a light projector, such as a line laser, and an intensity camera(s). The intersection of the projected plane with the object creates a light strip which is observed by the camera. Triangulation principles are then used to obtain a depth map of the surface points under the strip (Cantzler, 2014).

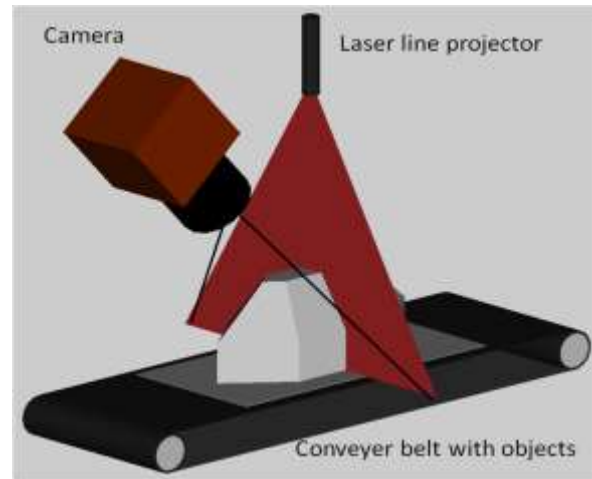


Figure A.24 Line laser and Triangulation used for 3D Imaging (Forest, 2014)

A.3.3.4 LIDAR

Three-dimensional (3D) imaging of road assets can generally be accomplished through different technologies, including 3D photogrammetry and 3D laser scanning or LIDAR (Light Detection and Ranging). Three-D video mapping uses the

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photogrammetric principle of triangulation to determine the distance to objects. LIDAR uses the time for a laser beam to reach an object and return to the scanner (time-of-flight) to determine distance. Laser scanners fire millions of pulses in a few seconds, in fixed angular increments. The

distance and orientation of each pulse allow determination of the associate xyz coordinates. The population of coordinates obtained from laser pulses is termed a 'point cloud', representing a detailed geospatial map (Olsen et al., 2013).

Summary of Concepts: Imaging

- Digital Imaging is the technology of electronically capturing, recording, processing, storing, transmitting, and reconstructing images.
- The most basic elements of imaging systems include the camera, lens, capturing hardware and software, and a referencing system.
- Parameters that characterize a camera include: Type of imaging sensor, monochrome or colour, sensor size, pixel count, dynamic range, light sensitivity, bit depth, ISO, iris, electronic shutter speed, frame rate or readout speed and readout method
- Parameters that characterize a Lens include: focal length and aperture, field of view (FOV) and depth of field (DOF)
- In the context of pavement surveillance, imaging systems can be used to capture:
 - Right of Way (ROW) images, and
 - Pavement distress images
- Important considerations of an Imaging system are:
 - Vast amounts of image data are to be captured, transferred and managed;
 - Balanced lighting and exposure at survey speeds, and
 - Correct referencing of captured images.
- The most basic imaging technology is frame imaging using area view cameras, where a two-dimensional array of pixels is captured in a conventional sequence of snapshots.
- Line scan cameras capture a continuous stream of concatenated lines (one-dimensional) to construct a two-dimensional image.
- Photogrammetry is the science of obtaining measurements from images through the principle of triangulation.
- Range imaging integrates distance measurement and imaging technology to reproduce the 3D structure of a scene. The images are also known as depth images, depth maps, xyz maps, surface profiles, and 2.5D images.
- Light Detection and Ranging (LIDAR) is a 3D laser scanning technology using laser scanners to emit light and detect reflected light, facilitating millions of incremental measurements in a few seconds. Distance and orientation of pulses allow determining the xyz coordinates of each point, together termed a 'point cloud'.

A.4. Planning a Survey

Collection of surveillance data should be a direct outflow of the data requirements as stipulated in TMH 22 for the various classes of road. To successfully collect and utilize this data, organizational abilities and constraints should be considered right from the start. It has been found that too often, the planning process focuses exclusively on the technical aspects of data collection, with limited consideration of processes, people, and technologies available within the organization (McPherson and Bennett, 2005). Consideration of the aforementioned resources, including available funding, will dictate the agency's survey strategy and objectives.

Once the objectives of the survey are clear, planning can proceed to detail the following essential survey elements:

- Equipment requirements;
- Equipment calibration and validation;
- Survey procedures, including safety;
- Quality Assurance, and
- Data processing, 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 compile specifications or contract documentation for automated road condition surveys. Detail aspects related to specific automated road condition measurements are provided in Parts B through G.

A.4.1 Survey Objectives

Whilst project level data support detailed decisions about appropriate treatments, network level data should be sufficient to support general planning, programming and policy decisions. Network level condition data may therefore be used in the following ways:

- For overall evaluation and monitoring of network condition on a regular basis (e.g. annually) or on an ad-hoc basis (e.g. once off survey);
- 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;
- To prioritize and/or optimize maintenance and rehabilitation actions, and

- Serve as inputs to prediction models used for the development of multi-year works expenditure programs.
- To develop or calibrate long term prediction models used above.

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

A.4.1.1 Agency Resources

Operating specialist equipment such as deflection measurement devices places high demands on an agency that may be difficult to meet. These demands include high capital cost, maintenance cost and operations, staff skills including training requirements, and quality assurance aspects. For this reason, most agencies make policy decisions to completely outsource specialist surveys. A combination of in-house operations and outsourcing is also used. It should, however, be recognized that even if an independent contractor performs the survey, the effort that has to go into management of a data-collection contract is considerable. If the contractor is experienced and a track record in the agency exists for data collection by contract, then the staffing levels may be less, but not substantially.

In addition, surveillance data can be complex and difficult to interpret. Specialist skills are therefore needed to understand the data and to be able to validate it. If the agency does not have the skills to implement quality assurance of the data, then an independent consultant should be appointed on its behalf. In any event, the cost implication remains.

A.4.1.2 The Survey Network

The network size, pavement types, and road classification can impact the survey strategy and objectives. For example, if concrete pavement sections form part of the survey, then special provisions may be required. Survey frequencies (time intervals) may also differ, depending on the road class. Budget constraints may force the agency to test only those sections where the return on investment will be greatest. Alternative approaches to define the survey network under different budget scenarios include (IRF, 2002):

- Full screen network: When resources are available and the network is of high importance;

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- Spatial sampling: A sample of the network is used to estimate the overall condition of the network;
- Temporal sampling: Surveys conducted on a larger portion of the network (e.g. third or fifth). Data for the entire network is collected in cycles of three to five years;
- Staged data collection: A network level database build up utilizing a combination of network level screens and detailed project level data.

A.4.1.3 Intended Use and Usability of Data

Sampling frequency (spatial intervals) and survey frequency (e.g. annually or biannually) depends on the intended use of the data. Naturally, both aspects have an impact on the cost of data collection, data storage, and usability of data. Where measurements are performed at discrete points, sampling frequency becomes an important consideration (compared to essentially continuous measurements, e.g. using laser based technology). Generally data should be collected at the minimum required level, given the agency's constraints and abilities. However, whilst agencies should guard against collecting too much data, considerable cost savings may be generated if project level data collection is strategically combined with network level surveys.

To assess representative pavement condition for network level analyses, the sampling process must be able to reflect significant differences in condition along the surveyed network. Different types of condition indicators and traffic data will allow the network to be divided into analysis or homogenous sections.

Different survey frequencies may be adopted for different road classes. Major roads may be surveyed more frequently - every one to two years - while minor roads may be monitored at two to five year intervals.

At the most basic level, data could be used to obtain a once-off, relative assessment of the network condition. Such information could be used to compare the relative conditions of different sections and to prioritize maintenance and rehabilitation actions.

At the most detailed level, surveys may be conducted annually to provide an absolute indication of the condition 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 a condition measurement. As a result, the cost of the survey will differ greatly depending on the intended use of the data.

A.4.1.4 Timing

In South Africa, most agencies contract out surveillance services to specialists. However, there are a limited number of surveillance vehicles in the country. Coupled with this is the fact that testing of some networks can take months to complete. The availability of equipment is thus a practical consideration that should be taken into account when surveys are programmed.

Seasonal effects can have a major impact on the variability of measurements from one year to the next, e.g. skid resistance and deflections. In general, agencies should aim to conduct successive surveys on a particular section at about the same time of the year to maximise consistency and to limit the impact of seasonal conditions on measurements within a region.

A.4.2 Device Selection

Few road network agencies can afford to buy and maintain their own surveillance equipment. The availability of devices, suitable for network level surveys is an obvious consideration.

The measurements provided by different types of devices can be significantly different and the results may not be interchangeable. To eliminate possible occurrences of systematic errors, the same type of device should be used across the network. Once selected, the device type should not be changed frequently. Different types of devices with their respective advantages and disadvantages are presented in Parts B through G.

A.4.3 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 requirements;
- Safety requirements;
- Calibration and validation;
- Measurement control;
- Survey procedures;
- Contract quality plan;
- Data requirements;
- Reporting, and
- Other aspects

General guidelines for the specification of each of these aspects are provided. It should be noted that the information provided 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. Measurement specific information is included in Parts B through G to complement the framework provided in Part A.

A.4.3.1 Equipment Specification

The equipment specification should define the minimum requirements for equipment, and should cover aspects such as instrument type, precision and recording intervals. Measurement specific aspects to consider when defining equipment specifications are included in Parts B through G.

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.

The equipment specification should define the minimum requirements for the following elements:

- Measurement system: Specifications for profilers (roughness, rutting and texture), skid resistance devices, deflection devices etc.
- Positioning system: GPS and inertial navigation system (INS)
- Survey vehicle: Minimum requirements may be specified for the towing, or host vehicle, to ensure that it is appropriate to operate safely on the network and meet local standards.
- Survey computer and operating system: It is important to ensure that that current software and hardware are used with available support and maintenance by leading suppliers for the duration of the contract.
- Software requirements: Specific features may be specified, such as real time data display to enhance quality control, location-referencing identification and distance reset, event location within data records etc.

A.4.3.2 Safety Requirements

Strict requirements should be enforced to ensure the safety of both the operators and motorists. Whilst safety should be a priority in all surveys, special consideration should be given to surveys where the process is either of a stop-start nature or where it proceeds slowly. Safety considerations may include:

- Operating within specified time limits;
- High visibility clothing for operators;
- High visibility signage and flash lights;
- Use of a high visibility support vehicle or traffic police travelling behind the device on high-risk roads.

A.4.3.3 Calibration or Validation

This part of the specification should deal with the procedures to be followed for component calibration, system calibration or system validation. Component calibration deals with the calibration of individual components of the system. System calibration or validation deals with the checks to ensure the accuracy of the measurement system as a whole.

a) Component Calibration

The purpose of component calibration is to:

- Ensure satisfactory repeatability and reproducibility of the measurements by conformance to international standards;
- Ensure that data elements are measurable to the accuracy defined in the specifications;
- Ensure continuous measurement stability, and,
- Define factors (or limitations) influencing the results, and to ensure that appropriate correction procedures are applied.

The requirements for calibration of system components (e.g. lasers, accelerometers, distance measuring transducers, load cells etc.) should be clearly specified, addressing the following issues:

- The specifications should require that the contractor produce calibration certificates that are current and traceable to international standards.
- If components are to be recalibrated during the course of the contract, the rules or conditions of recalibration should be specified.
- Critical components for which proof of calibration is required should be clearly specified.

b) Validation or System Calibration

The purpose of validation or system calibration is to:

- Ensure that the measurement methodology (which includes device operation, data acquisition, operation and output) will provide data in the correct format and to the specified quality, and
- To maintain consistency of results.

Validation essentially comprises a referencing exercise conducted on predetermined validation (or reference) sections. The survey equipment must be validated at each of the selected validation sites against a reference measurement. This is done by characterising the validation sections with the selected reference device and then measuring the same sections with the survey equipment.

If a pre-validation report is specified, then the first step in the validation process should be to obtain such a report from the contractor. The pre-validation report should contain calibration certificates for all survey equipment, including reference devices. 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 data as explained in Section A.4.1.

Another aspect which impacts on the design of a validation exercise is the experience that a client has with a specific device or contractor on a network. If a validation had been done previously for the same device and contractor (say within the last year), then the validation requirements may be relaxed. However, even in such cases efforts should be made to ensure that the equipment has not been altered and that the earlier validation is still applicable.

Aspects to be covered in the specifications for validation or system calibration include the following. Specific validation requirements are provided in the relevant Parts B through G.

- 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 safety requirements, measurement procedures, GPS equipment, distance measurement, etc.
- Selection of reference devices and validation section requirements.

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- Personnel: The training and experience of the operator can have a significant influence on the measurements. 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.

Due to the complexity of equipment and a variety of road conditions involved, specifications for equipment validation and control should allow for the network manager to override or amend certain requirements under special conditions.

A.4.3.4 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 validation sections to ensure that the device is still calibrated and valid, with no excessive drift in measurement.

A.4.3.5 Survey Procedures

The specifications for survey procedures should cover detailed aspects such as the facilities included (slow and fast lanes, ramps etc.), test positions (e.g. left wheel path), test frequency, survey start and end locations, tolerances, reference stations, and segment identification. The specifications should also note when a survey over a section should be postponed or repeated (e.g. if a section is under construction at the time of survey, or if adverse environmental conditions are encountered etc.). The specifications for survey procedures may also be

included as part of the measurement control specifications.

A.4.3.6 Contract Quality Plan

The contractor should ideally submit a contract quality plan as part of the tender documentation. The contract quality plan facilitates integration between the contract document and the contractor's quality management system. This plan therefore encompasses all aspects of the contract, including (or referenced) documented systems and procedures that will be used for quality control purposes.

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:

- Design and specification of survey equipment, including data processing details, sampling intervals, anti-aliasing and other filters where applicable.
- Software to be used and methods for validating software accuracy.
- The procedures and details of the training of personnel to conduct the survey.
- Procedures to ensure proper function of equipment throughout the survey, including 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 and positioning are accurate and valid.
- Data reporting formats (to match specifications).
- Control procedures to ensure accuracy of data processing (e.g. averaging over subsections) and reporting.

A.4.3.7 Data Reporting Format

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

Part A: General

- Raw data format (e.g. ASCII file, comma delimited) and where applicable for different data types.
- Processing procedures, e.g. for roughness, averaging procedures and segment length for reporting.
- 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, measurement (e.g. IRI for one or more wheelpaths) and measurement speed.

A.4.3.8 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 be documented.

A.4.3.9 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.

A.4.4 Validation Section Requirements

The identification and survey of validation 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 validation 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.

A.4.4.1 Selecting Validation Sections

Sections should be selected for validation of primary road condition measurements as well as other parameters such as road geometry parameters, positioning and distance measurements. If appropriate, the same sections may be used for validation of different parameters. Guidelines for selection of sections are outlined below:

- The sections should be representative of the survey network. Different surfacing types and conditions should be considered.
- Representative parameter ranges should be determined based on the characteristics of the network. It should be attempted to allocate sites approximately proportional to the ranges identified. Each parameter range should be represented by at least one section.
- Four to six sites with lengths of 200 m to 500 m long are typically selected to validate one parameter. All sections should have the same length for the parameter validated.
- For practical reasons, it is recommended that sites be located relatively close to the centre of operations.

Part A: General

- The selected sites should not be subject to rapid deterioration. If validation sites are rehabilitated during the course of the contract, another site within the same parameter range should be selected and surveyed.
- Naturally, the positions of validation sites are important and apart from availability of GPS coordinates, these sites should be clearly marked for revalidation purposes.

A.4.4.2 Reference Surveys

In addition to selecting appropriate validation sections, these sites need to be characterised independently before the network survey starts. Normally, reference devices are used for this purpose. These aspects are addressed for different measurement types in TMH 13 Parts B through G.

A.4.5 Summary

Detail aspects related to specific surveillance measurements are provided in Parts B through G. Table A.8 summarises control or decision aspects when planning a survey with reference to relevant sections presented in Part A.

Table A.8 Checklist for Planning a Network Level Survey

| Item | Control or Decision Aspect | Section in Part A |
|------|--|-------------------|
| 1 | Define budget and manpower constraints | |
| 2 | Define survey objectives and type or frequency of testing | Section A.4.1 |
| 3 | Obtain typical costs for surveying with recommended device types | |
| 4 | Determine equipment availability | |
| 5 | Decide on equipment type | Section A.4.2 |
| 6 | Determine contract period and compile project specifications | |
| 7 | Compile specifications for equipment | |
| 8 | Compile specifications for calibration and validation | |
| 9 | Compile specifications for measurement control | Section A.4.3 |
| 10 | Compile specifications for survey procedures | |
| 11 | Compile specifications for the contract quality plan | |
| 12 | Compile specifications for the data reporting format | |
| 13 | Compile specifications for reporting | |
| 14 | Identify calibration sections | |
| 15 | Obtain reference profile on calibration sections | Section A.4.4 |
| 16 | Process calibration section reference profiles as needed | |

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A.6. 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).

Coefficient of Friction: Normalized friction. The frictional force divided by the normal force (the load). Term used interchangeably with 'friction coefficient'.

Deflection Bowl: a two-dimensional representation of the curved shape of a pavement surface induced by a load on the surface. According to the pre-draft EN Standards Part 1 (for FWDs), the deflection bowl is the envelope curve connecting the peak values of the deflection time histories as a function of the offsets of the deflection sensors.

Deflection Bowl Parameters: also called deflection basin parameters, or basin shape factors, which describe characteristics (size and shape) of the deflection bowl and defined through mathematical relations between deflections at different offsets from the centre of the load. These parameters are indicators of relative stiffness associated with different zones within the pavement structure. Common parameters include maximum deflection, radius of curvature, base layer index, middle layer index, and lower layer index.

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).

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.

Frame imaging: Or are scanning uses a two-dimensional array of pixels in a conventional sequence of snapshots (Wang and Smadi, 2011, p. 4).

Friction: The resistance an object encounters in moving over another object. Often the force needed to move the object, the frictional force. In this document, pavement surface friction and friction is used interchangeably, referring to the friction contributed by the surface.

Geo-reference: The process of assigning a coordinate system and location information to a point or points in space (NCHRP 15-44, Olsen et al, 2013, p. 224).

GPS: Global Positioning System.

Hydroplaning: Phenomenon in which a vehicle tire is separated from the pavement surface by the water pressure that builds up at the pavement–tire interface.

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 wheeltrack. In the IRI calculation, the measured profile is processed using a mathematical transform which filters and cumulates the wavelengths encountered in the profile.

IMU: Inertial Measurement Unit. A device which utilises a combination of gyroscopes and accelerometers to provide velocity and orientation information (NCHRP 15-44, Olsen et al, 2013, p. 225).

Line scan imaging: Uses a single line of sensor pixels to build up a two dimensional digital image. The second dimension results from the motion of the sensors/ imaging system or the object (Wang and Smadi, 2011, p. 4).

LIDAR: Light Detection and Ranging. A method of measuring the flight time of a beam of light to calculate range to objects at predetermined angular increments, implemented using a laser scanner and resulting in a point cloud (NCHRP 15-44, Olsen et al, 2013, p. 226).

Macrotexture: Deviation of a pavement surface from true planar surface with characteristic dimensions along the surface of 0.5 mm to 50 mm (definition after ISO 13473-2:2002)

Mechanistic-Empirical: Analysis which combines fundamental mechanistic models (such as linear elastic theory) with empirically derived models. The output from the mechanistic analysis is typically used as input to an empirical model.

Microtexture: Deviation of a pavement surface from a true planar surface with characteristic dimensions along the surface of less than 0.5 mm (definition after ISO 13473-2:2002)

Part A: General

Modified Structural Number: Also known as SNC includes the contribution of the subgrade (see Structural Number, SN), i.e. $SNC = SN + SNSG$. These terms can be derived from deflection measurements for pavement structural capacity determination at the network level as explained in Appendix A.

Modulus of Elasticity: Also known as elastic modulus is the mathematical description of a material's tendency to be deformed elastically (non-permanently) when a force is applied to it. The elastic modulus of a material is defined as the slope of its stress-strain curve in the elastic deformation region (definition after Wikipedia, 2009).

Pavement Deflection: the response of a pavement under a load in the form of elastic deformation in the vicinity of the load on the pavement surface and with depth. When measured, the deflection at a given offset from the load centre is the peak value of the deflection time history.

Photogrammetry: The science of making measurements from photographs, especially for recovering exact positions of surface points (<en.wikipedia.org/wiki/photogrammetry>, 2014).

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.

Rut depth: In South Africa, rut depth is commonly defined as the maximum permanent deformation measured under a two meter straight edge placed transversally over the rut. Rut depth is one of several parameters that can be used to characterise the transverse surface profile, or rutting.

Rutting: Rutting is the longitudinal permanent deformation that occurs in the wheel paths of flexible pavements.

SBAS (Satellite Based Augmentation System): This is a more general term, which encompasses WAAS, StarFire and EGNOS type corrections.

Skid Resistance: The ability of the traveled surface to prevent the loss of tyre traction. In this document skid resistance is synonymous with microtexture and is always associated with wet surface conditions.

Structural Number: Abbreviated SN, is a single number that provides an indication of strength of a pavement structure above the subgrade. Low values (e.g. 2) represent relatively weaker pavements and high values (e.g. 5) represent relatively stronger pavements.

Transverse Surface Profile: Two-dimensional sample of the pavement surface in the transverse direction measured by sensors (such as lasers).

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).

WAAS (Wide Area Augmentation System): US satellite system that provides a set of corrections for the GPS satellites, which are valid for the North American region. They incorporate satellite orbit and clock corrections.

WGS-84 (World Geodetic System 1984): The current standard datum for global positioning and surveying. The WGS-84 is based on the GRS-80 ellipsoid.

APPENDIX A-1

GEOGRAPHIC CO-ORDINATE SYSTEM

Part A: General

A Geographic Co-ordinate System is a co-ordinate system that enables every point on earth to be defined by a set of numbers. The co-ordinate system is chosen so that one number represents the vertical position and the other two the horizontal position. A common choice is Latitude, Longitude and Height.

Latitude

Latitude is defined as the angle between the equatorial plane and a line that is normal to the reference ellipsoid. Lines joining points with the same Latitude is called a Parallel (parallel to the equator). The North Pole is at 90°N ($+90^{\circ}$) and the South Pole at 90°S (-90°)

Longitude

Longitude is the angle separation between a point's meridian and a reference meridian (usually the Greenwich meridian). The figures below illustrate Latitude and Longitude.

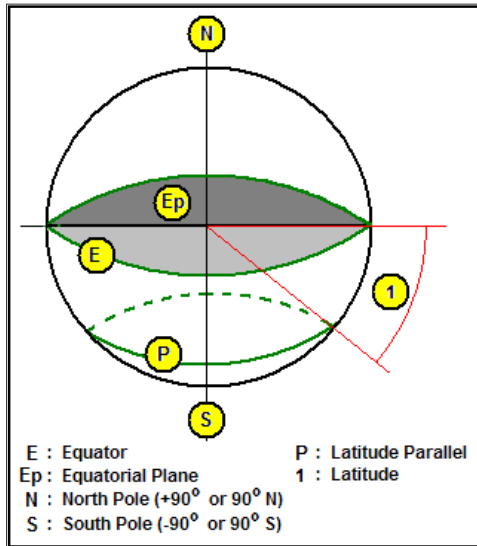


Figure A-1.1 Latitude Definition

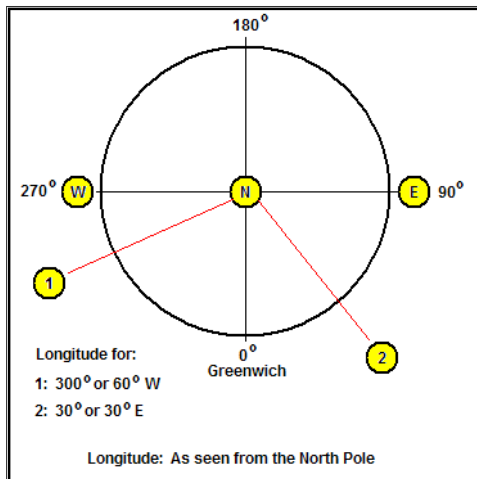


Figure A-1.2 Longitude Definition

Height

Height is expressed relative to a pre-defined vertical reference point (datum)

Co-ordinate Notations

The notation for Latitude and Longitude could be one of the following:

- Sexagesimal (base 60) where the angle is shown as Degrees, Minutes and Seconds (i.e. $23^{\circ}15'36''\text{S}$)
- Decimal fraction where the angle is shown as a decimal fraction of Degrees (i.e. 23.26°S)
- Combination of sexagesimal and decimal where the angle is shown as degrees and decimal fractions of minutes (i.e. $23^{\circ}15.6'\text{S}$)

Conversion between the notations is done using the following:

- 1 Minute ($'$) = 60 Seconds ($''$)
- 1 Degree ($^{\circ}$) = 60 Minutes ($'$) = 60×60 Seconds ($''$) = 3,600 Seconds ($''$)

World Geodetic System (WGS)

The World Geodetic System includes the following:

- Geographic Co-ordinate System
- Spheroidal Reference Surface (Datum or Reference Ellipsoid)
- Gravitational Equipotential surface (Geoid)

The WGS evolved through WGS60, WGS66 and WGS72 to the current revision of WGS84

WGS84 is the standard used by GPS receivers.

Main Parameters

- Co-ordinate Origin: Located at the Earth's centre of mass.
- Meridian of zero longitude:

IERS Reference Meridian and lies 5.31 arc seconds east of the Greenwich Prime Meridian (102.5 metres)

- Datum Surface: Pole flattened (oblate) spheroid with:
 - Major radius $a = 6,378,137$ m at the equator
 - Minor radius $b = 6,356,752.314$ 245 m at the poles
- Geoid: The 1996 Earth Gravitational Model (EGM96) as revised in 2004. This geoid defines the nominal sea level surface by means of a spherical harmonics series of degree 360 (which provides about 100km horizontal resolution). The deviations of the EGM96 geoid from the WGS84 reference ellipsoid range from -105 m to +85 m.

Part A: General

Geoids and Ellipsoids

The earth's physical surface is a tangible one encompassing the mountains, valleys, rivers and surface of the sea. It is highly irregular and not suitable as a computational surface. A more smoothed representation of the earth is the Geoid.

There are a number of definitions for this surface which can be described as follows: 'that surface that would be assumed by the undisturbed surface of the sea, continued underneath the continents by means of small frictionless channels.'

The Ellipsoid is a smooth mathematical surface that best fits the shape of the geoid and is the next level of approximation of the actual shape of the earth.

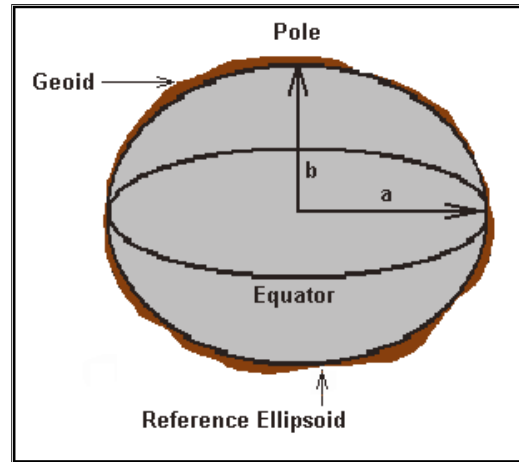


Figure A-1.4 Geoid differ from Reference Ellipsoid

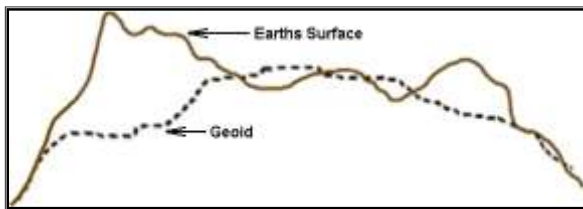


Figure A-1.3 Earth's Surface and Geoid

Elements of an ellipse

- a = Semi Major Axis
- b = Semi Minor Axis
- f = Flattening = (a-b)/a
- PP' = Axis of revolution of the earth's ellipsoid

The table to follow indicates different ellipsoids used in southern Africa and their associated parameters.

Table A-1.1 Ellipsoids used in southern Africa and their associated parameters.

| Ellipsoid | a | b | Unit | Used by |
|------------------|-------------|-------------|----------------------|----------------------------|
| Mod. Clarke 1880 | 6378249.145 | 6356514.967 | International meters | R.S.A., Botswana, Zimbabwe |
| WGS 84 | 6378137.000 | 6356752.314 | International meters | Globally |
| Bessel | 6377397.155 | 6356078.963 | German Legal meters | Namibia |
| Clarke 1866 | 6378206.400 | 6356584.467 | International meters | Mozambique |

Cape Datum

The co-ordinate reference system, used in South Africa as the foundation for all surveying, engineering and geo-referenced projects and programs, is the Cape Datum.

This Datum is based on the Clarke 1880 ellipsoid and has its origin point at Buffelsfontein near Port Elizabeth. The Cape Datum is based on the work of HM Astronomers Sir Thomas Maclear, between 1833 and 1870, and Sir David Gill, between 1879 and 1907, whose initial geodetic objectives were to verify the size and shape of the Earth in the Southern Hemisphere and later to provide geodetic control for topographic maps and navigation charts.

From these beginnings, this initial network was extended to eventually cover the entire country and now comprises approximately 29 000 highly visible trigonometrical beacons on mountains, high buildings and water towers as well as approximately 20 000 easily accessible town survey marks.

As with other national control survey networks throughout the world, which were established using traditional surveying techniques, flaws and distortions in these networks have become easily detected using modern positioning techniques such as the Global Positioning System (GPS). In addition to these flaws and distortions, most national geodetic networks do not have the centre of their reference ellipsoids co-incident with the centre of the Earth thus making them useful only to their area of application.

The upgrading, re-computation and repositioning of the South African co-ordinate system has thus been driven by the advancement of modern positioning technologies and the globalisation of these techniques for navigation and surveying.

Parameters of the Cape Datum

- The Modified Clarke 1880 is the reference ellipsoid.
- The initial point for the existing South African Datum is the Buffelsfontein trigonometrical beacon, near Port Elizabeth.
- The orientation and scale characteristics were defined by periodic astronomic azimuth and base line measurements.

Hartebeesthoek94 Datum

As from the 1st January 1999, the official co-ordinate system for South Africa is based on the World Geodetic System 1984 ellipsoid,

commonly known as WGS84, with the ITRF91 (epoch 1994.0) co-ordinates of the Hartebeesthoek Radio Astronomy Telescope used as the origin of the system. This new system will be known as the Hartebeesthoek94 Datum. At this stage all heights will remain referenced to mean sea level, as determined in Cape Town and verified at tide gauges in Port Elizabeth, East London and Durban.

Parameters of the *Hartebeesthoek94 Datum*

- The WGS84 is the reference ellipsoid.
- The initial point is the Hartebeesthoek Radio Astronomy telescope, near Pretoria.
- The scale and orientation characteristics were defined within the GPS operating environment and have been confirmed and have been confirmed to be co-incident with ITRF91 determination.

Datum Relationship

At the most elementary level, a 2D Helmert Transformation (which uses 2 translations, rotation and scale factor) can be used to define the relationship between the two datums. This model is very effective over small areas (up to 40km) and should only be used when heights are not relevant.

A Geocentric Cartesian Translation, between the two datum's geocentres (dX, dY, dZ), can also model the relationship between the two datums. This is commonly known as the Moledensky (3 Parameter)

Transformation: The Chief Directorate: National Geospatial Information computed translation values by using the Hartebeesthoek94 Datum and the Cape Datum co-ordinates of a number of accurately determined trigonometrical beacons.

Note: These transformation parameters will yield co-ordinates in the other datum with residuals not exceeding 15 metres. This transformation is ideal for local areas where much better accuracies are attainable. The magnitudes of these translations are:

$$dX = 134 \text{ m} , dY = 110 \text{ m} , dZ = 292 \text{ m}$$

More complex models such the Bursa-Wolfe (7-Parameter) Transformation can be used to model the datum relationship. This model uses 3 translations, 3 rotations and scale and is more suitable for larger areas.

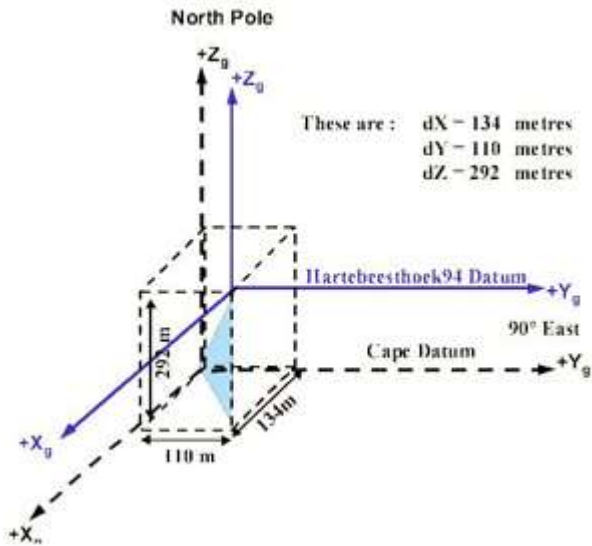


Figure A-1.5 Cape- and Hartbeesthoek 94 Datums

Projected Co-ordinates

Plane co-ordinates (x, y, z) are the simplest type of co-ordinates to use for everyday practical applications. To achieve this simplicity, the ellipsoidal latitude and longitude co-ordinates, or 3-D geocentric co-ordinates, must therefore be projected onto a plane surface. It is not possible to do this without some distortion. This can be demonstrated by cutting a tennis ball in half and attempting to flatten it. Projections which have the properties of preserving angles and shapes are called Conformal or Orthomorphic projections. In South Africa the Gauss Conform Projection (an adaptation of the Transverse Mercator projection) is used for the computation of the plane YLo, XLo co-ordinates, commonly known as the "Lo. Co-ordinate system".

The figure to follow shows the -1° and +1° belts around the odd Longitude Meridians for South Africa. Projections for co-ordinates in the 19° belt are called Lo19 etc.

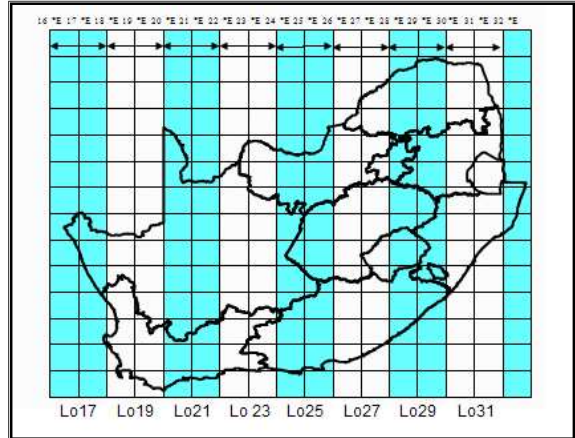


Figure A-1.6 Lo Belts for South Africa

The co-ordinate axes of the Gauss Conform System use the equator as the origin for the X-axis, with X increasing positive southwards. The Y axis can use any one of the 2° apart, odd Central Meridians (CM), which intersect the equator at right angles, as its origin. The Y values increase westwards of the CM and decrease eastwards of the CM. (See figure below)

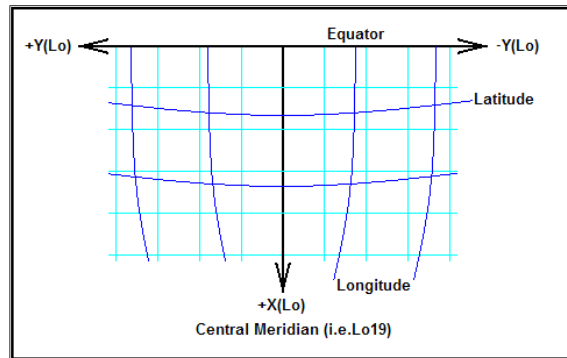


Figure A-1.7 Gauss Conform System

APPENDIX A-2

BASIC CONCEPTS OF ROAD PROFILE ANALYSIS

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 A-2.1 shows an idealized road surface that varies in a sinusoidal manner. The idealized profile of Figure A-2.1 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:

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

Where: Y = Elevation
 A = Amplitude
 λ = Wavelength
 X = Distance
 X₀ = Phase Shift

As can be seen from Figure A-2.1, 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 A-2.1, 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 A-2.1), 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/λ) is known as the wave number. The higher the wave number, the more waves per unit length and thus the shorter the wavelength.

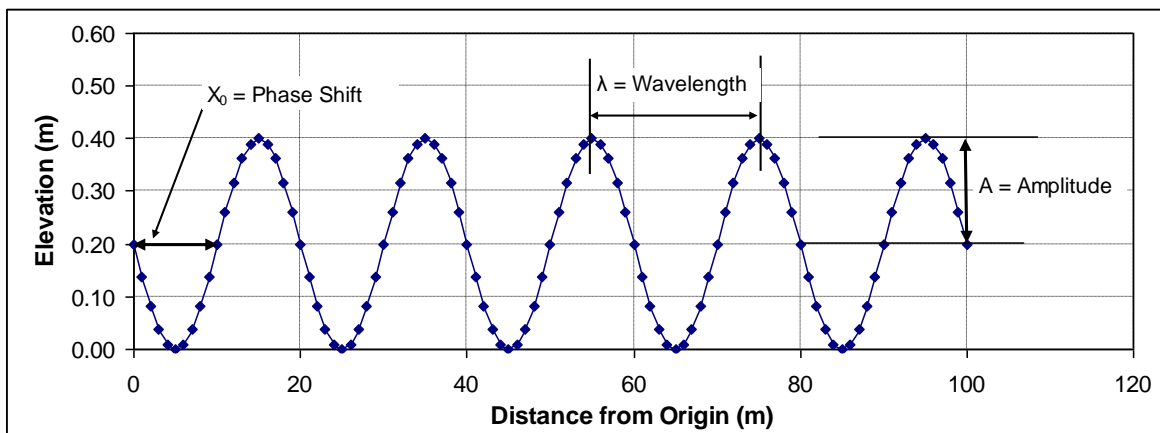


Figure A-2.6-1: Road Profile Showing Sinusoidal Variation

Profile Analysis using Power Spectral Density

The example shown in Figure A-2.1 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 A-2.1, for which the properties of each sinusoid varies in a specific manner.

Figure A-2.2 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 A-2.2, 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 A-2.3. This profile is a more realistic representation of a road profile. It looks almost “random” and any cyclic sinusoidal pattern is hard to discern.

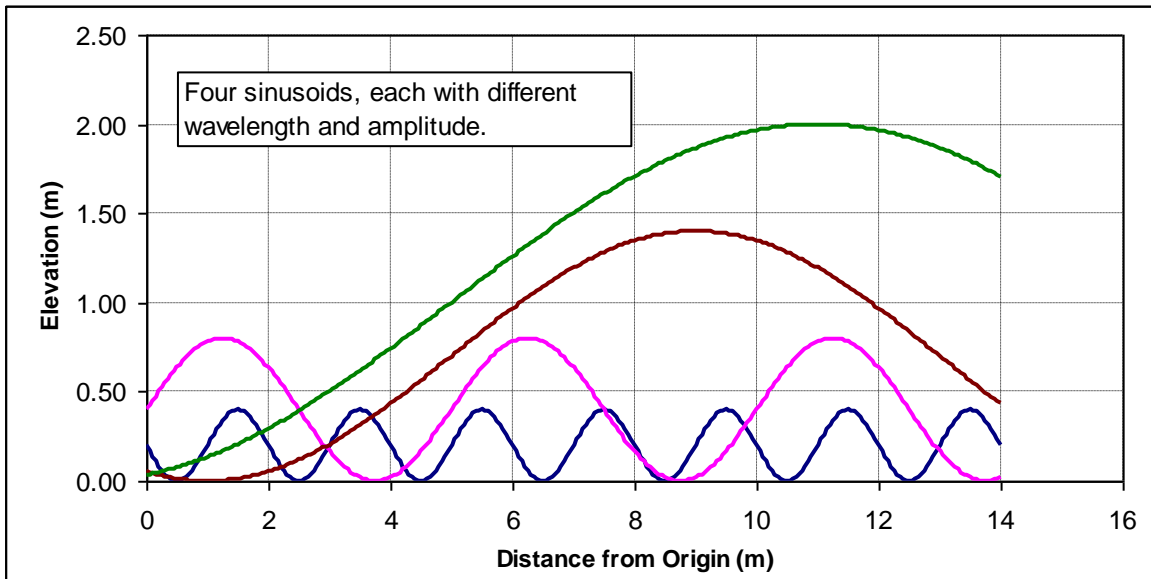


Figure A-6-2.2: Four Different Sinusoids

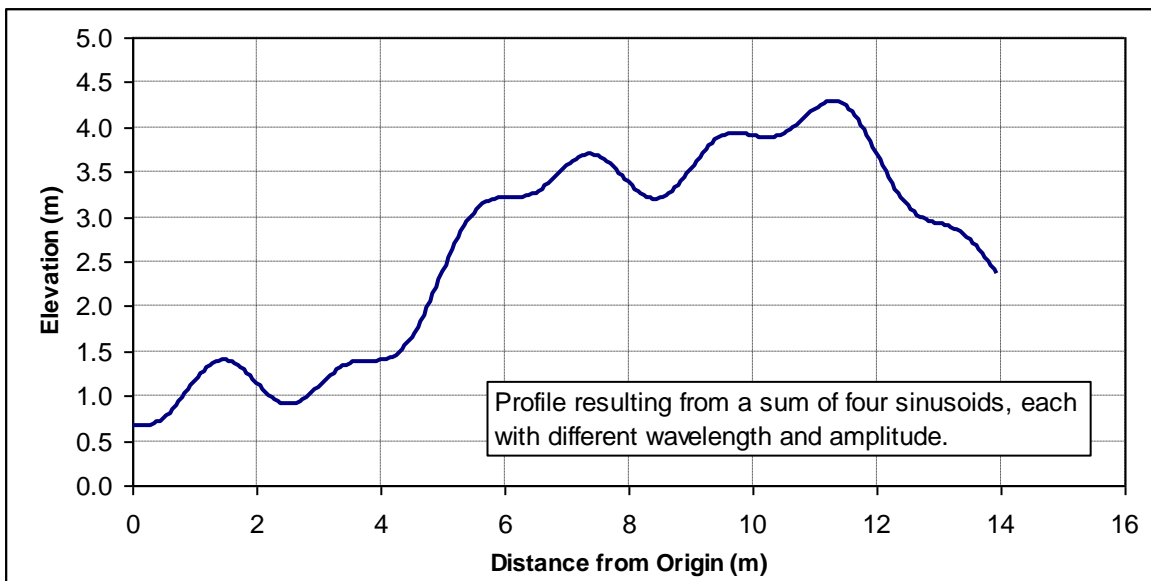


Figure A-2.6-3: Profile Resulting from Sum of Four Sinusoids

Part A: General

In Figures A-2.2 and A-2.3, 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 A-2.4.

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 PDS 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. shorter bumps (i.e. higher wave numbers) generally have lower amplitude than that of longer undulation-type roughness. It should be

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 A-2.6. The formulation of this profile is identical to that shown in Figure A-2.3, 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 A2.2.

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 A-2.2). 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 A-2.7 shows the original profile (as in Figure A-2.6), with a filtered profile consisting of the moving

Part A: General

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 A-2.7.

If we compare the moving average line in Figure A-2.7 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. However, we can now apply a second filter in which we subtract the original profile from the moving average value at that point. This new profile gives us an indication of the how much the profile deviates from the smoothed profile at each point. This filter is called a anti-smoothing (or high-pass) filter, and is denoted by the blue line in Figure A-2.7. As we can see, the final filtered profile has removed much of the larger up-down movements in the profile, and now highlights the roughness with higher wave numbers (i.e. shorter wavelengths).



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).

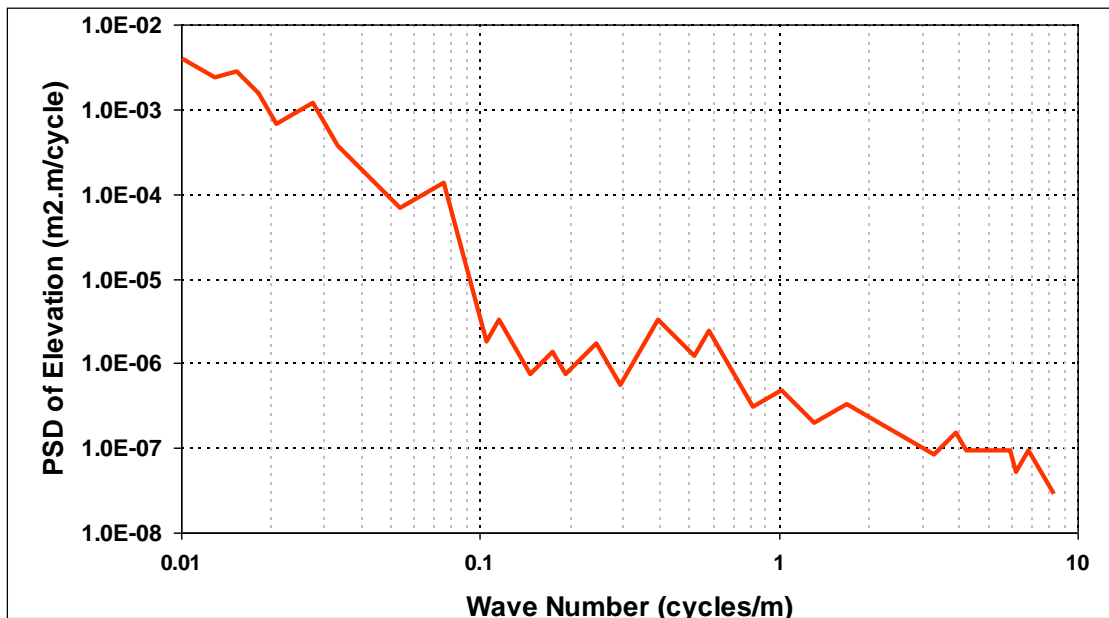


Figure A-2.6-4: Example of a PSD Plot

Part A: General

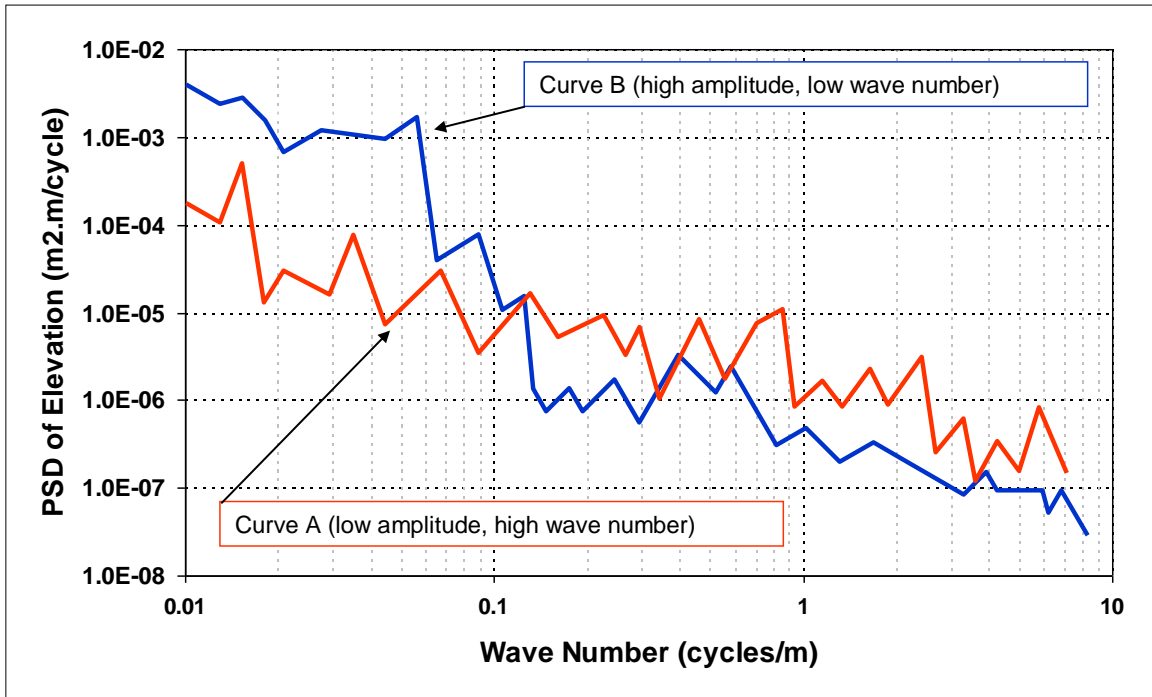


Figure A-2.6-5: PDS Analysis of Two Profiles

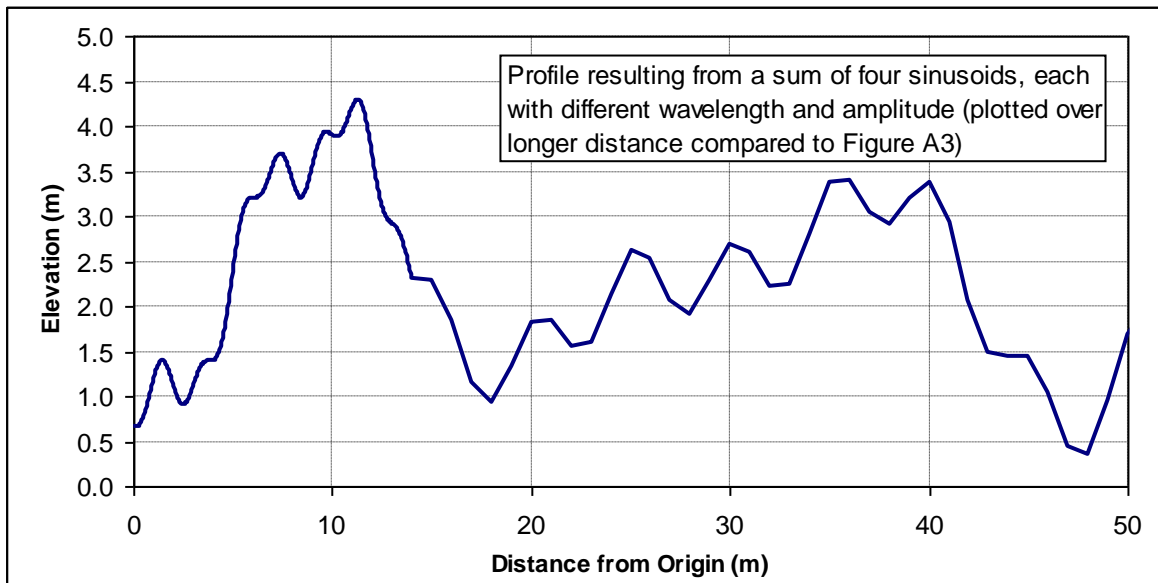


Figure A-2.6-6: Profile as shown in Figure A3, Extended Over a Longer Length of Road

Part A: General

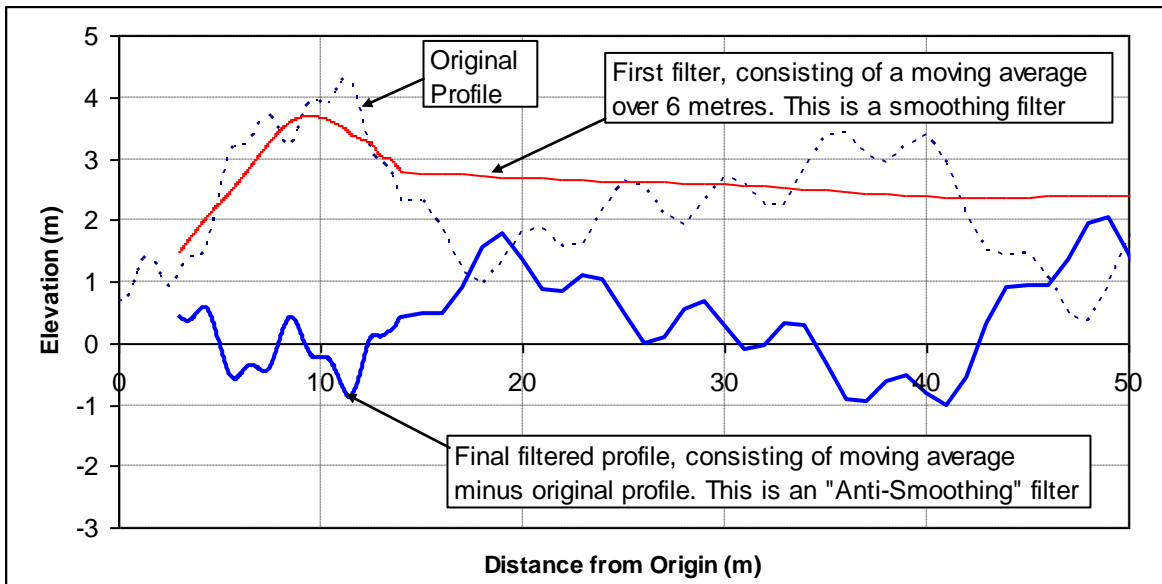


Figure A-2.6-7: Filtered Profiles