South Africa

COTO

Committee of Transport Officials

TMH13

AUTOMATED ROAD CONDITION ASSESSMENTS
PART F: SURFACE DEFLECTION

Committee Draft Final

May 2016

Committee of Transport Officials

TECHNICAL METHODS
FOR HIGHWAYS

TMH 13

AUTOMATED ROAD CONDITION ASSESSMENTS
Part F: Surface Deflection

Committee Draft Final
May 2016

Committee of Transport Officials

Compiled under auspices of the:

Committee of Transport Officials (COTO)
Roads Coordinating Body (RCB)
Road Asset Management Systems (RAMS) Subcommittee

Published by:

The South African National Roads Agency SOC Limited
PO Box 415, Pretoria, 0001

Disclaimer of Liability

All rights reserved

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.

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.

Table of Contents

List of Figures

List of Tables

F.1 Introduction

F.1.1 Context and Scope

TMH 13 *Part F* is the sixth of seven parts on Automated Road Condition Assessments. Part F provides guidance and methodologies on the planning, execution and control of pavement surface deflection measurements. This part should be read in conjunction with TMH 13 Part A which includes basic concepts and key definitions of pavement deflection. Part A also covers general aspects related to the planning of automated road condition surveys.

TMH 13 Part F is a companion document to TMH 22 which is the official requirement for Road Asset Management of the South African Road Network. Part F complements TMH 22 on requirements for the collection and use of pavement deflection data providing important information on strength related parameters used to estimate remaining useful life of an asset. Whilst the document addresses aspects of data management and reporting, reference is made to TMH 22 and TMH 18, respectively, for supplemental information and detail requirements. In general, reference is made to other documents in the series along with appropriate standards.

The scope of these guidelines are primarily concerned with the needs of roads agencies or managers of road networks. Although some details of measurement procedures are discussed, the emphasis remains on the needs of the network manager, and not on the needs of the contractor in charge of the actual measurements.

F.1.2 Objective

The primary objective of Part F is to assist road network management personnel to plan, execute and control the measurement of surface deflections over a road network. Secondary and associated objectives are to provide background, definitions and clarification of key concepts. Content related to the secondary objectives is included in Part A: General.

F.1.3 Layout and Structure of Part F

The document is written in concise format as far as possible to enable network managers to use it firstly as a practical guide, and only secondly as a source of general information on deflection measurement. Specifications, formulae, or complex but non-essential aspects, are relegated to appendices to ensure that the information can be helpful on the first reading.

Concept summaries and checklists are included and clearly highlighted. A comprehensive reference list is provided and related but non-essential aspects are discussed in sidebars. Sidebar boxes are also used to highlight references to other related TMH documents and specifications. The guidelines are structured as follows:

Section F.2 introduces the main types of deflection measuring devices. The main device types covered for measurement of surface deflections are slow moving devices, falling weight deflectometers, and high speed deflectometers.

Section F.3 provides detailed guidelines on calibration and validation of deflection measurement devices. Component calibration, calibration trials, validation schemes and aspects of control testing are outlined.

Section F.4 covers operational procedures for deflectometers, and also discusses data capture, troubleshooting and documenting aspects. Detailed discussions on factors influencing deflection measurements are included to equip managers with knowledge required during inspection and interpretation of deflection data.

References are provided in **Section F.5**, while **Section F.6** contains the glossary.

Appendix F-1 provides details on the calculation of the deflection-based structural number (SN).

Appendix F-2 contains a protocol for validating FWDs using a single reference FWD device.

Appendix F-3 includes equations to normalize deflections for asphalt temperature effects.

Appendix F-4 illustrates the effects of seasonal variation on deflection measurements.

F.2 Deflection Measurement and Strength Parameters

This section introduces different approaches to measure deflections including the most common devices used. Deflection measurement can be divided into the following categories according to the characteristics of the load applied to the surface:

- Static and slow moving devices;
- Vibratory deflectometers;
- Falling weight deflectometers, and
- High speed deflectometers

The first generation of devices were of the static or slow moving type, often categorized as deflection beams. The second generation involves application of a dynamic vibratory load, and the third generation measures deflections resulting from a dynamic impact load. Dynamic impact devices, also known as Falling Weight Deflectometers (FWD), attempt to simulate the effect of a moving wheel load. The next generation of devices measure deflections at traffic speeds.

In the sections that follow, each of the categories listed above are presented. For each, a brief background is provided, the operational principles discussed and advantages and disadvantages noted.

F.2.1 Static and Slow Moving

F.2.1.1 Static Deflection Beams

The **Benkelman Beam** has been the most widely used device for many decades and was developed in the early 1950s at the WASHO road experiment. It is still used today, and is sometimes the only available equipment in many third world countries. Figure F.1 shows a typical Benkelman beam setup. The device operates on a lever arm principle and is used with a truck that provides the axle load. The tip of the beam – with measuring point in contact with surface – is placed in line with the spacing between the rear dual tyres and the maximum deflection is measured with a dial gauge while the truck moves at creep speed. Two methods of measurement determine the starting position of the tyres relative to the beam tip (Smith and Jones, 1980):

- Transient deflection: the tyres approach the tip of the beam, and
- Rebound deflection: from a stationary position, the tyres move away from the tip of the beam. This deflection is susceptible to errors caused by plastic deformation.

Many different versions of the Benkelman Beam evolved to suit the trucks commonly used in different countries and to improve on the original design. The Road Surface Deflectometer (RSD) is a South African design which improved significantly on the stability of the device and accuracy of measurement. The main advantage is the use of a linear variable differential transducer (LVDT) instead of a dial gauge, which facilitates continuous measurement of deflections and capturing of the full deflection bowl (Prozzi, 1995).

Figure F.1 Benkelman Beam (Courtesy of John Harvey)

F.2.1.2 Automated Deflection Beams

Various developments of automated deflection beams, generally known as Deflectographs, have made the deflection beam principle more viable for application at the network level. A truck mounted beam assembly is slung beneath the truck, while kept in position by guides. The truck moves at slow speed, typically between 2 to 4 km/h, while the beam assembly is pulled forward at about twice the vehicle speed between measurements. The beam assembly is in a stationary position during measurements, while the truck continues to move forward at slow speed.

The **Lacroix Deflectograph**, developed in the mid 1960s in France, was the first commercially produced automated deflection beam device. Many modifications of the Lacroix followed in the UK, Denmark, Australia and in South Africa. The South African device was acquired in 1972 and was modified to measure deflections at several positions, thereby obtaining the full deflection bowl (Prozzi, 1995).

Figure F.2 South African Deflectograph (Courtesy of Roadlab)

Naturally, manually operated deflection beams, such as the Benkelman beam and RSD, are not suited for network level applications. Deflectographs, in turn, provide a high coverage but traffic control is required due to the slow operating speed. Although measurements are performed at realistic load levels, the duration of loading may be unrealistic. The cost of automated systems is relatively high (Irwin, 1994; Prozzi, 1995).

F.2.2 Vibratory Deflectometers

Vibratory deflectometers have not been used in South Africa and the device is only briefly introduced here. These second generation deflection devices measure dynamic deflections produced under a steady state (non-changing) sinusoidal vibratory load. The sinusoidal vibration is superimposed on a static preload applied to the pavement surface. A relatively large static preload is required to prevent the load wheels or plates from lifting off the surface during the loading cycle. Pavement deflections are measured with a set of velocity transducers (geophones) lowered to the surface and set at fixed offsets from the load. The full deflection bowl can be obtained.

Equipment is either mounted on a trailer or in a vehicle and the device is stationary when measurements are taken. Traffic control is therefore required.

The equipment is highly reliable and maintenance cost low. Although the frequency and dynamic force can be varied, the maximum achievable dynamic loads are low relative to typical heavy vehicle axle loads. These devices are most suitable for use on thinner, more flexible pavement structures (Irwin, 1994; Prozzi, 1995).

F.2.3 Falling Weight Deflectometers

Falling Weight Deflectometers (FWDs) are the most common deflection measurement devices throughout the world (Bennett, 2008). These devices have been used in South Africa on network and project level surveys since the early 1990s. The concept of applying a transient (short duration) impulse load to simulate a moving wheel load was formulated and prototypes built by French engineers around 1960. The first commercial devices were developed in Denmark and produced in 1968 (Bohn, 1989).

With the FWD, a dynamic impulse (or impact) load is applied to the surface by releasing a weight from some specific height onto a rubber buffer system that transmits the force to a standard load plate, usually 300 mm in diameter. By using different weights and drop heights the applied load can be varied, typically up to about 120 kN. A target load of 40 kN (to simulate an 80 kN axle) is typically used in South Africa whilst measurements are also done at 50 kN on the national network, in line with European practice. The duration of the load pulse is between 20 and 30 milliseconds, which is controlled by the buffer characteristics to simulate a moving wheel load.

To date mostly trailer mounted FWDs have been used in South Africa. To perform a test, the vehicle is stopped and the load plate and sensor bar lowered to the surface. Two to three drops are usually performed at each test position, of which the first is a “settling drop”.

Deflections are typically measured with seven to nine geophones (velocity transducers) to capture the deflection bowl up to approximately two metres away from the load. Figure F.3 shows the loading plate and sensors of a Dynatest FWD. Although the positions of these sensors are adjustable, they are normally fixed at standard offsets from the centre of the load plate.

In South Africa, sensors are standardized at offsets 0 (under the load), 200, 300, 400, 500, 600, 750, 900, 1200, 1500, and 1800 mm. A split loading plate is shown in Figure F.3. Such a plate improves settlement on surfaces with slight longitudinal deformation. Quartered plates are also available.

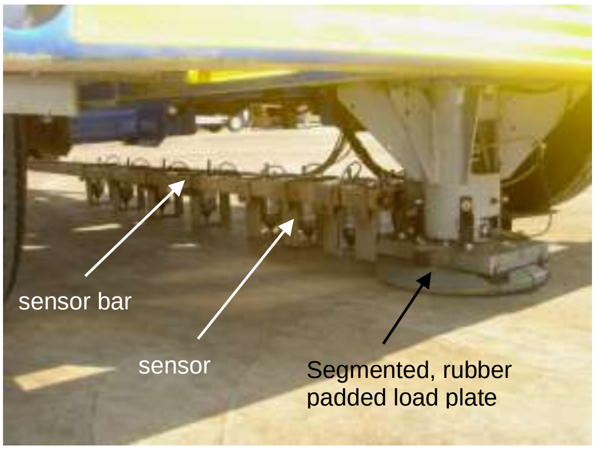


Figure F.3 FWD Load Plate and Geophones (SRT, 2009)

The most common commercially available FWDs are manufactured by Dynatest, Carl Bro (previously Phønix), JILLS, and KUAB. Typical devices are shown in Figures F.4 and F.5. FWDs differ in terms of trailer design, hydraulic and mechanical systems and data acquisition systems. Subtle differences between FWD brands are addressed by modern calibration protocols (COST336, 2005; FHWA, 2009). Nowadays, most manufactures also produce Heavy Weight Deflectometer (HWD) models with loading capabilities typically in the order of 250 kN. These devices were developed for use on heavy airport and industrial pavements.

Figure F.4 Dynatest FWD (SRT, 2009)

Figure F.5 Carl Bro FWD (Grontmij/Carl Bro, 2009)

FWDs are currently considered to be the most suitable device to simulate the actual magnitude and duration of moving wheel loads. In addition, only a small preload is applied to the pavement surface. The vehicle is stationary for about one minute during testing and traffic control is therefore required. The initial cost of FWDs is relatively high and the equipment is somewhat complex.

F.2.4 Traffic Speed Deflectometers

Development of these devices aimed at producing a reliable tool to enable continuous network level deflection surveys to be carried out at traffic speeds, avoiding traffic disruptions and expensive traffic management. A number of traffic speed deflectometers have been conceptualised and prototypes constructed since the early 1980s. Deflection measurements are generally performed using laser-based technologies.

The **Rolling Wheel Deflectometer (RWD)** (ARA, 2005) and the **Road Deflection Tester (RDT)** (Andrén, 2006) originated in the US and Sweden, respectively. These prototype devices make use of rangefinder (distance measuring) spot lasers mounted on a rigid beam system which is fitted to a truck. Any beam movements are detected by inertial sensors. The lasers determine the deflected and un-deflected (or reference) surface states and the deflection is the difference between the two states. The RWD is equipped with four spot lasers longitudinally arranged; three front lasers measure the un-deflected surface and a rear laser measures the deflected surface. The RDT measuring system uses two arrays of twenty lasers that collect transverse surface profiles, one representing the unloaded case and the other the loaded case.

The first prototype **Traffic Speed Deflectometer (TSD)** was initiated by Greenwood Engineering and the Danish Road Institute in Denmark in 2000. In 2005, the Transportation Research Laboratory (TRL) procured the second prototype device on behalf of the UK Highway Agency.

The South African National Roads Agency (SOC) Ltd. (SANRAL) acquired a Traffic Speed Deflectometer in 2014. The TSD is a loaded truck travelling up to 80 km/h while performing non-contact deflection measurements at intervals of 25mm using Doppler laser sensors. The Doppler sensors measure the pavement deflection velocity which relates to surface displacement.

The instrumentation is housed in an insulated container mounted on a single rear axle trailer assembly (Figure F.6). The compartment is kept at a constant temperature of 24ºC to ascertain accurate readings. The weight on the rolling axle comprises the weight of the trailer, the measuring system, and weights in a detachable load compartment. Bags filled with lead beads are stored inside the load compartment.

The SANRAL TSD is fitted with 10 Doper lasers (9 measuring and 1 reference) configured similar to FWD sensors with an additional sensor positioned at the 100 mm offset. Lasers are fitted on a rigid beam (Figure F.7) equipped with inertial sensors mounted on the beam to monitor any movement. Lasers are positioned in front of the rear axle with the last laser placed at a distance of 3.5 m from the axle (outside the deflection bowl) where it serves as a reference (SANRAL, 2014).

Due to the relatively high cost of these devices, it is not expected that TSD testing will be available from local service providers in the foreseeable future. For this reason, the methods and guidelines in sections to follow focus on Falling Weight Deflectometers.

Figure F.6 Rigid beam containing Doppler Laser sensors (SANRAL, 2014)

More about Doppler Lasers

The Doppler principle provides an instant measurement of surface velocity where a change in laser light frequency is caused by the deflecting pavement surface. The method therefore does not depend on the comparison of two measurements from the same point on the surface. The sensor mountings are angled to split the measured velocity into two components from the measured horizontal pavement direction. These components are required to calculate the deflection. However, the angles of the lasers have to be known with great accuracy as they have a significant effect on the final outputs. Calibration of the laser angles (geometric calibration) have been a key consideration in the development of this technology in recent years (Jenkins, 2009).

Figure F.7 SANRAL RHINO High Speed Survey Vehicle (SANRAL, 2014)

F.2.5 Equipment Specifications

The equipment type to be used in the network survey must be selected by the road owner before preparing the specification. Minimum requirements focus on Falling Weight Deflectometers (FWDs). The equipment specification should define the minimum requirements for the following elements:

- 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.
- Deflection measurement system: Typical specifications for FWD systems are provided in Table F.1. For FWDs, the loading plate is commonly required to be split or segmented, with a patterned rubber membrane (≥ 5 mm) footing, and 300 mm in diameter. In addition, the system should be equipped with a thermometer (typical accuracy: ± 0.5℃), and Distance Measuring Instrument (typical accuracy: ≤ 0.1% of true distance).
- Global Positioning System (GPS) coordinates should be linked directly to the data.
- 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.

F.2.6 Deflection Derived Strength Parameters

TMH 13 Part A introduces deflection concepts and discusses different deflection derived strength parameters. Section F.4, with reference to TMH 18 and TMH 22 note data that need to be reported during the survey. In terms of pavement strength evaluation on the network level, the following parameters are required as a minimum:

- **Deflection bowl parameters** as described in Part A and included in Table F.2 for convenience.
- **Structural Number (SN)** described in Part A and calculated according to method in **Appendix F-1**.

Table F.2 Deflection Bowl Parameters

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		

Calculation of Deflection Derived Structural Number (SN)

Appendix F-1 includes the algorithms for calculating Structural Number (SN) from FWD surface deflections.

Table F.1 Equipment Specifications for Deflectometers

Parameter	Minimum Specification for		
	Displacement Sensors	Load Cell	Data Acquisition System
Component Type	Geophone, accelerometer or equivalent	Strain Gauged Bridge	Supply information in required format
Number and positions	11 at off-sets (mm): 0, 200, 300, 400, 500, 600, 750, 900, 1200, 1500, 1800	At 0 mm offset	Not Applicable
Resolution	0.1 µm	50 N	16 Bit
Measuring Range	0 to 2000 µm	0 to 120 kN	> Sensor Output
Repeatability	5 µm	0.5%	±1 LSB
Recorded Resolution	1 µm	100 N	Not Applicable
Frequency Response	DC to 1 kHz	DC to 1 kHz	Sample Rate ≥ 100 kHz
Temperature Stability	50 ppm/℃	50 ppm/℃	25 ppm/℃
Operating Temperature	0℃ to 50℃	0℃ to 50℃	0℃ to 50℃
Long Term Drift	< 0.25%	< 0.25%	< 0.002% ±1 LSB
Legend: LSB = Least Significant Bit; ppm = parts per million			

F.3 Calibration and Validation of Deflectometers

TMH 13 Part A introduces general aspects of calibration and validation that require consideration during the deflection survey planning process. **Calibration** refers to the individual components or units of a system that has to measure to a given standard, whilst **Validation** tests the accuracy, repeatability and reproducibility of the system as a whole under normal survey conditions.

This section commences by introducing calibration of different deflection measuring devices and highlights important aspects of available standards. Due to the complexity and variety of modern deflectometers, calibration of these devices received much attention since the early 1990s. Because measurement with FWDs is considered as the accepted method worldwide (Bennett, 2008) and in South Africa, specific attention is given to protocols developed for these devices. Network managers are provided with a basic understanding of the procedures and their relevance as part of the validation process.

F.3.1 Calibration

Depending on the calibration protocol(s) adopted or agency specific requirements, certain calibration actions may be performed by the operator, while others should be performed at a calibration station or by an independent certified technician.

Calibration procedures depend on the type of device used. Whilst ASTM D4695 provides general guidelines on the calibration of all types of deflectometers, national and international efforts to develop, harmonize, and maintain standard calibration protocols focused on FWDs, i.e. the protocols developed under the United States Federal Highway Administration (FHWA) SHRP Program (FHWA, 2009) and the European COST Action 336 (COST336, 2005).

Since these developments, a special working group under CROW (Contract Specification in Civil Engineering, The Netherlands) published a set of updated protocols considering the outcomes of both the European and American studies. Table F.1 summarises the protocols representing the minimum requirements for the calibration of FWD devices adopted in TMH 13.

Calibration of the load cell and sensor(s) of deflectometers are required. General aspects of the calibration of these components and others, such as the temperature probe and odometer are provided in the following paragraphs.

F.3.1.1 Load Cells

Independent *reference calibration* should be performed periodically using the manufacturer's recommended procedures or the adopted standard. Calibration on an annual basis is common, except where the load relies on a truck load. In such cases, the load should be checked prior to testing (ASTM D4695).

F.3.1.2 Sensor(s)

Independent *reference calibration* of deflection sensors should be performed periodically using the manufacturer's recommended procedures or the adopted standard. Routine calibration checks of deflection sensors and verification of sensor positions should be conducted at least once per month.

Where multiple sensors are involved (typically for FWD's), *relative calibration* is also required to ensure that all sensors on a given device are in calibration with each other. Relative calibration forms part of periodic independent calibration as well as the routine calibration checks performed by the user.

F.3.1.3 Other Components

For other system components such as the thermometer and odometer or distance measuring instrument, the manufacturer's calibration procedures should be used.

Calibration of Falling Weight Deflectometers

Protocols based on the outcomes of prominent European and American studies, compiled by a special working group under CROW (Contract Specification in Civil Engineering) are adopted in TMH13. The protocol activities, implementation frequencies, and references are included in Table F.2.

Table F.2 FWD Calibration Protocols

Calibration Action	Frequency	Protocol[1]
General		
FWD calibration scheme	N/A	Protocol 1
For Operators/ Users		
Verification of FWD deflection sensor positions	Monthly	Protocol 2
FWD short-term repeatability verification	Monthly	Protocol 3
FWD long-term repeatability verification	Three monthly	Protocol 4
Relative calibration of FWD deflection sensors	Three monthly	Protocol 5
For Calibration Centre/ Certified Technicians		
Laboratory reference calibration of FWD deflection sensors	Annually	Protocol 6
Dynamic reference calibration of FWD deflection sensors	Annually	Protocol 7
Dynamic reference calibration of FWD load cell	Annually	Protocol 8
Static reference calibration of FWD load cell	Annually	Protocol 9
FWD Calibration Trials		
FWD calibration trial	Once per two years	Protocol 10
FWD pairwise correlation trial	On request	Protocol 11

[1] CROW (2011): <http://www.crow.nl/publicaties/falling-weight-deflectometer-calibration-guide>

Important!

It should be noted that long-term repeatability testing are influenced by climatic effects. For this reason, road agencies are encouraged to be pro-active with establishment of validation sections and early monitoring thereof.

F.3.1.4 Calibration Trials

The use of FWD calibration trials is obligatory in The Netherlands since 1993 and has been used in the UK since 1999. Even if all load cells and deflection sensors have been calibrated satisfactorily, reproducibility among devices may not be achieved (COST336, 2005). For this reason it is recommended that national calibration trials be conducted to develop device specific harmonization factors. In such a trial, a group of devices is compared against a reference group of devices. Testing is performed on various types of flexible pavements representing different subgrades and structural capacity. Apart from reproducibility, such a trial also verify that a device produce consistent results on a specific test site.

Table F.2 indicates that FWD group calibration trials must be performed once every two years. In such an exercise the correlation factor for al FWDs participating in the trial is determined. The objective of this group trial is to enhance reproducibility among FWDs. Protocol 10 contains the procedure to be followed. Guidelines for planning a FWD correlation trial are included in both the FHWA (2009) and CROW (2011) publications.

Protocol 11 (Table F.2) makes provision for determining the FWD correlation factor for one or more FWDs referenced to a single FWD that successfully participated in an FWD correlation trial. Whilst this protocol provides an opportunity for FWDs that have failed to pass the correlation trial it is not be used as an alternative to the group calibration trial. A pairwise correlation trial may be requested for new FWDs where validation is required on short notice and the next group trial is scheduled months ahead. Network managers may also request pairwise correlation trials for FWDs to be used on their networks as part of the validation requirements.

Planning a FWD Correlation Trial

- CROW FWD Calibration Protocols: Appendix A (CROW, 2011)
- SHRP FWD Calibration Protocols: Appendix II (FHWA (2009)

F.3.2 Validation

General considerations when planning a survey and aspects to be covered in the specifications are outlined in TMH 13 Part A. This section should therefore be read in conjunction with Part A.

If the deflectometer was certified in the previous and currently valid calibration trial, then the device may be accepted as valid. If the device is valid, only control testing (see Section F.3.4) is needed to ensure that repeatability is maintained throughout the survey contract. As qualified in Section F3.1.4, a pairwise correlation trial may be approved under special circumstances where a FWD could not take part in the most recent group calibration trial. Validation through a pairwise correlation trial may also be required if the accuracy of the deflections are under suspicion, or as part of the contract requirements.

The reference deflectometer should be fully certified, including participation in the previous group calibration trial.

At least four test stations should be selected for a reproducibility test and three to conduct a short-term repeatability test. Stations should represent various pavement structures and supporting conditions, and hence different deflection bowls. The sites should be smooth and level, with no visual distress. Convenience of access and safety of operation should be considered when selecting the sites.

FWD Validation

Reference should be made to Protocol 11 (Table F.2) for validation of FWDs. When required, FWD(s) participate in this correlation trial where a single reference FWD is used with similar load pulse durations. This protocol includes specifications for:

- Reproducibility, and
- Short-term repeatability

F.3.3 Validation of Positioning Equipment

The validation of positioning equipment involves checking of the Global Positioning System (GPS), Inertial Navigation System (INS), and Distance Measuring Instrument (DMI). *Checks and approaches to validation these systems are included in TMH 13 Part B*.

F.3.4 Control Testing

Control testing should be performed from time to time during the survey to ensure that the equipment output is still valid and that the accuracy and precision of the device is still within specification. The following protocols are recommended for control testing of deflectometers throughout the survey contract:

- Short-term repeatability (Table F.2, Protocol 3), and
- Long-term repeatability (Table F.2, Protocol 4).

Whilst long-term repeatability testing should be performed at validation stations, short-term repeatability may be performed at the first test site of each day of operational testing. However, control testing need not be performed on all validation sections, and normally testing on two or three sites would suffice.

Control testing should be performed on a regular basis as part of the survey process. If control testing shows that the measured values are no longer within the specified limits, then any data collected since the last successful control test should be discarded and re-measured.

It should be obvious that the cost and time implications of a failed control test are severe. For this reason, control testing should be carried out as frequently as possible within the constraints of the network and survey budget. Unless specified otherwise, the frequencies required by Protocols 3 and 4 should be sufficient. According to these protocols, short-term repeatability tests should be performed at least on a monthly basis or when the instrument returns from servicing of components or repairs. Long-term repeatability tests should be performed at least once every three months.

F.4 Operational and Quality Control Procedures

This section of Part F deals with the daily checks and procedures that need to be carried out during the course of deflection measurement surveys. It should be noted that, while the guidelines cover the basic operational aspects and their influence on measurement, the guidelines are intended mainly for network managers, and not for contractors. The network manager is not responsible for performing daily checks or following of proper operational procedures. However, a proper understanding of the elements that influence measurement and of the procedures that a contractor should perform each day, will allow the network manager to exercise better control over the measurement process.

The *operators* of measurement devices should – in addition to the elements covered in this section – have an in-depth understanding of the influence of all operational elements on the measurement process. Relevant standards and operational manuals should be consulted for detailed procedures.

F.4.1 Operational Procedures

Device specific operational procedures should be those furnished by the manufacturer of the device. Apart from periodic calibration (see Section F.3), the following general operational and quality control aspects should be checked on a daily basis or as often as required.

- Survey Requirements: A job card should be available indicating the system set-up and testing requirements. For example, these may include: Definition of test sections (location and stations); required peak load or different load levels, or axle load and tyre pressure specifications where appropriate; sensor spacing, sensor test locations and orientation (geometry); test interval, and; special test requirements (such as variations at climbing lanes etc.)
- Safety: Check project specific requirements and arrangements regarding traffic control and placement of flaggers. Check equipment, including high visibility jackets, flags, cones, flashing arrows, fire extinguishers, and first aid kits. Check that the vehicle is generally safe with no loose or misplaced components or foreign objects present.
- Maintenance: A daily maintenance inspection checklist should be available and followed before departing for testing. Some components should be checked on a daily basis, whilst others require checking on a weekly or monthly basis according to the manufacturer's recommendations. Check that the essential tools and spare parts are available.
- Calibration/ Verification: Check that all requirements are up to date, especially after a service and repairs. A record of monthly actions performed by the operator should be available and up to date, e.g. sensor position verification, sensor relative calibration, and verification of long-term repeatability.
- Cleanliness: The deflection sensors and temperature sensors with holders should be clean. All other components should be free from excess dirt that may affect the system operation.
- Warm-up Time: The measuring and data acquisition systems as well as load conditioning equipment (such as rubber buffers, if applicable) should be subjected to sufficient warm-up time according to the manufacturer's recommendations.
- Load: Check that weights are in place to facilitate the specified load. For FWDs, check the weights, guide system, rubber buffers, and condition of the load plate with rubber pad. For devices dependant on axle weight, check the condition of tyres and that the loaded material is secure.
- Sensors: Check that the raise/lower bar or beam assembly and sensor holder(s) are undamaged and that the holder(s) with sensors are fitted securely in position.
- System Functionality: Check that mechanical and hydraulic parts are in good working order. Check the system response before each test sequence, e.g. for FWDs, check the dynamic response by an automatic signal test on the background noise level of all sensors.
- Repeatability: A deflection repeatability check should preferably be performed at the first section tested each day. Where applicable, a load repeatability check should be performed at least once a week.

Table F.3 Checklist for Operation Control Checks on Deflectometers

Control or Decision Aspect
1. Check the vehicle and test device and ensure it is the same as used in the validation exercise. 2. Ensure that the driver is the same as the one who conducted the validation exercise. 3. Ensure that the calibration records are up to date and valid and inspect the service record of the vehicle. 4. Request and inspect the daily checklists (set-up, maintenance, safety, warm-up). Ensure it meets the Quality Control Plan format. 5. Inspect the vehicle and ensure that all sensors are clean and that the equipment is free of excess dirt etc. 6. Request the operator(s) to perform a functionality test on the equipment. Check the load and deflection responses for conformance with specifications (e.g. target load level; deflection pulse rise time of ±30 ms) 7. Request the operator(s) to perform deflection and load (if applicable) repeatability tests. 8. Confirm the correct operation of the GPS and other positioning equipment

F.4.2 Data Capture and Documentation

The contract specifications should provide details on the data format and/or compatibility requirements for different data types. It should be specified whether raw data files are required and/ or if any pre-processing is required (such as normalization of deflections). As a minimum, the specifications should state the format of the required files (e.g. Comma Delimited ASCII file, Spreadsheet format) and the required columns (or fields). For deflection surveys, the required data items typically include the following:

- Operator name;
- Date and time of record;
- Location of test point:
  - Section information;
  - Pavement type (bituminous, concrete, or concrete with bituminous overlay);
  - Kilometre;
  - Lane;
  - Geometry (e.g. wheel path, centre of slab etc.);
  - DGPS coordinates;
- Pavement surface temperature and ambient air temperature at time of test;
- Applied load and pressure (actual and/or normalized where applicable);
- Measured deflection at each specified sensor location (actual and/ or normalized where applicable);
- Comments:
  - Visual condition at the test location;
  - Subsurface concrete structures (such as culverts) at the test location.

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

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

The contractor should flag any data files or parts thereof for which measurements are regarded as unusual because of operating conditions or any other cause. Operators should therefore be trained not only in vehicle operation aspects, but also in the interpretation of perceived deflection values. With adequate knowledge of the impact of different conditions on the precision of deflection measurements, files recorded under non-optimal conditions can be accurately flagged for detailed analysis.

F.4.3 Data Checking and Troubleshooting

The specification may require that data acquisition systems include automatic data quality checks. For example, five specific error checking methods are defined for FWD type devices (NCHRP, 2008):

- Roll-off: When a single sensor fails to return to 0 within 60 ms of the weight being dropped;

- Non-decreasing deflections: When deflections measured do not decrease as distance from the load increases;
- Overflow: when a deflection sensor measures a deflection beyond its range. Also known as an "out-of-range" error;
- Load variations: When the drop load varies by more than 0.18 kN plus 2 percent of the average load, and
- Deflection variation: when the measured deflection from the same drop height vary by more than 2 µm plus 1 percent of the average deflection.

After receiving the deflection data, the network manager should perform some control checks on a few data files. The objective of these checks should be to ensure the measured values correspond with basic engineering judgement, and that the data are consistent with that of earlier surveys.

For these control checks, the network manager should select a few sections for which the deflection characteristics are known. For example, from verified historic data, the network manager may know sections with inherent deflection spikes or other characteristic features. If surveys were undertaken in preceding years, then the data can be graphically compared to the data collected in previous years.

If the data check reveals an inconsistency between measured deflections and those reported in the previous survey, then the data file should first be checked for comments from the operator regarding the visual condition and possible subsurface concrete structures. The time of testing within the day and year can also influence results. These aspects are discussed in more detail in sections to follow.

F.4.4 Factors that Affect Deflection Measurements

TMH 13 Part A broadly introduces factors that influence deflection measurements, including load, climate, pavement type and condition. The following discussions attempt to equip the network manager with a more detailed knowledge which may be applied when interpreting deflections for network level purposes. Errors generally addressed through calibration and validation of devices is excluded from this discussion – All equipment should be calibrated and validated according to the methods and guidelines presented in Section F.3.

F.4.4.1 Load Level

- Target load: Naturally the selection of the target load or pressure will influence the magnitude of deflections. It is therefore preferable to keep the load or pressure constant from one survey to the next.
- Normalization: Small random deviations from the target load or pressure always occur due to equipment and/or pavement surface effects. It is custom to normalize all deflections to the target reference load or pressure level that does not deviate more than 10 percent from the actual applied load. Linear interpolation is used by multiplying each deflection by the target load or pressure over the measured load or pressure, respectively.

F.4.4.2 Test Location

- Referencing: Spatial variability inherently associated with pavement structures will affect measurements from one test point to the next and from one survey to the following. Establishment of well referenced test locations is therefore recommended to minimize the variability associated with the position of testing from one survey to the next.
- Geometry: The longitudinal gradient at the test location should preferably not exceed 10 percent to ensure accurate testing (COST336, 2005).
- Edge effects: The presence of kerbs and visibly different shoulders should be noted. Testing should preferably not be executed closer than 800 mm from the pavement edge unless it is specified otherwise.

F.4.4.3 Surface/ Pavement Aspects

- Surface condition: Because of surface irregularities and loose debris, deflection sensors are not always seated firmly during placement. FWD sensors are usually seated by doing one or two initial drops without recor ding data. Extensively cracked surfaces may pose a seating problem and may cause anomalies in the data when sensors bridge an active crack. The entire loading plate area should be in contact with the surface.

This contact may be affected by deformed surfaces. However, the use of a segmented and well lubricated swivel plate should address most problems with unevenness adequately.

- Very flexible pavements: For flexible and especially very flexible pavements, the sensor at the 200 mm offset is normally too close to the edge of the loading plate to produce a useful deflection result.
- Very stiff pavements: When very stiff subgrades are encountered with corresponding outer sensor deflections less than 20 microns, the significance in any inaccuracies in the measured deflections will increase. To compensate for this effect, testing at higher load levels may be considered (COST 336, 2005).
- Equilibration and changes in behavioural state: New pavements experience an equilibration period where after the structure reaches a balanced state. For this reason, the UK Highways Agency omits deflection testing from their routine network surveys on new pavements for the first two years after construction (UKPMS, 2005). With time, changes in the behavioural state of pavements will also affect deflection measurements. Network managers should not assume that deflections for any given pavement will increase with time and traffic. This may be true in cases where weak or overstressed subgrades exist or where cracking of bound materials occur.
  Pavement stiffening, however, is possible through aging of thick asphalt layers or densification of granular layers with time and traffic.

F.4.4.4 Measurement Environment

- Rainfall: No testing should be performed in standing water on the road surface, i.e. when the surface texture is filled with water.
- Temperature: Temperature has a significant effect on the stiffness of bituminous materials due to their visco-elastic nature (i.e. they exhibit low stiffnesses at high temperatures and high stiffnesses at low temperatures). The effect of thick (>40 mm) asphalt surfacings and asphalt base layers is more significant. It has also been reported that the stiffness of granular layers change with daily temperature variations. This is believed to be the result of changes in moisture suction in these layers (Netterberg and Haupt, 1999). For network level purposes it is recommended that deflection bowls be normalized to a standard reference temperature of 25°C. Since only surface temperatures (and not in-depth temperatures) are measured during network level surveys, the BELLS3 equation (FHWA, 2000) can be used to correct measurements for temperature gradient with depth. Once the representative temperature has been determined, normalization of the inner bowl deflections to the specified reference temperature can proceed. To implement this approach both air and surface temperatures should be recorded throughout the survey:
  - At the start of the survey section;
  - At the last test point of the survey section;
  - At least every four hours, preferably more frequently, or
  - When conditions change, e.g. changing weather, or alternate shady surfaces.

Appendix F-2 provides a procedure for normalization of deflections to account for temperature variations in bituminous layers.

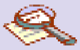
F.4.4.5 Seasonal Variation

Seasonal moisture and temperature fluctuations cause variations in pavement response to wheel loads. The fact that seasonal changes can cause significant variations in deflection measurements is well-established (see information block: More about Seasonal Variation)

Unfortunately, the magnitudes of these variations are influenced by many factors which are site specific. This aspect makes the development of a generic approach to account for these variations problematic. The complexity of this phenomenon was illustrated by van Gurp (1995) and others by considering the impact of the following variables:

- Pavement composition and geometry;
- Properties of pavement materials;
- Temperature gradient through pavement;
- Precipitation and evaporation;
- Drainage conditions;
- Groundwater table level beneath pavement;
- Sealed and unsealed shoulders;
- Width of sealed shoulders;
- Extent of sealed and unsealed cracking;
- Trees near the road;

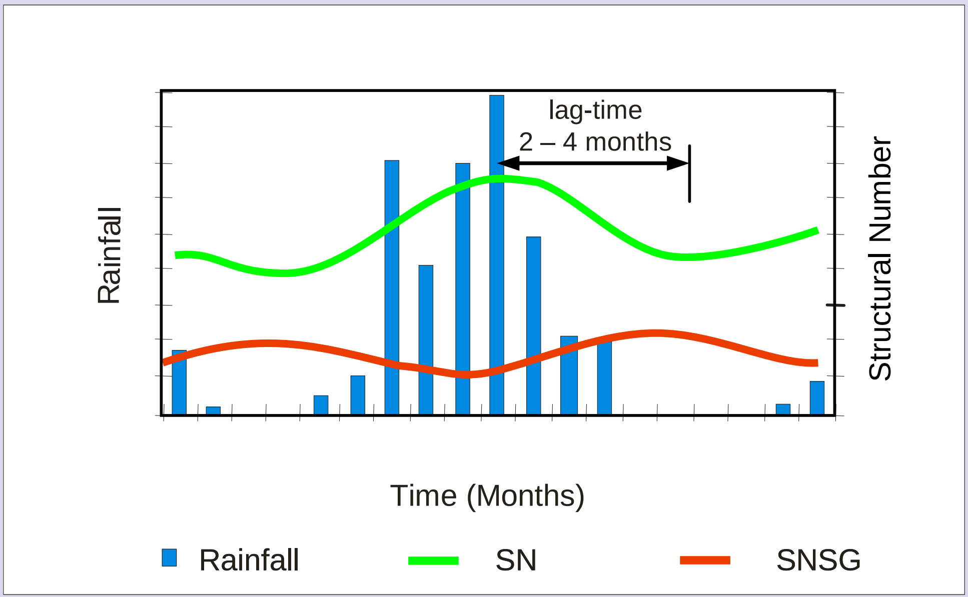
As discussed in the previous subsection, generic methods to account for the effects of temperature on the shape of the deflection bowl have largely been accepted. Adjustment for the effects of moisture, however, has been limited to maximum deflection (e.g. Austroads, 2009). Whilst pilot projects have been conducted locally to investigate seasonal patterns of common deflection bowl parameters (Hartman and Rohde, 1996), no formal procedure has been developed to date.



More About Seasonal Variation

The local study by Hartman and Rohde (1996) was conducted in the summer rainfall region of the Highveld. Findings from this study suggest that deflections originating from the upper pavement layers follow a general pattern of lower values during springtime which gradually increase to a peak in mid-winter. Because increase in moisture would tend to increase deflections, this trend suggests that a time-lag (two to four months) exists in pavement response to moisture ingress in the upper layers. In turn, deflections originating from the subgrade show higher deflections in early summer that decreases to a low in autumn. This trend corresponds with the summer rainfall pattern experienced in this region.

Based on initial trends observed, it is envisaged that the structural number approach presented in Appendix F-1 offers the potential to incorporate seasonal variation on the network level. This approach utilizes the full deflection bowl to derive the two component of the modified structural number: SNC = SN + SNG, where SN is the traditional structural number which is an indication of the strength of the layers above the subgrade, and SNG represents the strength of the subgrade. The following figure illustrates how the observed trends could conceptually be translated into the two structural number components.



F.5 References

AASHTO. 1993. **Guide for the Design of Pavement Structures**. American Association of State Highway and Transportation Officials, Washington, D.C.

Adrén, P. 2006. **Development and Results of the Swedish Road Deflection Tester**. Licentiate Thesis, Royal Institute of Technology, Dept. of Mechanics, Stockholm, Sweden.

ARA. 2005. Rolling Wheel Deflectometer Information Brochure. Applied Research Associates, Inc. Retrieved (2009) from **<http://www.ara.com/transportation>**

AUSTROADS. 2009. **Guide to Pavement Technology, Part 5: Pavement Evaluation and Treatment Design (Ed.2nd)**. Austroads Inc. NSW

Bennet, C.R. 2008. Procuring pavement management data-collection services. **Road & Transport Research**, Vol.17, No.3, pp. 13 - 22.

Bohn, A.O. 1989. The History of Falling Weight Deflectometers. Denmark. Retrieved (2009) from <**http://www.pavement-consultants.com>**

COST336. 2005. **Use of Falling Weight Deflectometers in Pavement Evaluation**. COST Action 336, Final Report, 2nd Ed. European Cooperation in the Field of Scientific and Technical Research. Published on-line by FEHRL Knowledge Centre at http://www.fehrl.org

CROW. 2011. **Falling Weight Deflectometer Calibration Guide**. Report D11-07. CROW, Ede, The Netherlands. <http://www.crow.nl/publicaties/falling-weight-deflectometer-calibration-guide>

FHWA. 2000. **Temperature Predictions and Adjustment Factors for Asphalt Pavement**. Report No. FHWA-RD-98-085, Federal Highway Administration, McLean,VA.

FHWA. 2009. **FWD Calibration and Operational Improvements: Redevelopment of the Calibration Protocol Equipment**. Report No. FHWA-HRT-07-040. Federal Highway Administration, McLean,VA.

Grontmij/ Carl Bro. 2009. Retrieved in 2009 from **<http://www.pavement-consultants.com>**

Hartman, A.M. and Rohde, G.T. 1996. **The Seasonal Variation of Nondestructive Pavement Deflections**. Research Report RR 93/593. Department of Transport, Pretoria.

Irwin, L., De Beer, M., and Rohde, G.T. 1994. **Pavement Deflection Analysis**; Short Course, 4 – 7 July, University of Pretoria, Pretoria.

Jenkins, M. 2009. **Geometric and Absolute Calibration of the English Highway Agency Traffic Speed Deflectometer.** European Conference of Transport Research Institutes, Torino, Italy.

NCHRP. 2008. **Falling Weight Deflectometer Usage, A Synthesis of Highway Practice**. NCHRP Synthesis 381. Transportation Research Board, Washington, D.C.

Netterberg, F. and Haupt, F.J. 1999. **Diurnal and Seasonal Variation of Soil Suction in Five Road Pavements and Associated Pavement Response**. 13th African Regional Conference on Soil Mechanics and Geotechnical Engineering. Preprint. Morocco (Marrakech). December 2003, 12pp: p. 427-438

Prozzi, J.A. 1995. **The Nondestructive Measurement of the Engineering Properties of Roads for use in the Rehabilitation of Roads**. Research Report RR 93/371. Department of Transport, Pretoria.

Rohde, G.T. 1994. **Determining Pavement Structural Number from FWD Testing**. TRR1448, Transportation Research Board, Washington, D.C.

SANRAL. 2014. **Presentation - RHINO Survey Vehicle**. The South African National Roads Agency (SOC) Ltd. Pretoria, South Africa.

Smith, H.R. and Jones, C.R. 1980. **Measurement of pavement deflections in tropical and sub-tropical climates.** TRRL Laboratory Report 935, Overseas Unit TRRL, Crowthorne, Berkshire.

SRT. 2009. Specialised Road Technologies. General Information from **<http://www.srt.co.za>**

Van Gurp, C.A.P.M. 1995. **Characterization of Seasonal Influences on Asphalt Pavements with the use of Falling Weight Deflectometers**. PhD thesis, Technical University of Delft,

Relevant Standards

ASTM D4694-96 (Reapproved 2003). Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device

ASTM D4695-03.(Reapproved 2008) Standard Guide for General Deflection Measurements

F.6 Glossary

BELLS3: Asphalt temperature assessment model version 3, developed by Baltzer, Ertman-Larsen, Lukanen, and Stubstad.

Calibration: Corrective activity in which calibration factors of an instrument or device under testing are adjusted to match the readings of the instrument or device under consideration within specified limits to those of reference instrumentation or to the mean of a set of readings of similar type instrumentation (COST336, 2005)

Deflection time history: Output signal of a deflection sensor expressed in terms of deflection versus time (COST336, 2005)

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.

Empirical: Experimentally determined, through experience, or observation of a phenomenon, also called phenomenological.

Load: Peak value of the load time history (COST336, 2005)

Load time history: Output signal of a load cell in terms of load versus time (COST336, 2005)

Modified Structural Number (SNC): 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 F-1.

Normalization: Linear interpolation technique used to convert readings to values that would have been obtained under target conditions (COST336, 2005)

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.

Pavement Response: The response of a pavement structure when subjected to a wheel load(s). In pavement analysis and design, these responses are typically stresses, strains, and deflections.

Pulse duration: Part of the time history elapsed between the onset of the ascent of the time history and the moment that the descent returns to zero level again (COST336, 2005)

Pulse rise time: Part of the time history elapsed between the onset of the ascent of the time history and the moment that the time history reaches the peak value (COST336, 2005)

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.

Reproducibility: A measure of the ability to reproduce a measured result 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.

Structural Number (SN): SN is a single number that provides an indication of strength of a pavement structure above the subgrade. The number is calculated by summing the product of layer thickness (t) and a layer coefficient (a) for each layer. Low values (e.g. 2) represent relatively weaker pavements and high values (e.g. 5) represent relatively stronger pavements.

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

Verification: The process of proving or disproving the correctness of a system or measurement device with respect to a certain formal specification.

APPENDIX F-1

CALCULATION OF DEFLECTION DERIVED STRUCTURAL NUMBER (SN)

Appendix F-1 is an extract from HDM-4 documentation. The approach presented is recommended by the World Bank based on an extensively validation using data sets from five countries and comparing seven different procedures. The proposed procedure to relate components of the modified structural number to characteristics of the deflection bowl was originally developed by Rohde (1994).

The Concept of Structural Number

The structural number was first defined in the AASHO road test:

$$SN = \sum_{i=1}^{nlayer} a_i \cdot h_i \qquad (F\text{-}1.1)$$

Where:

SN : pavement structural number;
hi : thickness of layer i (inches);
ai : layer coefficient of layer i, and
nlayer : number of pavement layers above the subgrade

The layer coefficient is a measure of the relative ability of a unit thickness of a given material to function as a structural component of the pavement. Layer coefficients were originally determined in the AASHO road test. The Transport and Road Research Laboratory (TRRL) introduced a subgrade component, SNSG, to account for variation in subgrade strength and defined the modified structural number, SNC:

$$SNC = \sum_{i=1}^{nlayer} a_i \cdot h_i + SNSG \qquad (F\text{-}1.2)$$

Where:

SNC : modified structural number

And:

$$SNSG = -0.85(\log CBR)^2 + 3.51(\log CBR) - 1.43 \qquad (F\text{-}1.3)$$

Where:

CBR : California Bearing Ratio of subgrade material in per cent

Calculating SN from FWD Deflections

First, the structural index of the pavement, SIP, is calculated. This index represents the relative stiffness of the structure above the subgrade and is defined as:

$$SIP = D_0 - D_{1.5 \cdot HP} \qquad (F\text{-}1.4)$$

Where:

SIP : structural index of the pavement
D_0 : maximum deflection
HP : total pavement thickness above the subgrade
$D_{1.5HP}$: the surface deflection at an offset 1.5 times HP from the centre of the loading plate under a standard 40 kN FWD load (mm)

The structural index of the pavement relates to structural number in the following way:

$$SN = a0 \cdot SIP^{a1} \cdot HP^{a2} \qquad (F\text{-}1.5)$$

Where:

$a0$ to $a2$: coefficients given in Table F-1

Calculating SNSG from FWD Deflections

The structural index of the subgrade represents the relative stiffness of the top 300 mm of the subgrade:

$$SIS = D_{1.5 \cdot HP} - D_{1.5 \cdot HP + 450} \qquad (F\text{-}1.6)$$

Where:

SIS : structural index of the subgrade
$D_{1.5HP + 450}$: surface deflection at an offset 1.5 times HP from the load

The structural index of the subgrade is related to subgrade stiffness as follows:

$$E_{sg} = 10^{a3} \cdot SIS^{a4} \cdot HP^{a5} \qquad (F\text{-}1.7)$$

Where:

E_{sg} : subgrade modulus in MPa
$a3$ to $a5$: coefficients given in Table F-1.1

The subgrade CBR can be calculated using the following equation:

$$E_{sg} = 41.19 \cdot CBR^{0.385} \qquad (F\text{-}1.8)$$

CBR is used in Equation A3 to calculate SNSG

Table F-1.1 Coefficients for Calculating SN and E_{sg}

Coefficients for SN – SIP Relationship			
Surface Type	$a0$	$a1$	$a2$
Bituminous seals Asphalt	0.1165 0.4728	-0.3248 -0.4810	0.8241 0.7581
Coefficients for E_{sg} – SIS Relationship			
Total Pavement Thickness	$a3$	$a4$	$a5$
HP ≤ 380 mm 380 mm < HP ≤ 525 mm HP > 525 mm	9.138 8.756 19.655	-1.236 -1.213 - 1.254	-1.903 -1.780 -2.453

The deflection at the two offsets, 1.5 times HP and 1.5 times HP + 450 mm can be determined using the following formula:

$$D_x = \frac{(R_X - R_B)(R_X - R_C)}{(R_A - R_B)(R_A - R_C)} D_A + \frac{(R_X - R_A)(R_X - R_C)}{(R_B - R_A)(R_B - R_C)} D_B + \frac{(R_X - R_A)(R_X - R_B)}{(R_C - R_A)(R_C - R_B)} D_C \qquad \text{(F-1.9)}$$

Where:

D_x : deflection at offset R_x
Di : deflection at sensor i
Ri : offset at sensor i
i : A, B, and C are the three closest sensors to point x
x : point at which the deflection is determined

APPENDIX F-2

NORMALIZING DEFLECTIONS FOR BITUMINOUS LAYER TEMEPRATURE EFECTS

The procedures presented in this appendix are intended to provide a method to adjust deflections for the effect of bituminous layers/ asphalt temperature. The procedures are extracts from the following draft standards developed as part of the Federal Highway Administration (FHWA) Long Term Pavement Performance (LTPP) program's Seasonal Monitoring Program (SMP).

Adjusting deflections for temperature effects includes the following procedures:

- Calculating a representative asphalt temperatures from asphalt layer thickness, surface and air temperature data, and
- Normalizing measured deflections to a reference temperature.

Estimating Asphalt Temperature

The significance of the temperature effect in asphalt layers on deflections varies and depends on asphalt thickness, base type and environmental parameters. Nowadays, algorithms such as the one presented here, can easily be included as part of automated data processing schemes. It is therefore recommended that defections be adjusted for asphalt temperature effects on a routine basis.

To obtain a representative temperature of the asphalt layer, in-depth measurements would be required. Such measurements are, however, time-consuming and especially not feasible for network level applications. Nowadays surface-temperature sensing equipment, such as infrared thermometers, is readily available as handheld devices or fitted to deflectometers. The surface temperature can therefore be measured at every test location. The method presented here provides a means of estimating the temperature at a representative depth in the asphalt layer (usually mid-depth) from surface temperature.

Apparatus

The surface temperature device can be an infrared thermometer, a handheld infrared thermometer mounted on the deflection testing device, or a surface contact thermometer.

Calculation

The BELLS3 Method for Production Testing has been developed for routine testing where temperature measurements on the surface have been shaded for less than a minute.

$$T_d = 0.95 + 0.892 \cdot IR + [\log(d) - 1.25] \cdot [-0.448 \cdot IR + 0.621 \cdot (1-day) + 1.83 \cdot Sin(hr_{18} - 15.5)] + 0.042 \cdot IR \cdot Sin(hr_{18} - 13.5) \qquad \text{(F-2.1)}$$

Where:

T_d	:	pavement temperature at depth d, °C
IR	:	infrared surface temperature, °C
log	:	base 10 logarithm
d	:	depth at which mat temperature is to be predicted, mm
1-day	:	average air temperature the day before testing, °C
Sin	:	sine function on an 18-hr clock system, with 2π radians equal to one 18-hr cycle
hr_{18}	:	time of day on a 24-hr clock system, but calculated using an 18-hr AC temperature rise-and-fall time cycle, as described in the note below.

Notes on handling time:
When using the *sin(hr₁₈–15.5)* (decimal) function, only use times from 11:00 to 05:00 hrs. If the actual time is not within this time range, then calculate the sine as if the time was 11:00 hrs (where the sine = -1). If the time is between midnight and 05:00 hrs, add 24 to the actual (decimal) time. Then calculate as follows: If the time is 13:15, then in decimal form, 13.25-15.50 = -2.25; -2.25/18 = -0.125; -0.125·2 π = -0.785 radians; Sin(-0.785) = -0.707. [Note that an *18-hr* sine function is assumed, with a "flat" negative 1 segment between 05:00 and 11:00]

When using the *sin(hr₁₈–13.5)* (decimal) function, only use times from 9:00 to 03:00 hrs. If the actual time is not within this time range, then calculate the sine as if the time was 09:00 hrs (where the sine = -1). If the time is between midnight and 03:00 hrs, add 24 to the actual (decimal) time. Then calculate as follows: If the time is 15:08, then in decimal form, 15.13-13.50 = 1.63; 1.63/18 = 0.091; 0.091·2 π = 0.569 radians; Sin(0.569) = 0.539. [Note that an *18-hr* sine function is assumed, with a "flat" negative 1 segment between 03:00 and 09:00]

Normalizing Deflections to a Reference Temperature

Once the temperature in the asphalt has been estimated, temperature adjustment factors should be applied to the measured deflections to remove the effects of temperature.

In this approach, deflections are normalized to values that would have been achieved at the same asphalt temperature. Normally, the effect

will only have an effect on the inner sensors. The adjustment factors can easily be assessed to determine the last sensor that would require adjustment.

In South Africa, normalization to a reference temperature of 25 °C is adequate. Relationships between asphalt temperature and deflection bowl parameters have been developed under the LTPP SMP. Parameters relevant to calculate adjustment factors for individual deflections include:

- Delta parameters: Maximum deflection (under load plate) minus deflection at some offset from the load centre.
- Deflection ratios: Maximum deflection divided by the deflection at some offset from the load centre.

The process is divided into the following steps:

- Use the delta parameters to determine the maximum deflection for the representative asphalt temperature(T_{Meas}) and the reference temperature (T_{Ref});
- Determine the deflection ratios at each offset for T_{Ref} and T_{Meas}.
- Determine the deflection at each offset for T_{Ref} and T_{Meas} using the maximum deflection and deflection ratios calculated at the respective temperatures.
- Determine the adjustment factor for the deflection at each sensor.
- Normalize the deflection at each sensor to the reference temperature.

Maximum Deflection

Select the appropriate delta parameter based on the thickness of the asphalt layer:

Layer Thickness	Delta Parameter
H ≤ 100 mm	Delta600 = D0 – D600
100 mm < H ≤ 200 mm	Delta900 = D0 – D900
H >200 mm	Delta1500 = D0 – D1500

Calculate the appropriate delta parameter for T_{Ref} and T_{Meas} using Eq. F-2.2, F-2.3 or F-2.4.

$$\log(Delta600) = 3.30 - 1.32\log(ac) + 0.514\log(\theta)\log(D900) - 0.00622T\log(\theta)\log(D900) + 0.00838T\log(ac)\log(\theta) \quad (F\text{-}2.2)$$

$$\log(Delta900) = 3.05 - 1.13\log(ac) + 0.502\log(\theta)\log(D900) - 0.00487T\log(\theta)\log(D900) + 0.00677T\log(ac)\log(\theta) \quad (F\text{-}2.3)$$

$$\log(Delta1500) = 2.67 - 0.770\log(ac) + 0.650\log(Delta900) + 0.00290T\log(ac) \quad (F\text{-}2.4)$$

Where:

ac	:	total thickness of asphalt, mm
θ	:	Latitude of pavement section
D900	:	deflection (normalized to 40.5 kN) at 915 mm from the centre of the load (μm)
T	:	temperature at mid-depth of asphalt layer, °C
log	:	base 10 logarithm (covert results back to natural values, e.g. result = Y; natural value = 10^Y)

Determine the maximum deflection (D0) for T_{Ref} and T_{Meas} by adding D900 to the delta parameters calculated using Eq. F-2.2, F-2.3, or F-2.4 (converted to natural values) at the respective temperatures.

Deflection Ratios

Calculate the deflection ratios associated with each deflection offset for T_{Ref} and T_{Meas} using Equations F-3.5 through F-3.10:

$$\log(Ratio200) = 0.183 + 0.0118\log(ac)\log(D900) + 0.0098T + 0.0696\log(\theta) - 0.133\log(ac) - 0.00416T\log(D900) \quad (F\text{-}2.5)$$

$$\log(Ratio300) = 0.200 - 0.117\log(ac)\log(D900) + 0.00861T + 0.126\log(\theta)\log(D900) - 0.00183T\log(\theta)\log(D900) \quad (F\text{-}2.6)$$

$$\log(Ratio450) = 0.952 - 0.450\log(ac) - 0.169\log(D900) + 0.327\log(\theta) + 0.00212T\log(ac) \quad (F\text{-}2.7)$$

$$\log(Ratio600) = 1.16 - 0.587\log(ac) - 0.210\log(D900) + 0.481\log(\theta) + 0.00257T\log(ac) \quad (F\text{-}2.8)$$

$$\log(Ratio900) = -0.0912 - 0.367\log(ac)\log(D900) + 0.489\log(D900) + 0.691\log(\theta) + 0.00298T\log(ac) \quad (F\text{-}2.9)$$

$$\log(Ratio1500) = 0.0726 - 0.336\log(ac)\log(D900) + 0.334\log(D900) + 0.872\log(\theta) + 0.00246T\log(ac) \quad (F\text{-}2.10)$$

Since the equations are based on the log transform of the dependent variable, all results need to be converted back in order to natural values, i.e. log(X) = Y, then X = 10^Y

Temperature Adjustment Factors

Calculate the deflections for T_{Ref} and T_{Meas} at each offset, X, as follows:

$$DX = D0/(RatioX) \qquad \textit{(F-2-11)}$$

Where:

DX	:	deflection at offset X
D0	:	maximum deflection calculated from Eq. C2, C3, or C4
RatioX	:	deflection ratio calculated at offset X, calculated from Eq. C5 to C9

The temperature adjustment factor (TAF) to be applied to the deflection measurement at each sensor is:

$$TAF = \frac{DX_{T_{Ref}}}{DX_{T_{Meas}}} \qquad \textit{(F-2.12)}$$