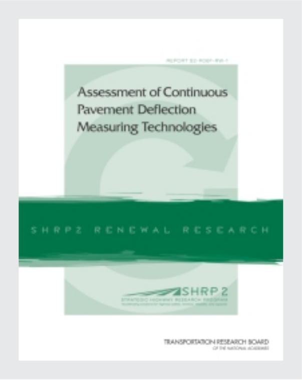

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The Second
STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-R06F-RW-1

Assessment of Continuous Pavement Deflection Measuring Technologies

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FOREWORD

James W. Bryant, Jr., Ph.D., P.E., *SHRP 2 Senior Program Officer*

The measurement of the response of a pavement to an applied load is a critical input for (1) structural analysis of in-service pavements, (2) identification of sections with structural capacity deficiencies at the network level, and (3) design of pavement renewal or rehabilitation treatments at the project level. The most widely used method for measuring pavement response to an applied load is the falling weight deflectometer (FWD), which is a time-consuming technology and may not be practical for a network-level structure monitoring. The use of continuous deflection measuring devices, which operate at speeds of 30 to 45 mph in some cases, allows for better spatial coverage with less impact on traffic. This project evaluated current technologies implemented in continuous deflection measuring devices.

The objective of this project was to critically assess the potential of existing continuous deflection devices to be practical and cost-effective tools for use in the development of optimum pavement rehabilitation strategies on rapid renewal projects. This assessment included (1) the potential value of and demand for continuous deflection data by transportation agencies; (2) the technical capabilities (including accuracy and repeatability of test results and ability to provide meaningful data), limitations (field applications, equipment configuration, and operating and safety characteristics), and other impediments to implementation of existing devices; and (3) suggestions for improvements to currently available technologies.

The main products of the project include a catalogue of existing continuous deflection measuring technologies, detailed assessment of the capabilities of the most-promising devices, case studies illustrating the application of the technology for supporting various pavement management decision-making processes, a fact sheet describing the main technologies identified for continuously measuring pavement deflections and their potential uses, training materials for a workshop on the topic, research needs statements for the most-pressing research identified (provided as an appendix), and a dissemination and implementation plan for this technology.

Technologies for continuous deflection measurement are still evolving. This report provides practical examples of how data from these devices can be used for network-level pavement management applications. As budgetary pressures continue to place a high demand of the effective allocation of resources, the ability to isolate areas for more-detailed and "-costly" pavement assessments will become desirable. The data collected by the devices investigated in this study can help a transportation agency ascertain the areas of pavement that need a detailed condition assessment. Demand for this type of technology will continue to increase. Information provided in this report helps to expand the knowledge base of what this technology can do and provides confidence and examples of how the technology can be used.

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Executive Summary

The measurement of pavement structural capacity is a critical input to perform structural analysis of in-service pavements, identify sections with structural capacity deficiencies at the network level, and design pavement renewal or rehabilitation treatments at the project level. Continuous deflection measuring devices are increasingly being used to support these and other pavement management business processes. These nondestructive pavement evaluation devices can measure pavement deflections caused by a moving load and, in some cases, with little or no traffic control. The ability to measure without disrupting traffic makes them more advantageous to use than stationary devices such as the falling weight deflectometer (FWD). SHRP 2 Renewal Research Project R06F, Assessment of Continuous Pavement Deflection Measuring Technologies, evaluated current technologies implemented in different types of continuous deflection measuring devices, identified the most promising devices for effectively supporting pavement management decisions, evaluated the capabilities of these devices, and identified and illustrated applications that could be useful for supporting pavement management. The main products of the project include a catalogue of existing continuous deflection measuring technologies; detailed assessment of the capabilities of the most promising devices; case studies illustrating the application of the technology for supporting various pavement management decision-making processes; a fact sheet describing the main technologies identified for continuously measuring pavement deflections and their potential uses; training materials for a workshop on the topic; research needs statements for the most pressing research identified, provided as an appendix; and a dissemination and implementation plan for the technology.

The critical performance parameters for the available equipment were assessed by the following research question: Is the technology capable of providing the quality information needed to support the main pavement management business functions identified by potential users? To answer this guiding question, the research team evaluated whether the devices can be used for screening pavements at the network level and thus identify weak (i.e., structurally deficient) sections, or whether the structural response information collected by the devices can be used to differentiate sections that may be good candidates for preservation from those that would likely require more substantial treatment.

For this report, a continuous deflection device is defined as a "constantly moving deflection measuring device that can collect data at intervals of approximately 300 mm (1 ft) or smaller using load levels typical of truck loading (i.e., 40 to 50 kN [9 to 11 kips] per wheel or load assembly)." The project started with a review of literature, case studies, and ongoing research to identify deflection measuring devices that had the potential to meet project requirements and to assess their potential to meet user requirements. Devices that met the definition of a continuous deflection device were the Portancemetre, the moving FWD, the Measuring Ball, the traffic speed deflectometer (TSD), the rolling dynamic deflectometer (RDD), the rolling wheel deflectometer (RWD), the airfield rolling weight deflectometer (ARWD), the road deflection tester (RDT), and the image deflection measurement device (IDM). This list of continuous deflection devices included laser-based devices that measure the deflection below a moving truck load, devices that apply a vibratory load, and one system still in early stages of development that uses image analysis methods to determine pavement deflections under loading.

The demand and potential value of continuous deflection devices for use in developing optimum pavement rehabilitation strategies for rapid renewal projects were evaluated through a survey of state and provincial departments of transportation (DOTs). The survey not only included questions to assess technical needs of the DOTs, but also aimed at determining the value assigned by the agencies to the collected data. The survey showed that by February 2010 the majority of agencies performed at least some deflection testing using the FWD. Most testing was performed to support project-level decisions, and only five agencies had incorporated deflection data into their pavement management system (PMS). Potential users in general agreed that the main advantage of a continuous measuring device (as compared with a stationary device) is to support network-level decisions. The assessment also identified the following parameters as important in the evaluation of equipment: survey speed (safety), repeatability, accuracy (and feasibility of establishing correlations with existing technologies, such as FWD), equipment cost, ease of operation, customer service (availability of service and maintenance), ease of use of the data collected, availability of software for interpretation of results, reliability, size of the vehicle, relevance of the information (e.g., use in the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) and its software package known as DARWin-ME), and past experience. A survey speed close to the speed of traffic was an important desired parameter identified in the survey, even if achieving such a speed resulted in some loss in equipment accuracy. For this purpose, a minimum device survey speed of 55 km/h (35 mph) was set as a critical selection criterion.

While responses to the initial survey suggested that users would like to be able to collect continuous pavement response data to support project-level decisions, follow-up interviews showed that respondents understood the current limitation of the technologies and agreed that network-level applications are the more likely application in the near future. Furthermore, respondents agreed on the need for pavement structural data to support network-level PMS decisions. At the network level, the primary application of the continuous deflection device would be (1) to help identify weak (i.e., structurally deficient) areas that can then be further investigated at the project level, (2) to provide network-level data to calculate a structural health index that can be incorporated into a PMS, and (3) to differentiate sections that may be good candidates for preservation (those that have good structural capacity) from those that would likely require a more substantial treatment (those that show structural deterioration or deficiencies). For the user, the ideal overriding requirement is that network-level data be collected at highway speeds.

A more detailed assessment of the capabilities of candidate devices, based on criteria provided by a survey of potential users, allowed further reduction of the list to two devices, the RWD and the TSD. The rest of the devices were eliminated because they did not apply loads similar to that of a heavy vehicle, they did not meet the survey speed requirement (a key requirement expressed by potential users), or the existing prototypes had been decommissioned or alternatively reassigned to other uses. Both the RWD and TSD devices conduct measurements (deflection or deflection velocity of a loaded pavement, respectively) under a truck axle and at close to highway speeds. The RWD is mounted within a custom-designed semitrailer and measures the response from one-half of an 80-kN (18-kip) single-axle load traveling at normal traffic speeds. It uses a spatially coincident methodology for measuring pavement deflection by comparing undeflected and deflected pavement laser scan profiles. The device can test approximately 320 to 480 lane-km (200 to 300 lane-mi) per day. The TSD is mounted on an articulated truck but uses a rear-axle load of 100 kN (22 kips). The TSD model evaluated uses four Doppler lasers mounted on a height-adjustable rigid beam to record the vertical deflection velocity of a loaded pavement under one of the dual-wheel assemblies. One laser is mounted away from the loaded wheels to measure the unwanted movement of the rigid beam. This movement is then subtracted from the other laser measurements to provide the vertical pavement deflection velocity at each sensor. The deflection velocity is divided by the instantaneous vehicle speed to give a measurement of deflection slope, which is generally expressed in mm/m.

The capability of continuous deflection technology to support network-level pavement management decisions was evaluated through a combination of literature review and data collected in combination with other efforts. The detailed field evaluation included measurements on pavement sections in the United Kingdom on different types of pavements, using various operational conditions, and reference FWD deflection testing equipment where possible. The sites evaluated included flexible, composite, and rigid pavement sections, and all attempts were made to include subsections with good, fair, and poor functional conditions within each of these pavement types. Some sites were measured several times. A similar evaluation was planned for the RWD in the United States, but field verification was not possible because the device had not been available during the second phase of the project.

The analysis of collected data showed that the repeatability of both systems depends on the aggregation length and appears to be appropriate for network-level applications. Except for a few sections with significant surface deterioration, the TSD repeatability was independent of the type of pavement and the value measured, ranging from 0.065 to 0.201 mm/m (mean = 0.089 mm/m) for 10-m averaging, and from 0.022 to 0.114 mm/m (mean = 0.028 mm/m) for 100-m averaging. On the basis of limited data collected in Virginia, repeatability of the RWD was evaluated to be 51.4 µm (2 mils) for 160-m (0.1-mile) averaging. However, it must be noted that the data used for assessing the RWD were collected using a previous version of the equipment. It is likely that recent enhancements made to the device have improved the quality of the measurements.

The direct analysis of the relationship between the TSD and FWD measurements showed that there are two distinct relationships between TSD deflection slope and FWD deflection depending on pavement type (one for flexible and composite pavements and another for rigid pavements). This could be expected, as two different quantities (deflection slope and deflection) are measured by each device. These quantities are affected differently by the pavement type. The comparability of the TSD with FWD was assessed by using two surface indices, the surface curvature index (SCI) and base distress index (BDI), quantities that can be obtained from both devices. In this case, the relationship between the quantities measured with the FWD and those measured with the TSD (measurements averaged over 10 m in length) was the same for all pavement types and reasonably close to the equality line. However, there is a significant variation and bias in this relationship. For example, for an average SCI or BDI value of 300 µm, the bias was 30 µm (FWD values lower than TSD values) and the comparability was 380 µm. The analysis of RWD comparability with FWD (using measurements averaged over a 160-m [0.1-mi] interval) showed, based on limited data from an earlier version of the RWD, that the coefficient of variation (cov) was found to be relatively unchanged as a function of deflection. The relationship showed a bias of 11.6% (FWD deflection lower than RWD deflection) and a repeatability of 64.6% (range of [–43.2%; 21.4%]). FWD results tended to be lower than the results of either TSD or RWD.

The example applications demonstrated that continuous deflection measurement devices can be used to estimate many parameters important to modern pavement management applications. The analysis showed that, at least for the section investigated, the strains at the bottom of the asphalt layer estimated with measurements using the FWD and TSD resulted in an approximately one-to-one relationship. Similarly, the effective structural number (SN) estimated with measurements obtained from TSD testing at two sites broadly matched the expected SN calculated from the layer composition and surface condition.

Within this study it has not been possible to examine in detail the operational characteristics of the equipment being assessed. Although external factors, such as temperature, road geometry, road profile, texture profile, moisture, acceleration, deceleration, and so forth, may have been recorded during the surveys, it was not possible to control these factors. Therefore, it was not easy to assess their effects on the measurements. This report briefly discusses the potential impact of speed, road geometry, texture profile, dynamic loading, acceleration, and deceleration determined on the basis of a limited examination of the data collected. Both devices use laser-based noncontact sensors, which fail to measure correctly when the road is damp or wet. Laser reflection is degraded by water on the surface. Other potential limitations include difficulties in measuring along sharp curves (especially for the RWD), impact of surface texture on measurements, and variations on the load applied because of the vehicle dynamic (response to the road profile, acceleration, and deceleration).

Updated versions of the devices have become available during the final phases of the project. Recent modifications to the RWD have placed the lasers in a temperature-controlled enclosure and have added a sensor to the RWD at a second position further away from the rear axle to provide some information about the deflection bowl shape. The second generation of TSD equipment includes a custom trailer, more sensors (up to seven, enabling the derivation of the full deflection bowl), and a more robust system to measure vehicle speed, which is a vital part of the measurement process. The sensor mounting beam has also been installed on longitudinal rails so that its position can be varied, thus enabling more reliable calibration.

More research is recommended for conducting additional field tests with the latest versions of both the RWD and TSD at the same locations and with different pavement designs, for developing tools for using technology to support network-level pavement management business functions, for assessing the potential for using output from the selected equipment to provide advice on pavement rehabilitation alternatives (e.g., preservation versus renewal), and for verifying the accuracy of testing equipment by conducting measurements on instrumented sections to compare measured parameters with the response of in-situ transducers measuring absolute deflection and strain.

In conclusion, the study performed in this project has demonstrated that at least one continuous deflection measurement device, the TSD, can (1) provide adequate repeatability for network-level data collection, (2) collect deflection measurements and indices that are broadly comparable to those collected by traditional measurement devices such as the FWD, and (3) provide measurements that can be used for supporting some of the most critical network-level applications identified by the potential users. Although information collected in the first phase of the project suggests that the RWD may be able to provide the same type of capabilities, this has not been confirmed because of the unavailability of the equipment for detailed evaluation in the second phase of the project.

However, the technology is only just maturing. Future research would further assess the measurement capabilities of these devices and the usefulness of the collected data. For example, at least one assessed device demonstrated some ability to identify localized structural deterioration, which may indicate a potential for project-level use. Potential enhancements to the devices that may help improve the quality of information obtained from measurements and widen the range of possible applications include (1) providing a more complete deflection bowl shape; (2) enhancing the quality of measurement signals so that local structural deterioration can be reliably identified, that is, down to 1-m (3-ft) features; (3) providing pavement layer thickness measurement capability, for example, by adding ground-penetrating radar equipment; and (4) measuring the dynamic load on the loading-wheel assembly.

CHAPTER 1

Introduction

A growing area of interest in pavement research is the development of technologies that are well suited for nondestructive assessment of the pavement structure without causing delays to the traveling public. These technologies are needed as the nation's highway infrastructure systems continue to age and the determination of appropriate rehabilitation strategies becomes ever more important to network mobility preservation. The measurement of the response of a pavement to an applied load is a critical input for (1) structural analysis of in-service pavements, (2) identification of sections with structural capacity deficiencies at the network level, and (3) design of pavement renewal or rehabilitation treatments at the project level. A recent survey showed that most state departments of transportation (DOTs) routinely use deflection measurements, obtained mainly with falling weight deflectometer (FWD) testing, at the project level and some are also starting to use them at the network level (Figure 1.1).

Although the FWD is a very useful tool for assessing the pavement structural or bearing capacity, and for determining the moduli of the component layers, this technology has the limitation of allowing only stationary measurements at discrete points along the pavement sections. Since the test requires the equipment to remain stationary on the road for a short period of time (typically 1 to 4 minutes depending on the protocol), it disturbs traffic and requires traffic control. This limits productivity and the number of data points at which measurements can be obtained. The use of continuous deflection measuring devices, which in some cases operate at traffic speed, allows for better spatial coverage with less negative impact on mobility. The currently available continuous devices are becoming increasingly popular as practical alternatives to stationary FWD devices, especially for network-level structural monitoring. For example, the traffic speed deflectometer (TSD) is currently being used in four countries in Europe (Greenwood, 2012) and it has recently completed a survey of 18,000 km in Australia (Baltzer et al., 2010).

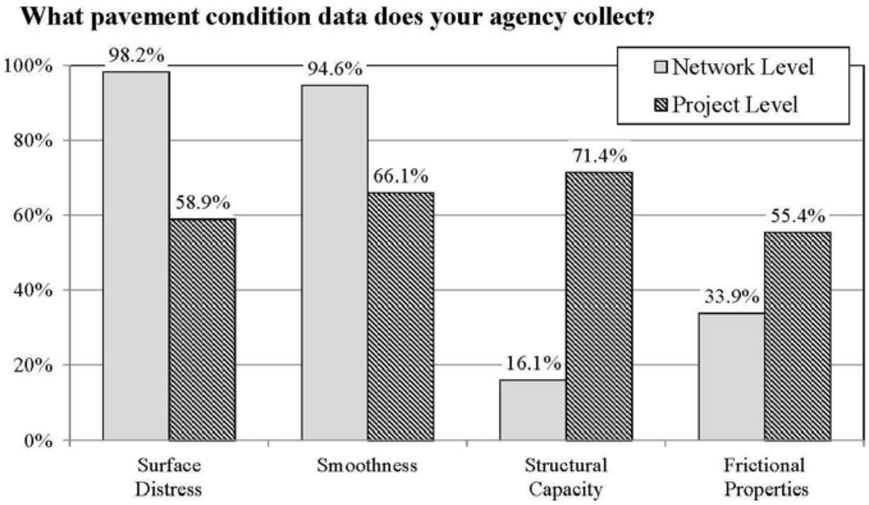
Objective

The objective of the SHRP 2 R06F project was to carry out a critical assessment of (1) the potential of existing continuous deflection devices as practical and cost-effective tools for use in the development of optimum pavement rehabilitation strategies on rapid renewal projects, and (2) the capability of these devices for screening structural deficient sections and scoping their needs at the network level.

To accomplish these two objectives, the research team examined the following: (1) the potential demand by and value to public agencies; (2) the technical capabilities (including repeatability, ability to be compared with FWD test results, ability to provide meaningful data), limitations (field applications, equipment configuration, operating and safety characteristics, costs), and possible impediments to implementation of existing devices; and (3) further development of the technology, including both hardware and software, needed to make these tools practical for use. Potential practical uses of the technology are showcased through example applications.

Critical Research Questions

The critical performance parameters for the available equipment were assessed using a combination of available existing information and data from field trials. The trials were organized in cooperation with existing activities to control costs and avoid duplication of efforts. The evaluation of the equipment was guided by the following research question: Is the technology capable of providing the quality information needed to support the main pavement management business functions identified by the potential users?



Source: Flintsch and McGhee, 2009.

Figure 1.1. Summary of current practices for pavement data collection in North America.

To answer this guiding question the research team evaluated the following:

- Whether the devices can be used for screening pavements at the network level and thus identify weak (i.e., structurally deficient) sections, which could then be further investigated at the project level (e.g., using FWD).
- Whether the structural response information collected by the devices can be used to differentiate sections that might be good candidates for preservation (good structural capacity) from those that would likely require a heavier treatment (showing structural deterioration or deficiencies).

Evaluating the equipment required assessing how accurately and consistently the most promising continuous deflection devices identify the location of structurally weak sections of the road network, whether the measurements can help distinguish between sections with good and poor structural capacity, and whether the measurements of the candidate devices can provide a structural health index, or indices, which can be incorporated into a pavement management system (PMS). The consistency of a device in locating weak sections can be assessed by examining how regularly test sections fall within a threshold range in repeat surveys. The assessment of accuracy of locating weak sections depends on examining the relationship between the continuous deflection measurements and reference structural condition information. Since no direct structural condition information is available, information derived from FWD measurements was taken as a proxy. Other secondary objectives to support the primary focus included evaluating the agreement of the measurements with actual FWD measurements and the devices' repeatability and operational limitations.

Methodology and Report Overview

The report summarizes the results of the two phases of the project; although the project could be considered as part of a three-phase process. The first phase identified two continuous deflection devices based on a literature review and user needs obtained from a survey and from follow-up interviews, and a plan for assessment of the devices was prepared and approved by SHRP 2. The second phase included limited site trials on selected sections of highway. The results of these trials highlighted the capabilities of the technology to meet user needs and identified needed improvement and implementation routes for such equipment. The third phase of this process would require comprehensive evaluation trials of one or more recommended devices, ideally as side-by-side comparisons. These trials were not conducted as part this project but are recommended for a subsequent phase.

The report is organized into four main chapters and an introduction, Chapter 1. Chapter 2 presents the research approach and Chapter 3 the main analysis and findings of the research, including the results of the literature review, the survey of state DOTs, the devices selected for further evaluation, and the analysis of the data collected. Chapter 4 presents example applications of the TSD, new devices that emerged during the analysis phase, and recent developments of the devices evaluated. Chapter 5 summarizes the main findings and conclusions and gives recommendations.

Two important issues addressed in this report are device repeatability and reproducibility. Repeatability is a measure that answers the following question: If two deflection measurements at the same location are obtained from two different runs, in general, how much different will these two measurements be? Repeatability is evaluated as the 95% confidence interval on the difference between two repeated measurements calculated as $1.96\sigma_d$ where σ_d is the standard deviation of the difference between two measurements. Comparability (used instead of reproducibility because we are comparing different technologies) was similarly defined as the 95% interval on the difference between two measurements obtained using two different devices. This definition of repeatability (or comparability) has many advantages over a definition based on calculating the correlation between two measurement series.

CHAPTER 2

Research Approach

This chapter presents the approaches used for the following:

- Identification of the most promising technologies;
- Determination of user needs;
- Selection of candidate devices;
- Data collection, data analysis, and interpretation;
- Development of example applications; and
- Identification of recent developments and possible improvements.

Identification and Assessment of Available Technologies

The project started with a review of literature, case studies, and ongoing research in order to (1) identify the deflection measuring devices that had the potential to meet the project requirements and (2) assess their potential to meet user requirements. The review was completed in two stages. The first stage consisted of an Internet search for relevant papers, performed by searching for related key words such as "continuous deflection device"; the second stage consisted of using the same key words to search the English language International Transport Research Documentation (ITRD) and Compendex databases for any relevant papers stored therein. This was complemented with the extensive personal archives of the members of the research team who have had many years of experience in this research field. Once these searches were completed, the papers and documents were used to compile a list of available survey vehicles capable of measuring pavement deflection, whether at traffic speed or otherwise.

Prescreening of Candidate Devices

The list of survey vehicles was then summarized in a comprehensive table detailing the important aspects of each device (e.g., survey speed, measurement interval, personnel requirements, etc.). After reviewing this table, some devices were disregarded as irrelevant to this project, and an abridged version was produced grouping similar devices (e.g., variations on the deflectograph). Information presented in this table includes equipment type, model, characteristics, survey speed, and development status (whether the device is a current or former production model or a working prototype). The devices were further subcategorized into three groups: static measurement devices, moving measurement vehicles with stationary measurement apparatus, and moving measurement vehicles with nonstationary measurement apparatus.

Definition of Continuous Deflection Device

The purpose of this project was to identify current measurement devices capable of continuously measuring pavement bearing capacity without the need for the vehicle or measurement equipment (relative to the vehicle) to remain stationary while surveying. For this report, a continuous deflection device has been defined as a deflection measuring device constantly moving that can collect data at intervals of approximately 300 mm (1 ft) or smaller using load levels typical of truck loading (i.e., 40 to 50 kN [9 to 11 kips] per wheel or load assembly); the ideal solution would be a device requiring no traffic control. It should be noted that this definition covers the interval at which the data are collected, not reported. The latter is often much greater than the former because of the significant measurement noise level generated during data collection. Averaging over these longer lengths reduces the noise considerably while retaining the important pattern of the road's deflection in response to strength variations.

Determination of User Needs

The demand and the potential value of continuous deflection devices for use in developing optimum pavement rehabilitation strategies for rapid renewal projects were evaluated through a survey of state and provincial DOTs. The survey included questions to assess technical needs and also endeavored to determine the value assigned by the agencies to the collected data.

The survey of state and provincial DOTs was divided into two stages. In the first stage, a web survey was sent to the different DOTs. The survey was divided into five sections based on the type of information requested. The first section collected contact information about the respondents. The second section focused on current practices and uses of deflection testing by DOTs. The third section inquired about pavement rehabilitation design procedures and how, if applicable, deflection testing results are used for this purpose. The fourth section focused on whether and how deflection testing results are used in pavement management applications. The fifth and final section gave respondents the opportunity to provide general comments. In the second stage of the survey, follow-up phone interviews were conducted with nine states where continuous deflection devices have already been used or the states are facing substantial renewal challenges on high-traffic-volume roadways. These states were identified based on the web survey results.

Selection of Candidate Devices

Following the literature review, an assessment of the capabilities of available continuous deflection devices (moving measurement vehicles with nonstationary measurement apparatus), and considering the information obtained during the user needs survey, two devices that offer the most promising technologies to address the needs of end users were chosen for further study. These devices are the rolling wheel deflectometer (RWD) and the traffic speed deflectometer (TSD). Sample data from the two devices were collected and processed as part of the preliminary assessment of their capabilities.

Data Collection

To assess the capability of continuous deflection technology to support network-level pavement management decisions, relatively long sections with uniform and variable structural conditions were selected for site testing. These network-level sites included flexible, composite, and rigid pavement sections. All attempts were made to include subsections with good, fair, and poor functional conditions within each of these pavement types. This enabled the evaluation of the capabilities of the devices for network-level use. Some sections were measured several times in succession in a single day, as discussed in the following sections.

The evaluation included testing on different types of pavements, under various operational conditions, and reference FWD deflection testing equipment where possible. The plan included sections that were evaluated following a protocol applicable for network-level data, and a subset of these sections was subject to a detailed evaluation as discussed in the following sections (illustrated by Figure 2.1). The final experimental design focused mainly on evaluating the capabilities of the general technology of traffic-speed continuous deflection measurements and the application of this technology for supporting pavement management decisions.

From the network-level testing routes, a few carefully selected evaluation sections were also assessed using FWD measurements. The data collected in these locations were used to assess the ability of the systems for detecting weak spots.

TSD Data Collection

To answer the main evaluation question posed earlier (that is, the capability of the devices to support network-level pavement management decisions), researchers assessed the TSD in the United Kingdom by identifying a number of evaluation sections. Each section measured approximately 2 to 4 km (1.25 to 2.5 mi) in length and generally incorporated weak subsections; researchers conducted repeat TSD surveys of these sections, as well as FWD surveys on most sections, at spacing of up to 20 m (60 ft). The accuracy and consistency with which the TSD identifies any strong and weak sections was also evaluated. Sites were chosen by examining the construction and structural condition of a significant sample of the English road network. These evaluation sections covered a variety of structural designs and ages. In general, road sections were selected to cover a range of structural conditions as shown by the deflection response.

Table 2.1 lists these sites and a summary of the key parameters of each site. The nominal deflection responses are equivalent peak central FWD deflections at a load of 50 kN (11 kips). The table includes the following:

- Flexible sites, where the main structural layers are of asphalt or granular construction and can be broadly classified as fully flexible (i.e., with asphalt upper layers and granular lower layers);
- Composite sites, where asphalt and cement-bound layers are both structural layers (i.e., with asphalt upper layers, usually greater than 150 mm [6 in.] thick, hydraulically bound base layers without joints, usually termed “lean concrete” in the United Kingdom); and
- Rigid sites, with pavement quality concrete as the primary load-bearing layer, sometimes with asphalt upper surfacing layers, less than 75 mm (3 in.) thick.

Some of these sites, at least two from each pavement type, were each surveyed repeatedly during the course of one day. Comparisons with FWD measurements were made on three of the flexible sites, one of the composite sites, and two of the rigid sites.

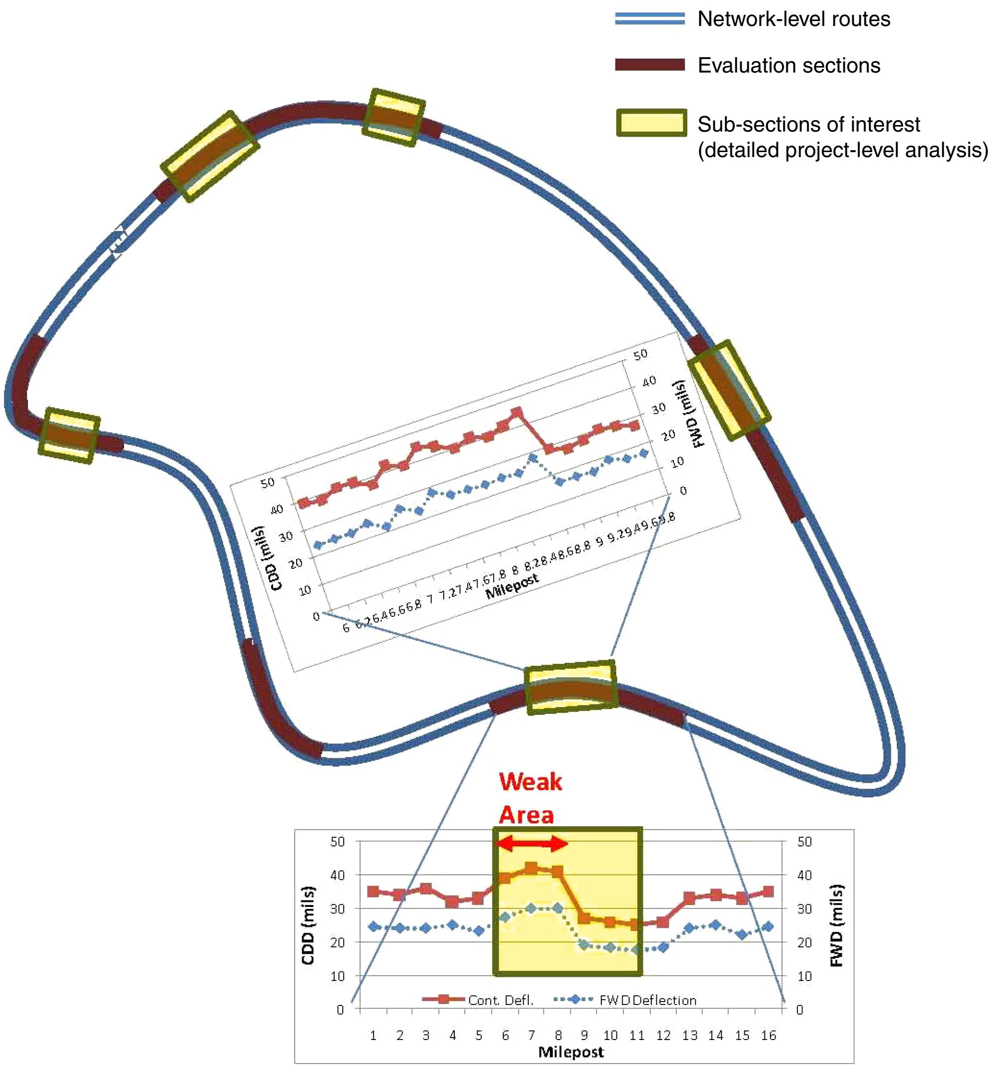


Figure 2.1. Schematic of the section selection.

Table 2.1. Summary of Potential Network-Level TSD Sites

Site	Length mi (km)	Asphalt Thickness in. (mm)	Cement Bound Thickness in. (mm)	Nominal Deflection Response mils (mm)	Structural Variability	Site Use
Flexible						
UK_F1	1.25 (2.0)	3 (75)	NA	8–32 (0.2–0.8)	Very high	R and C
UK_F3	2.0 (3.2)	10.5 (270)	NA	4–8 (0.1–0.2)	Low	R and C
UK_F5	2.0 (3.2)	12 (310)	NA	4–10 (0.1–0.25)	High	R and C
UK_F6	2.2 (3.5)	12.6 (320)	NA	4–12 (0.1–0.3)	Low	R
Composite						
UK_C1	2.5 (4.0)	7 (175)	7 (175)	2–14 (0.05–0.35)	High	R
UK_C2	2.1 (3.4)	6.25 (160)	8.25 (210)	2–8 (0.05–0.2)	Low	R
UK_C3	1.3 (2.1)	6.25–11.5 (160–290)	6–14.2 (150–360)	2–14 (0.05–0.35)	High	R and C
Rigid						
UK_R2	0.9 (1.4)	4 (100)	8 (200)	8–80 (0.2–2.0)	High	R and C
UK_R3	1.9 (3.0)	3 (70)	9 (225)	NA	Low	R and C

Note: R = repeatability assessment; C = comparison with FWD measurements for comparability assessment; and NA = not available.

RWD Data Collection

The original plan included the collection of RWD data following a protocol similar to the one used for the TSD. The data analyzed in Phase I of the project were collected with an older version of the device; this allowed only a preliminary assessment of the device's capabilities. The device has since been upgraded, by modifying the lasers ensemble and truck suspension, and was expected to perform better than it had in the various applications reported in the literature. However, the upgraded device had some problems and was not fully operational during the second phase of the project. Thus, the planned tests were not possible within the time frame available and only data collected in the first phase of the project were used for the preliminary assessment of the capabilities of the RWD. Data from only two routes, one in Virginia and one in New Mexico, were used for assessing the repeatability and comparability of the RWD, respectively. The equipment operator, Applied Research Associates (ARA), in cooperation with the Federal Highway Administration (FHWA), is working to correct the problems. Once they have been corrected, FHWA plans to support additional field testing.

Data Analysis

Results from previous testing were analyzed in Phase I of the project. This preliminary analysis was performed using common methods such as correlation and regression analysis. These methods provide a quick analysis; they do not allow for accurate evaluation of equipment capabilities. For Phase II of the project, the data analysis was expanded to allow for accurate evaluation of repeatability and comparability. The collected data were analyzed to evaluate the repeatability of the TSD and RWD and the comparability of both devices by comparison with the FWD. Results of different studies that evaluated the RWD (conducted in the United States) and the TSD (conducted in Europe) were analyzed. It was noted in this analysis that repeatability and reproducibility were not uniformly defined across all those studies. Measures and methodologies used to evaluate the devices included correlation, regression analysis, standard deviation, and in some cases subjective visual inspection of plots. The drawbacks associated with the use of correlation and regression analysis to evaluate repeatability and comparability are discussed in this chapter. Then, repeatability and comparability analysis based on the limits of agreement (LOA) method suggested by Bland and Altman (1986) is recommended and used to evaluate the continuous deflection devices. A method of evaluating repeatability from one run is presented and compared to the method based on the LOA. Finally, the use of smoothing splines as a tool to remove the noise from TSD deflection slope measurements is investigated. This smoothing splines denoising methodology shows potential to improve the frequency at which useful information can be obtained (i.e., data averaging distance). In this report, repeatability (or comparability) is defined as the 95% confidence interval of the difference between repeated measurements (difference between measurements of TSD and FWD or RWD and FWD).

Example Applications

Based on the data collected and the analysis, a number of example applications for the data produced by the devices have been developed and are presented in Chapter 4. These applications illustrate the use of continuous deflection measurements for network-level pavement management. They are not meant to be comprehensive, but rather show how deflections can be used to address a number of issues applicable to modern pavement management practices.

The applications presented include using measurements obtained from continuous deflection measurement devices to do the following:

- Segment pavement sections into homogeneous sections;
- Estimate the strain at the bottom of the asphalt layer and the effective structural number (SN) of the pavement; and
- Identify relatively weak pavement sections as well as weak pavement sections defined by absolute thresholds.

The segmentation was performed using a statistically based binary segmentation algorithm. The strain at the bottom of the asphalt layer and the effective structural number were estimated using the difference between two deflection slope measurements from the TSD. The identification of relatively weak pavement sections was used to demonstrate the ability of the device to locate anomalies or locally weak sections within a network, whereas the identification of weak pavement sections based on thresholds demonstrated the ability of the device to repeatedly identify weak sections.

Current and Future Developments

Since Phase I of this study was completed, the research team has discovered one additional device that might meet the original requirements of this study. However, as this information was discovered since the commencement of the study, it has not been included in the data acquisition and comparison Phase II of the project. Furthermore, both the RWD and the TSD have been developed further since Phase I was completed. A description of these developments is presented in Chapter 4, along with recommendations for further improvement.

CHAPTER 3

Analysis and Findings

This chapter summarizes the results of the literature review, survey of practice, and selection of the most promising technologies. It also provides a comprehensive assessment of these technologies, including repeatability, comparability, and operational characteristics.

Catalogue of Deflection Measuring Devices

Using this definition, several devices can be removed from consideration. Static impulse loading devices (e.g., FWD variations and Dynaplaque) are capable of sample intervals of less than 300 mm (1 ft) but must be stationary to record measurements. The FWD was thus removed from consideration as a continuous measurement device, but it is used as a reference device for field testing for the continuous deflection devices. Plate loading devices, certain rolling wheel load devices (Benkelman beam, Dehlen curvature meter), vibrating load devices (e.g., Dynaflect), and the Flexigraphe laser were also omitted from consideration. The devices considered are listed in Table 3.1.

There are also several devices that, although the vehicle is nonstationary while testing, keep the measurement equipment stationary while sampling. Because this does not coincide with the definition of continuous used for this report, these devices were also omitted from further investigation. These include the traveling deflectometer (6 to 11 m [20 to 36 ft] spacing), Deflectograph variations (3 to 10 m [10 to 33 ft] spacing), and the Curviametre (5 m [16 ft] spacing). These devices are listed in Table 3.2.

Devices that met the definition of a continuous deflection device were the Portancemetre, the moving FWD, the Measuring Ball, the traffic speed deflectometer (TSD), the rolling dynamic deflectometer (RDD), the rolling wheel deflectometer (RWD), the airfield rolling weight deflectometer (ARWD), the road deflection tester (RDT), and the image deflection measurement (IDM) device. These are presented in Table 3.3.

Among the devices listed in Table 3.3, the TSD, RWD, RDT, ARWD, RDD, and IDM can apply loads similar to that of a truck, but only the first three are capable of surveying without the need for traffic control (each capable of surveying at 70 km/h [45 mph] or faster). The Portancemetre, the Measuring Ball, and the RDD operate at walking pace and are based on a vibrating wheel whose acceleration is doubly integrated to produce deflections. The TSD, RWD, RDT, and ARWD use laser measurements to determine the pavement deflection or deflection slope. Finally, the IDM, which uses image analysis methods to determine pavement deflections under loading, is still in the early stages of development. Descriptions of each device are presented below.

Overview of the Most Promising Devices

Portancemetre

The Portancemetre continuously measures the bearing capacity of a road. A 10-kN (2.2-kips) test wheel is mounted on a specific trailer using a retractable axle (Figure 3.1). A system comprising a hydraulically unbalanced mass makes the wheel vibrate at a 35 Hz frequency providing an additional 6 kN (1.3 kips) loading. The instrumentation allows the measurement of the vertical acceleration components of the vibrating and suspended masses. Double integration of the vertical acceleration signal determines the vertical load applied to the ground and the corresponding deflection. This method allows the measurement of the rigidity of the structure. Since the vibrating wheel is pulled at a slow speed (3 to 4 km/h [2 to 2.5 mph]), measurements are taken every 30 mm (1.2 in.), and peak deflection is normally reported at 1-m (3.3-ft) intervals.

Measuring Ball and Moving FWD

The Measuring Ball is a vibrating steel wheel mounted in a two-wheel, one-axle trailer towed by a car at about 5 km/h

Table 3.1. Static Measurement Devices

Generic Name	Equipment Type	Model	Equipment Characteristics	Nominal Load Speed While Testing (km/h)	Status as of 2010
Impulse loading device	Falling weight deflectometer	Falling weight deflectometer	Automated impulse load	0	Production model
		Heavy weight deflectometer (HWD)		0	Production model
		Light weight deflectometer (LWD)		0	Production model
		Loadman LWD		0	Production model
		Dynaplaque	Impulse generator developed by LCPC for foundation assessment	0	Production model
Rolling wheel load	na	Benkelman beam		0	Production model
		Dehlen curvature meter	a.k.a. South African curvature meter	0	Production model
Plate load test	Plate load test	NA	Static load applied by circular plate; primarily for foundation assessment	0	Production model
	The Thumper	NA	Plate test affixed to van	0	Production model
Vibrating load device	Dynaflect	Dynaflect	Oscillating load applied through steel wheels	0	Production model
		Schwinger	Swiss version of Dynaflect	0	Production model
		Road Rater	Similar to Dynaflect but higher loading	0	Production model
Laser-based device	Flexigraphe laser	NA	Laser and photocell	0	Production model

Note: na = not applicable; NA = not available.

Table 3.2. Moving Measurement Vehicles with Stationary Measurement Apparatus

Generic Name	Equipment Type	Model	Equipment Characteristics	Nominal Load Speed While Testing (km/h)	Status as of 2010
Rolling wheel load	na	Traveling deflectometer	California vehicle with 2 Benkelman beams attached	1–1.5	Former production model
	Deflectograph	Deflectograph (original model)	Automated Benkelman beams developed by LCPC, France	2.4	Production model
		Double-beam deflectograph	LaCroix deflectograph developed for use on rigid pavements with both beam arms on same side	2.4	Production model
		Pavement deflection data logging machine (PDDL)	U.K. version of LaCroix deflectograph	2.5	Production model
		Deflecto	Variation on LaCroix deflectograph	3.5	Production model
		PASE (pavement strength evaluator)	Australian version of LaCroix deflectograph	4	Production model
		Deflectolab	Australian version of LaCroix deflectograph	5	Production model
		Flash	Updated, faster LaCroix deflectograph by LCPC	3–10	Production model
	na	Curviametre	Geophones mounted on chain stationary on pavement measuring vertical deflection	18	Production model

Note: na = not applicable.

Table 3.3. Moving Measurement Vehicles with Nonstationary Measurement Apparatus

Generic Name	Equipment Type	Model	Equipment Characteristics	Nominal Load Speed While Testing (km/h)	Status as of 2010
Vibrating mass loading	na	Portancemetre	Vertical accelerations measured from steel wheel vibrations developed by LCPC, France	3.6	Production model
		Moving FWD	Developed by KUAB, Sweden	30	Early prototype
		Measuring Ball	Similar to Portancemetre	5	Early prototype
		Rolling dynamic deflectometer	Vibrating load applied through coated steel wheels developed in Texas	5	Prototype
Rolling wheel load	na	Airfield rolling weight deflectometer	Loaded and unloaded longitudinal profiles measured by lasers; developed by QuestUSA for U.S. Air Force	35	Decommissioned prototype
	na	Road deflection tester	Loaded and unloaded transverse profiles measured by lasers; developed by VTI, Sweden	70	Prototype
	na	Rolling wheel deflectometer	Loaded and unloaded longitudinal profiles; developed by ARA for FHWA	Up to 80	Prototype
	na	Traffic speed deflectometer	Doppler laser sensors measuring vertical pavement velocity; developed by Greenwood, Denmark	60–80	Prototype
Image deflection measurement	na	IDM device	Developed by LCPC, France, using structured light pattern; tested in laboratory and statically on test track	4	Early prototype

Note: na = not applicable.

(3 mph). The vertical vibration of the wheel is measured by means of an accelerometer mounted at the wheel hub. The measurement principle is based on the idea that the stiffness of the ground will cause an acceleration at the wheel. The acceleration is processed in a computer housed in the towing vehicle, and the relationship between the highest acceleration peak and the resulting sinusoidal acceleration signal is calculated. The result is a measure of the relative stiffness of the ground and is expressed in terms of a scale from 0 to 150. The peak load generated by the vibration is not known but is likely to be significantly less than a typical heavy vehicle wheel load.

Figure 3.1. The Portancemetre.

Through private correspondence it has been found that a device was developed by KUAB of Sweden. This device was referred to as a moving FWD and measured, without stopping, one test point every 15 m (50 ft) at 30 km/h (19 mph). The device did not measure with the same quality as an FWD, but more like a deflectograph or Benkelman beam. It was not developed further into a commercial model because it was not as accurate as the FWD, and it no longer exists.

Rolling Dynamic Deflectometer

The RDD is a heavy truck weighing about 200 kN (45 kips) that surveys at 4.8 km/h (3 mph). It carries a servo-hydraulic vibrator capable of producing dynamic loads up to 310 kN (70 kips) in the frequency range of 5 to 100 Hz superimposed on a static load that can be selected within the range of 65 to 180 kN (15 to 40 kips). The load is transmitted to the road using two sets of dual wheels mounted side by side on separate axles with a spacing of 1,180 mm (4 ft) between them, meaning they are rolling inside of the road wheels of the truck (Figure 3.2). Deflections are measured by means of accelerometers mounted between further sets of dual wheels rolling between the loaded wheel sets and isolated from the dynamic system. The deflections are obtained by the double integration of the acceleration signal. Using an accelerometer, however, means that only deflections caused by the dynamic load variations can be detected.

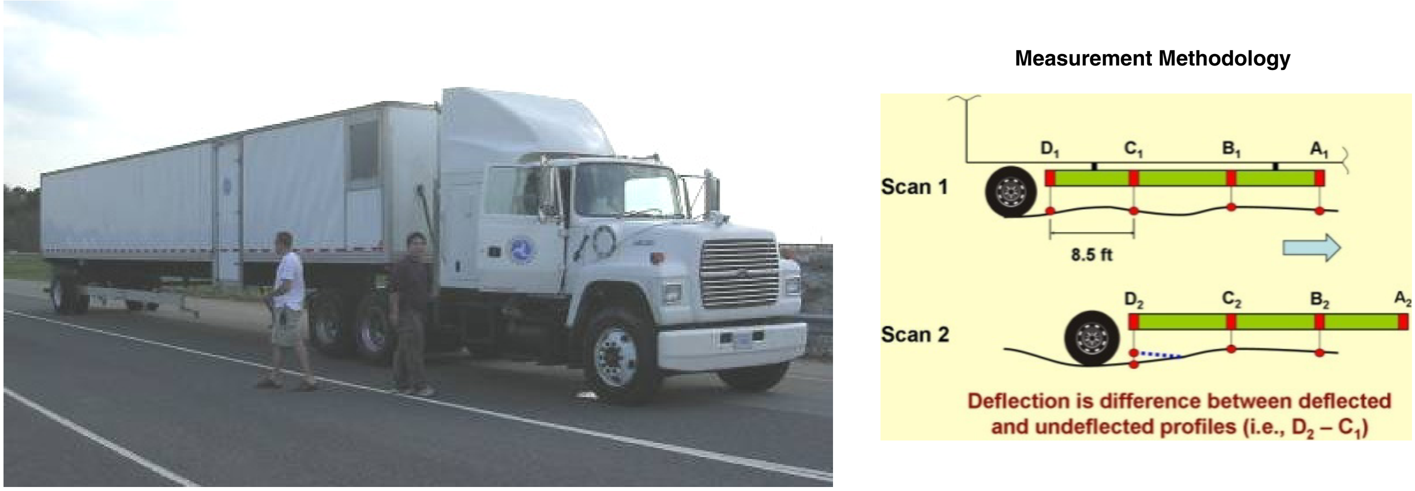
Source: Arora et al., 2006.

Figure 3.2. Rolling dynamic deflectometer.

Traffic Speed Deflectometer

The TSD (Figure 3.3) is an articulated truck with a rear axle load of 100 kN (22 kips), which, in the model evaluated, uses four Doppler lasers mounted on a servo-hydraulic beam to record the deflection velocity of a loaded pavement. Three Doppler lasers are positioned such that they measure deflection velocity at a range of distances in front of the rear axle: 100, 200, and 300 mm (4, 8, and 12 in.); and 100, 300, and 750 mm (4, 12, and 30 in.) in the two present prototypes. The fourth sensor, acting as a reference laser, is positioned 3.6 m (12 ft) in front of the rear axle largely outside the deflection bowl. The beam on which the lasers are mounted moves up and down in opposition to the movement of the trailer in order to keep the lasers at constant height from the pavement surface. To prevent thermal distortion of the steel measurement beam, a climate control system maintains the trailer temperature at a constant 20°C (68°F). Data is recorded at a survey speed of 70 km/h (45 mph) at a rate of 1000 Hz, that is, a 20-mm (0.8-in.) spacing of the raw measurements. These results are usually reported as averaged over 10 m (33 ft).

Figure 3.3. Two TSD devices at the Transport Research Laboratory (TRL) test track and a computer-generated schematic.



Source: FHWA, 2009.

Figure 3.4. Rolling wheel deflectometer and its measurement principle.

Rolling Wheel Deflectometer

The RWD (Figure 3.4) is based on the spatially coincident method for measuring pavement deflections. Three lasers located in front of the dual tires (away from the applied load and, therefore, deflection bowl) are used to measure the unloaded pavement surface, and a fourth laser (additional lasers have been added in a newer version, as discussed later in the report) located between the dual tires and just behind the rear axle measures the deflected pavement surface. Deflection is calculated by comparing "spatially coincident" scans as the RWD moves forward. The RWD applies a 40-kN (9-kips) load through 2 wheels spaced 330 mm (13 in.) apart and surveys at speeds up to 80 km/h (50 mph). The deflection profile is obtained by subtracting the profile of the deflected shape from that of the undeflected shape measured in the same location. The RWD surveys with a 2 kHz sampling rate, that is, every 11 mm (0.5 in.) at 80 km/h, and averages the deflection values over longer sections, typically 160 m (0.1 mi), to produce a single deflection measurement.

Airfield Rolling Weight Deflectometer

The ARWD was designed to measure runway deflections under a wheel load of 40 kN (9 kips) moving at a speed of 35 km/h (20 mph). The ARWD was developed by Quest Integrated, Inc. in the 1990s for the U.S. Air Force. The equipment was updated in the mid 2000s with the help of Dynatest after the equipment was transferred to the U.S. Army for repair. The equipment was decommissioned in 2010 by the Air Force after failed attempts to repair the system. The sensors were returned to Quest.

The device uses four sensors to estimate the deflection due to an applied wheel load. The ARWD places one sensor near the load wheel and three sensors ahead of it in line with the first sensor and beyond the deflection bowl (Figure 3.5).

Distances to the pavement surface are measured by the first three sensors and then again by the second, third, and fourth sensors. The measurements are timed so that they are spatially coincident. The sensors are placed 2.74 m (9 ft) apart based on the idea that the deflection bowl in most pavements at highway speeds is generally less than 2.74 m (9 ft) in radius. This implies that the beam in which the sensors are mounted must be greater than 8.22 m (27 ft) long. However, the deflections of the beam tend to cause significant errors, which are magnified in computations. To overcome these limitations, the ARWD uses a laser beam that is

Figure 3.5. Airfield rolling weight deflectometer.

passed inside the physical beam as a reference to measure the deflection of the physical beam and makes corrections for this deflection in the computations. This process overcomes the problem of thermal expansion and vibrational bending of the beam.

Road Deflection Tester

The RDT (Figure 3.6) consists of a truck that has been retrofitted with two arrays of laser range finders, each consisting of 20 sensors arranged in a line transverse to the direction of travel. The first array is positioned 2.5 m (8 ft) behind the front wheels, and the second array is placed 0.5 m (1.6 ft) behind the rear wheels. Thus, the distance between the two arrays is approximately 4 m (13 ft). The first array measures the transverse deflection profile largely outside of the deflection basin; the second measures the deflection profile near the center of the deflection basin. The truck has two weights of 4 kN (1 kip), which can be moved back and forth. During testing, these weights are moved to the rear of the truck. The weights are moved back to the front of the truck during transportation for better weight distribution. The engine of the truck is also placed in the rear, and together with the weights it can produce a force of 40 to 70 kN (9 to 15.7 kips) on the rear axle. The sampling hardware operates at a sampling frequency of 1 kHz, and at a speed of 70 km/h (45 mph). Samples are stored every 20 mm (0.8 in.), but are normally reported at 50-m (165-ft) intervals.

Image-Based Deflection Measurement Device

This equipment has been recently developed by the LCPC Nantes and LRPC Strasbourg in France using the projection of a structured pattern on the road surface. A camera captures the surface; and software analyzes the pattern deformation, thereby measuring the pavement deflection. The technique has been checked in the laboratory, in static tests, and with a load moving at 4 km/h (2.5 mph). The latter tests were carried out on the LCPC circular accelerated loading facility at Nantes (Figure 3.7). Development is ongoing to turn this device into a robust operational measurement tool.

Summary of Promising Devices

Several continuous deflection devices exist that can measure when constantly moving and can collect data at intervals of approximately 300 mm (1 ft) or smaller using load levels typical of truck loading (i.e., 40 to 50 kN [9 to 11 kips] per wheel or load assembly). These include the following three main types of devices:

- Laser-based devices that measure the deflection below a moving truck load—including the TSD, RWD, RDT, and ARWD;
- Devices that apply a vibratory load—including the Portancemetre, the Measuring Ball, and the RDD; and
- The IDM device, which uses image analysis methods to determine pavement deflections under loading; this represents a very promising technology, but it is still in the early stages of development.

Only the devices in the first group are currently capable of surveying without the need for traffic control. The vibratory devices operate at walking pace, and the IDM was still being tested in a stationary mode at the time of the evaluation.

Figure 3.6. Swedish road tester.

Figure 3.7. IDM prototype being tested at LCPC's pavement accelerated load facility.

Survey of State DOT Practices and Needs

The demand and the potential value of continuous deflection devices were evaluated through a survey of state and provincial DOTs. The two-stage survey included questions to assess technical needs and also aimed to determine the value assigned by the agencies to the collected data.

Stage I: Web Survey

For the web survey, a list of potential participants provided by National Cooperative Highway Research Program (NCHRP) for a similar project was complemented with personal contact from the project team. The final list comprised 63 potential participants. A commercial web-based survey application, SurveyMonkey, was used. The web survey link was sent to 56 of the potential participants because seven had the survey service blocked. Of the 56 recipients, 44 completed the survey, resulting in a response rate of 79%.

Practices and Uses of Deflection Testing

Thirty-five of the survey respondents (84%) replied their agency uses pavement deflection testing. As presented in Table 3.4, most deflection testing is performed exclusively in-house (77%), while only 9% of deflection testing is exclusively outsourced. A number of agencies (five, or 14%) rely on both in-house collection and outsourcing. The main uses of the deflection testing are as follows:

- To determine the subgrade modulus or bearing capacity (97%) for flexible pavements; and
- To evaluate the joint/crack transfer efficiency (59%) for rigid pavements.

Deflection testing is performed mainly at the project level, but several agencies indicated that they are also doing so at the network level. All respondents use static deflection testing devices (FWD), which probably explains why more testing is performed at the project level rather than at the network level. These results are consistent with those reported by Flintsch and McGhee (2009). The average spacing between FWD tests is 133 m (437 ft) and 396 m (1,297 ft) for project and network level, respectively (Table 3.5).

Table 3.4. Summary of Responses to Question: How Does Your Agency Currently Collect Pavement Deflection Data (Please Check All that Apply)?

Answer Option	Response Percentage	Response Count
In-house collection	77.1%	27
Outsourced	8.6%	3
Both	14.3%	5

Note: This question was answered by 35 respondents and skipped by nine.

Table 3.5. Summary of Responses to Question: If Your Agency Routinely Uses Deflection Testing, Please Indicate an Estimate of the Typical Testing Spacing in Feet

Answer Option	Response Average	Response Count
Project (ft)	437	24
Network (ft)	1,297	14

Note: This question was answered by 25 respondents and skipped by 19.

A number of respondents suggested it would be very valuable to them to have a continuous deflection device, most importantly for network-level data collection. The main desired uses for the continuous device would be to do the following:

- Determine subgrade modulus (65%);
- Calculate overlay thickness (65%); and
- Select the most appropriate type of rehabilitation (50%).

The main concerns for the adoption of a continuous deflection device, voiced by the respondents, were safety, accuracy, and cost and savings. The average costs reported for project- and network-level deflection measurements were variable ($28 to $3,000 and $10 to $790, respectively). These numbers were primarily based on best estimates, with some respondents reporting typical agency values. The average current cost for network-level data collection was estimated to be around $100/km ($167/mi), based almost exclusively on rough estimates.

Pavement Rehabilitation Design Applications

Whether rehabilitation design procedures are based on empirical or mechanistic–empirical (ME) methods, deflection measurements data can provide valuable information. This is supported by the survey responses, which indicate that 85% (29 out of 34 respondents; 10 respondents skipped the question) of agencies incorporate deflection testing into their pavement rehabilitation design procedure. The main uses of deflection measurements to support their pavement rehabilitation design procedures include subgrade modulus determination and overlay thickness determination

Table 3.6. Summary of Responses to Question: What Are the Key Engineering Parameters that You Would Wish to Derive from Deflection Testing?

Key Engineering Parameter	Number of Respondents	Percentage	Breakdown by Pavement Type			
			Flexible	Composite	JCP	CRCP
Subgrade bearing capacity	**31**	**86%**	31	16	14	6
Deflection values	**26**	**72%**	26	14	12	5
Layer moduli	**25**	**69%**	25	12	8	3
Joint/crack transfer efficiency	19	53%	2	8	19	4
In-service structural number	18	50%	18	10	6	2
Deflection basin area	18	50%	17	7	7	1
Pavement remaining service life	14	39%	14	10	8	4
Depth to bedrock	6	17%	6	3	2	1

Note: JCP = jointed concrete pavement; CRCP = continuously reinforced concrete pavement.

(65% of responses each), followed by determination of type of pavement rehabilitation (50% of responses). In most cases (91% of responses), agencies use deflection testing results to determine multiple parameters (two or more).

Most of the respondent agencies still rely on an empirical pavement design methodology, mainly the AASHTO 1993 methodology or some modification of it (26 of 34 respondents or 76%). Although several agencies (16 out of 34 respondents or 47%) also use mechanistic–empirical design methods, only four agencies (12%) were exclusively using an ME design procedure.

Table 3.6 summarizes the main engineering parameters that survey respondents would like to derive from the deflection measurements. Flexible pavements' subgrade structural bearing capacity was the most frequently mentioned parameter, followed by deflection values and layer moduli (in bold).

Pavement Management Applications

Perhaps the primary benefit from a continuous deflection measuring device is its ability to provide an overall assessment of the structural condition of the pavement network. Deflection test results can be incorporated into an agency's pavement management system (PMS) to support maintenance and rehabilitation strategy scoping and resource allocation decisions, among other asset management business functions. Although most of the respondent agencies (93%) have implemented a PMS, only five incorporate the results of deflection testing into their PMS. The dollar amount that agencies are willing to pay to obtain continuous deflection is in the same range as the amount they currently pay for FWD measurements, around \$6 to \$125/km (\$10 to \$200/mi).

Stage II: Follow-Up Interviews

Using results of the survey, the research team identified a subset of states to interview. A more detailed questionnaire was prepared, and interviews were conducted over the phone with the following nine state DOTs: Arizona, Florida, Indiana, Kansas, Montana, New Hampshire, New Mexico, Oregon, and Virginia. This list includes states that use network-level deflection testing in their PMS (Arizona, Florida, Indiana, Kansas, and Virginia), as well as states that have some experience with a continuous deflection device, mainly the RWD (Indiana, Kansas, New Hampshire, Oregon, and Virginia). Questions were divided into three categories: (1) desired capabilities and applications of a continuous measuring device, (2) use of deflection data within the PMS, and (3) experience with the RWD.

Desired Uses and Capabilities

The responses indicate that most respondents envision using a continuous deflection device for network-level data collection. Within this framework, speed is perceived as the most critical characteristic even if it means sacrificing some accuracy, as long as results are comparable to static deflection measurements, such as with the FWD. However, a few respondents indicated a desire to obtain a deflection basin, area parameter, or some other parameter that can be used to assess the structural capacity of the various pavement layers or detect hidden problems (e.g., stripping) in some of the undersurface layers. Ground-penetrating radar (GPR) to determine layer thicknesses was reported as a desired feature that could be easily added to the system. Other desirable characteristics, which would facilitate the adoption of the technology, include: (1) ease of operation, (2) availability of fast data processing software and service support, and

(3) data format compatibility with the current agency database structures.

The primary application of the continuous deflection device at the network level would be to do the following:

- Help identify "weak" (i.e., structurally deficient) areas that can then be investigated further at the project level;
- Provide network-level data to calculate a "structural health index" that can be incorporated into a PMS; and
- Differentiate sections that may be good candidates for preservation (good structural capacity) from those that would likely require a heavier treatment (showing structural deficiencies).

A desired application at the project level would be to provide input for rehabilitation pavement design (e.g., input to the *Mechanistic–Empirical Pavement Design Guide* (MEPDG)/DARWin-ME or other overlay thickness design method). Other desired applications mentioned include determination of long-term trend in structural capacity, overall evaluation of bounded layers (e.g., detecting stripping), and calculation of remaining service life.

Important parameters that users indicated should be considered in evaluation of the equipment include speed (safety), repeatability, accuracy (and feasibility of establishing correlations with existing technologies, such as the FWD), equipment cost, ease of operation, customer service (availability of service and maintenance), ease of use of the data collected, availability of software for interpretation of results, reliability, size of the vehicle, relevance of the information (e.g., use in MEPDG/DARWin-ME), and past experience.

Current PMS Uses

The parameters that have been used by DOTs that currently use FWD data in a PMS include the effective structural number (SN) and layer moduli for flexible pavements, and AREA and k-value for rigid pavements (Virginia). Results of deflection testing have also been used to compute a structural index (Indiana) and as part of a decision tree for project scoping (Indiana and Virginia), as well as for pavement overlay design and pavement deterioration monitoring (Virginia). The Kansas DOT uses the FWD's center and last deflections to make remaining-life calculations.

Some reasons cited for not incorporating results of deflection testing into the PMS include cost associated with data collection, technical issues such as software and programming, and organizational issues related the agency's structure (i.e., one division does the data collection and another runs the PMS; planning division versus maintenance division).

Experience with Existing Continuous Deflection Measuring Equipment

A number of interviewed state DOTs (Indiana, Kansas, New Hampshire, Oregon, and Virginia) have had some experience with the RWD, mostly through FHWA-sponsored demonstration projects. In general, the representatives found RWD test results to be repeatable, successful in identifying problem areas, and generally well correlated with FWD test results (except in the case of Virginia). The main data collected included maximum deflections every 0.1 mi (temperature corrected) and location, along with speed in some cases. Some reports provided by state DOT representatives also included repeated test and correlations with the FWD; these are discussed in detail in the following sections.

In addition to the demonstration projects, the Kansas DOT independently contracted measurements on one segment of a four-lane rural interstate highway, I-70. Testing was conducted as a screening tool to detect potential hidden problems along the highway corridor. Although no surprises were found, the assessment was that the equipment performed well.

Summary of User Needs

The majority of agencies perform at least some deflection testing using the FWD. Most testing is performed to support project-level decisions, and only a small number of agencies (five) have incorporated deflection data into their PMS. Potential users in general agree that the main advantage of a continuous measuring device would be for supporting network-level decisions. The assessment of user needs suggests the following:

- Important parameters that users indicate should be considered in the evaluation of the equipment include: speed (safety), repeatability, accuracy (and feasibility of establishing correlations with existing technologies, such as FWD), equipment cost, ease of operation, customer service (availability of service and maintenance), ease of use of the data collected, availability of software for interpretation of the results, reliability, size of the vehicle, relevance of the information (e.g., use in MEPDG), and past experience.
- While the responses to the initial survey suggested users would like to be able to collect continuous pavement response data to support project-level decisions, the follow-up interviews showed that respondents understand the current limitation of the technologies and agree that network-level applications are more likely in the near future. Furthermore, respondents agreed on the need of pavement structural data to support network-level PMS decisions.

- At the network level, the primary application of the continuous deflection device would be to (1) help identify "weak" (or structurally deficient) areas that can be then investigated further at the project level; (2) provide network-level data to calculate a "structural health index" that could be incorporated into a PMS; and (3) differentiate sections that may be good candidates for preservation (good structural capacity) from those that would likely require a heavier treatment (showing structural deterioration and deficiencies).

Selection of Candidate Devices

A more detailed summary highlighting the current knowledge of the capabilities of the continuous deflection devices is presented in Tables 3.7, 3.8, and 3.9. These tables provide a somewhat subjective evaluation of the various technologies in the following broad categories:

- Measurement capability;
- Types of pavements suitable for measuring;
- Sampling rate;
- Accuracy;
- Operating conditions;
- Development status;
- Available interpretation methods for different types of applications; and
- Extent of usage for different applications.

It should be noted that these tables have not been updated since they were produced for Phase I of this study in early 2010. The FWD is also included because it was adopted as the reference device by which to evaluate the comparability of the continuous deflection measurement devices. Although the authors understand that this technology has limitations, it represents the most common mobile deflection measuring device available worldwide with some degree of standardization. Thus, the FWD can be used as a reasonable reference in both U.S. and European assessments of the equipment.

Based on information collected in the literature review and summarized in Tables 3.7, 3.8, and 3.9, the research team identified two devices as the most promising to deliver the information needed by users under operating conditions compatible with SHRP 2 objectives. These devices are the rolling wheel deflectometer (RWD) and the traffic speed deflectometer (TSD).

As indicated in the Catalogue of Selection Measuring Devices, static loading devices in which the vehicle is nonstationary while testing but keeps the actual measurement equipment stationary while sampling (e.g., the deflectograph) were not considered because they did not conform to the adopted definition of a continuous deflection device. The device was defined as a deflection measuring device constantly moving that can collect data at intervals of approximately 300 mm (1 ft) or smaller using load levels typical of truck loading (i.e., 40 to 50 kN [9 to 11 kips] per wheel or load assembly).

Devices that met the definition of a continuous deflection device were evaluated in detail in Tables 3.7, 3.8, and 3.9. The Portancemetre and the Measuring Ball were eliminated from consideration because they do not apply loads similar to that of a heavy vehicle. The Portancemetre measures the response of a pavement under an oscillating load with an average value of 10 kN (2.2 kips) and an amplitude of 6 kN (1.3 kips) at a speed of 3 to 4 km/h (2 to 2.5 mph). Similarly, the Measuring Ball is towed by a car at about 5 km/h (3 mph) and applies a load significantly lower than a typical heavy vehicle wheel load. Since the magnitude of the load is small and the speed slow, these devices are primarily used for quality checks on unpaved surfaces. The RDT and ARWD were also eliminated from further consideration because the existing prototypes have been decommissioned or reassigned to other uses.

The IDM system appears to be very promising; however, an operational prototype is not yet available and, at present, does not meet the survey speed requirement. The most recent published information on the IDM device described trials in which the measuring device was stationary and only the loaded wheel was moving, at just 4 km/h. The preliminary trial concentrated on measuring the bowl shape in the area of maximum change, partly for convenience and partly because associated modeling and analysis has suggested that such information is a useful supplement to maximum deflection when assessing pavement condition. In an ongoing project, developers hope, by mounting a version of the system on a heavy truck and with the aid of a fast camera, to measure deflection in a continuous fashion. Benefits of this system are the potential for continuous measurements and the potential to measure across joints if the geometry of measurement close to the loaded wheel can be resolved.

The RDD was also originally identified as a good candidate, especially for measurements on concrete pavements; however, it was not selected for further evaluation because the user needs survey indicated that the majority of the users would prefer a device that can measure at traffic speed, that is, at least at 55 km/h (35 mph). The original machine operated at around 1.5 km/h (1 mph); it has recently been updated to operate at 5 km/h (3 mph). This is still far short of operating at a speed that does not require traffic control on busy roads. Nevertheless, the combination of a suitable frequency (generally between 5 and 100 Hz) and relatively low survey speed enables the assessment of the deflection response at the joints in concrete pavement that provides valuable guidance as to required rehabilitation measures.

Table 3.7. Detailed Device Evaluation Table

Short Description		Measurement Device			
		FWD (Denmark)	IDM (France)	Portancemetre (France)	Measuring Ball (Sweden)
Measurement capability	Measures nominal peak deflection or equivalent	Yes	Unknown	Yes	Unknown
	Measures nominal deflection bowl shape or equivalent	Yes	Unknown	No	Unknown
	Transverse measurement position	1 (mid-vehicle)	1	1 (mid-vehicle)	1
	Type of load	Impulse on 300-mm diameter plate	Unknown	Oscillating at 35 Hz on 1-m (3-ft) diameter wheel	Unknown
	Peak load level	50 kN (11 kip)	Unknown	10 ± 6 kN (2.2 ± 1.3 kip)	Unknown
Pavement type suitability	Fully flexible	Yes	Unknown	No	Unknown
	Rigid	Yes	Unknown	No	Unknown
	Granular	Yes	Unknown	Yes	Unknown
Sampling rate	Normal sampling rate	na	Unknown	30 mm (1.2 in.) at 3 km/h	Unknown
	Normal reporting rate	na	Unknown	1 m (3 ft)	Unknown
Accuracy	Repeatability	Very good	Unknown	Moderate[a]	Unknown
	Comparability	Good (many devices)	Unknown	Moderate[a] (several devices[a])	Unknown
	Relation to other devices	na	Unknown	Unknown	Unknown
Operating conditions	Typical survey speed	0	4 km/h (2.5 mph)	3 km/h (2 mph)	5 km/h (3 mph)
	Surface conditions	Any	Dry[a]	Any[a]	Unknown
	Traffic management required	Yes	Yes	Yes	Yes
Status	Production/development status	Production model	Laboratory prototype	Production model	Unknown
	% commercially developed	100	10	100	Unknown
Available interpretation methods for pavement types	Flexible pavements	Yes	No	No	Unknown
	Rigid pavements	Yes	No	No	Unknown
	Granular pavements	Yes	No	Yes	Unknown
Use	Distance surveyed	Unknown	0	Unknown	Unknown
	Surveying Flexible/rigid/composite pavements	Unknown	0	Unknown	Unknown
	Screening structurally deficient sections	Yes	Unknown	No	Unknown
	Defining rehabilitation strategies	Yes	Unknown	No	Unknown
	Designing rehabilitation treatments	Yes	Unknown	No	Unknown

Note: na = not applicable.

[a] Author's estimate, which could not be verified by available information at this stage.

Table 3.8. Detailed Device Evaluation Table

Short Description		**Measurement Device** **RDD (United States)**	 **Moving FWD (Sweden)**	 **ARWD (United States)**
Measurement capability	Measures nominal peak deflection or equivalent	Yes	Yes[a]	Yes
	Measures nominal deflection bowl shape or equivalent	Yes (4 points)	Unknown	No
	Transverse measurement position	1 (mid-vehicle)	1	1 (mid-vehicle)
	Type of load	Oscillating at 30 Hz[a] on 300-mm[a] (12-in.) diameter wheel	Impulse[a] load every 15 m at 30 km/h	Fixed dual wheel assembly
	Peak load level	55 ± 20 kN (12 ± 4.4 kip) on rigid pavement	Unknown	40 kN (9 kip)
Pavement type suitability	Fully flexible	Yes	Yes	Yes
	Rigid	Yes	No	No
	Granular	Yes	Yes	No
Sampling rate	Normal sampling rate	13 mm at 5 km/h (0.5 in.)	Unknown	3 m at 35 km/h (9 ft)
	Normal reporting rate	0.6–0.9 m (2–3 ft)	15 m at 30 km/h (50 ft)	25 m (90 ft)
Accuracy	Repeatability	Good[a]	Unknown	Unknown
	Comparability	na (Only one device)	Unknown	na (Only one device)
	Relation to other devices	Strong with FWD	Unknown	Unknown
Operating conditions	Typical survey speed	1.5–5 km/h (1–3 mph)	30 km/h (19 mph)	35 km/h (22 mph)
	Surface conditions	Any[a]	Unknown	Dry
	Traffic management required	Yes	Yes	Probably
Status	Production/development status	Working prototype	Decommissioned prototype	Decommissioned prototype
	% commercially developed	80	Unknown	60
Interpretation methods available for . . .	Flexible pavements	Yes[a]	Unknown	No
	Rigid pavements	Yes[a]	Unknown	No
	Granular pavements	No	Unknown	No
Use	Distance surveyed	Unknown	Unknown	Unknown
	Flexible/rigid/composite pavements surveyed	Unknown	Unknown	Unknown
	Screening structurally deficient sections	Yes[a]	Unknown	Unknown
	Defining rehabilitation strategies	Y[a]	Unknown	Unknown
	Designing rehabilitation treatments	Y	Unknown	Unknown

Note: na = not applicable.

[a] Author's estimate, which could not be verified by available information at this stage.

Table 3.9. Detailed Device Evaluation Table

Short Description		**Measurement Device**		
		RWD (United States)	**RDT (Sweden)**	**TSD (Denmark)**
Measurement capability	Measures nominal peak deflection or equivalent	Yes	Yes	Yes[a]
	Measures nominal deflection bowl shape or equivalent	No	Yes	Yes[a] (3 points)
	Transverse measurement position	1 wheelpath	2 wheelpaths	1 wheelpath
	Type of load	Fixed dual wheel assembly	Fixed dual wheel assembly	Fixed dual wheel assembly
	Peak load level	40 kN (9 kip)	40–70 kN (9–16 kip)	50 kN (11 kip)
Pavement type suitability	Fully flexible	Yes	Yes	Yes
	Rigid	No	No	Maybe
	Granular	No	No	No
Sampling rate	Normal sampling rate	11 mm at 80 km/h (0.4 in.)	20 mm at 70 km/h (0.8 in.)	20 mm at 70 km/h (0.8 in.)
	Normal reporting rate	30 m (100 ft)	50 m (165 ft)	10 m (30 ft)
Accuracy	Repeatability	Good[a]	Moderate[b]	Good[b]
	Comparability	na (only one device)	na (only one device)	Good[b] (two devices)
	Relation to other devices	Strong with FWD	Poor with FWD and deflectograph	Strong with FWD and deflectograph
Operating conditions	Typical survey speed	80 km/h (50 mph)	70 km/h (45 mph)	70 km/h (45 mph)
	Surface conditions	Dry	Dry	Dry
	Traffic management required	No	No	No
Status	Production/development status	Working prototype	Prototype reassigned to other uses	Two working prototypes
	% commercially developed	80[a]	60	95
Interpretation methods available for pavement types	Flexible pavements	Yes[b]	No	Yes[b]
	Rigid pavements	No	No	No
	Granular pavements	No	No	No
Use	Distance surveyed	12,000+ km (7,500+ mi)	Unknown	30,000+ km (19,000+ mi)
	Flexible/rigid/composite pavements surveyed	Mostly Flexible/composite	Unknown	Mostly Flexible/composite
	Screening structurally deficient sections	Yes	No	Yes[b]
	Defining rehabilitation strategies	Yes[b]	No	Yes[b]
	Designing rehabilitation treatments	No	No	No

Note: na = not applicable.

[a] Measures vertical deflection velocity, which is converted to deflection slope by dividing by the horizontal vehicle velocity. Three deflection slopes enable maximum deflection and part of the bowl shape to be estimated.

[b] Author's estimate, which could not be verified by available information at this stage.

Detailed Description of the Selected Equipment

This section expands on the characteristics of the selected devices and provides a preliminary assessment of their technical capabilities based on the information collected from trials and demonstration projects from the United States and Europe. Both selected devices, the RWD and TSD, conduct measurements (deflection or deflection velocity of a loaded pavement, respectively) under a truck axle and at speeds close to that of traveling traffic.

By contrast, the technology currently in use, the FWD, applies an impulse load (using known weights that are dropped from specific heights onto a load plate) and measures the response (deflections) to those loads at seven to nine surface locations, starting at the center of the loading plate and extending radially up to 1.8 m (72 in.) from the load plate center. The deflection basin at each test location is indicative of the stiffness of the underlying pavement structure and given the various sensors, allows a quantification of the structural capacity of various layers or layer types. A production rate of approximately 4 lane-km (2.5 lane-mi) per day is typical, assuming testing at an interval of 23 m (75 ft). This testing scheme is best suited for project-level testing. Agencies employing FWD for network-level FWD test protocol may adjust this test spacing to achieve a production rate of approximately 32 to 40 lane-km (20 to 25 lane-mi) per day, assuming an interval of 320 m (0.2 mi) (Diefenderfer, 2010).

Rolling Wheel Deflectometer (RWD) Detailed Description

The RWD has been developed by Applied Research Associates, Inc. (ARA), with support from the FHWA. The RWD system is mounted within a custom-designed 17-m (53-ft) semitrailer. The measured deflection is the response from one-half of an 80-kN (18-kip) single-axle load traveling at normal traffic speeds. In a previously tested version, an aluminum reference bar, suspended beneath the trailer, contained four laser sensors to measure the distance to the pavement surface (Figure 3.8). The RWD uses a spatially coincident methodology for measuring pavement deflection. This method was originally developed by the Transport and Road Research Laboratory (TRRL) and implemented by Dr. Milton Harr at Purdue University.

In the evaluated model, three lasers are used to measure the distance to the unloaded pavement surface (i.e., forward of and outside the deflection basin), and a fourth laser, located between the dual tires and just behind the rear axle, measures the distance to the deflected pavement surface. The deflection is calculated by comparing the laser scans profile as the RWD moves forward. The beam uses a curved extension to pass under and between the dual tires, placing the rearmost laser approximately 150 mm (6 in.) rear of the axle centerline and 178 mm (7 in.) above the roadway surface. The wheels are spaced a safe distance from the laser and beam using custom lugs spacers (Steele and Vavrik, 2006). The equipment has recently been retrofitted to enclose the laser sensors and an additional sensor has been added, as discussed in New Improvements to the Evaluated Equipment in Chapter 4.

At 89 km/h (55 mph), the RWD's 2-kHz lasers take readings approximately every 11 mm (0.5 in.), resulting in extremely large data sets. The average deflection every 160 m (0.1 mi) is typically reported; this averaging helps reduce scatter and file size. Figure 3.9 shows an example of the data collected during the demonstration in Virginia. Each square represent the average deflection for each 160 m (0.1 mi); the continuous line represents a 1.6-km (1-mi) moving average. The data is generally filtered to eliminate outliers due to bridges,

Source: Diefenderfer, 2010; and FHWA, 2009.

Figure 3.8. RWD during testing in Virginia and close-up of laser sensor placed between dual tires.

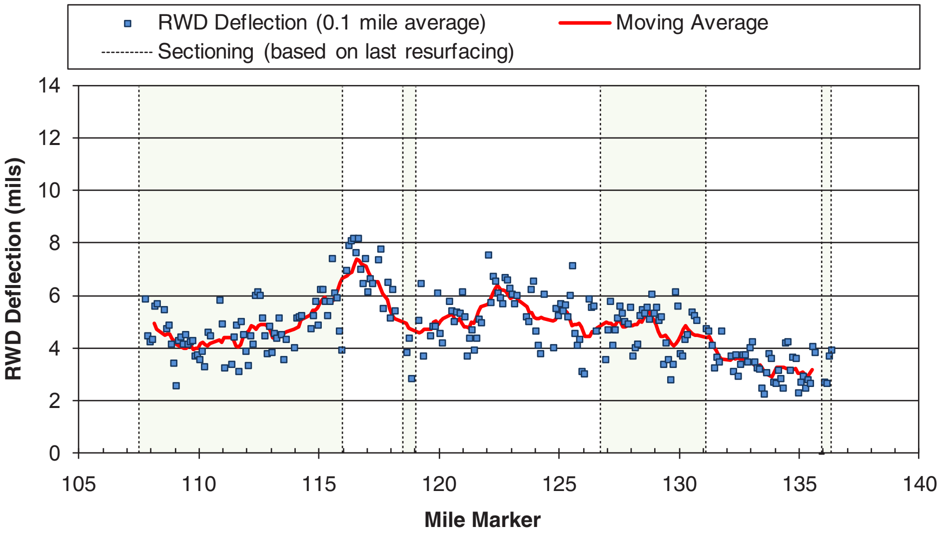


Figure 3.9. Example of deflection data collected on eastbound I-64 in Virginia in 2006.

sudden changes in speed, and so forth, before the analysis is performed. Additional details of the RWD deflection measurement process are presented elsewhere (ARA, 2005a; Steele and Hall, 2005). Recent upgrades to the RWD include improved laser sensors that are located within a temperature-controlled housing. The result of these improvements on comparison testing with FWD is ongoing and unknown at this time.

The RWD technology can test approximately 320 to 480 km (200 to 300 lane-mi) per day. A potential benefit of the RWD is that the load, loading mechanism, and loading rate of the RWD are thought to match more closely the actual dynamic effects on pavements caused by vehicle loading. In addition, the RWD testing is conducted at or near highway speeds with limited or no traffic control requirements and minimal interruption to the highway users. However, the RWD does not currently allow for some of the structural capacity analysis offered by the FWD. In its current state of development, it is anticipated that the RWD could be used to prescreen the pavement network to identify areas that might require additional and more detailed study at the project level using traditional techniques such as the FWD, or to identify segments that could be good candidates for pavement preservation.

The FHWA has sponsored RWD demonstration projects throughout the United States. Testing has been conducted in coordination with at least 16 U.S. state highway agencies, including those in California, Colorado, Connecticut, Indiana, Iowa, Kansas, Kentucky, Minnesota, New Hampshire, New Jersey, New Mexico, Ohio, Oregon, Texas, Virginia, and West Virginia; on a federal road under the jurisdiction of the federal lands (Natchez Trace); and on several test tracks including the National Center for Asphalt Technology (NCAT), Virginia Smart Road, and MnRoad.

According to documented test reports, the total mileage tested exceeded 11,300 km (7,000 lane-mi). Each state agency self-developed its test plan. Several of these tests included FWD measurements on the same sections; however, not all were conducted at the same time as the RWD measurements were taken. A few of the demonstrations included multiple runs to assess the repeatability of the device.

One of the earliest RWD test reports was authored by Arora et al. (2006) and described testing in Texas in 2004. The RWD was used to test approximately 425 km (264 lane-mi) (a variety of state routes with five repeat runs per roadway) with some companion FWD testing. FWD deflection values ranged from approximately 100 to 1,300 microns (4 to 50 mils). The authors stated that the RWD testing was repeatable, based on visual observation of the plotted deflection results. In discussing a relationship of RWD to FWD deflection results, the authors stated that some relationship exists although the data "shows some scatter especially at smaller deflection values." The authors suggested that lower deflection values might be measurable only at lower speeds.

Gedafa et al. (2008) reported on RWD testing of 333 km (207 mi) of non-interstate highway in Kansas in 2006. The results of the RWD testing were compared to FWD testing that was conducted from 1998 to 2006. RWD testing was performed at 89 km/h (55 mph) with deflection readings averaged every 160 m (0.1 mi). The FWD data were collected at 5 to 10 points per mile. The average FWD center deflection value ranged from approximately 0.13 to 0.45 mm (5 to 18 mils) (40 kN [9 kips] load). The results showed that the RWD deflection reading and the FWD center deflection value were statistically similar based on a significant difference test statistic. A linear regression analysis was also performed that showed a strong correlation between FWD and RWD deflection readings.

Virginia reported RWD testing on portions of two interstate routes and a loop consisting of primary rural highways in 2005 (Diefenderfer, 2010). All RWD testing was done at or near the prevailing traffic speed. Companion FWD testing was conducted in 2006 on the two interstate test sections. The FWD deflection values ranged from 0.08 to 0.38 mm (3 to 15 mils), with a majority less than 0.2 mm (8 mils) (40 kN [9 kips] load). The two interstate test sections comprised hot-mix asphalt (HMA) (200–300 mm [8–12 in.]) over compacted aggregate and HMA (100–150 mm [4–6 in.]) over CRCP (200 mm [8 in.]). Statistical testing of RWD repeatability was performed by use of a non-paired t-test assuming equal variances. The results showed that for 8 of 15 trials on interstate highways and all non-interstate test sections, the RWD data were repeatable. A poor linear correlation was found between the RWD and FWD measurements (adjusted R^2 values less than 0.2). However, the FWD measurements were taken several months after the RWD measurements and only on interstate sections with relatively low and uniform deflections. The results suggested that the deflection value may be influenced by surface texture as the standard deviation varied approximately at locations where the HMA surface mixture also varied.

Traffic Speed Deflectometer (TSD) Detailed Description

The TSD (Figure 3.10) is mounted on an articulated truck with a rear axle load of 100 kN (22 kips), which, in the model evaluated, uses four Doppler lasers mounted on a servo-hydraulic beam to record the vertical deflection velocity of a pavement as it is loaded by one of the dual wheel axles. Three Doppler lasers are positioned such that they measure deflection velocity at a range of distances in front of the rear axle. The fourth sensor is positioned 3.6 m (12 ft) in front of the rear axle, largely outside the deflection bowl, and acts as a reference laser. The beam on which the lasers are mounted moves up and down in opposition to the movement of the trailer in order to keep the lasers at a constant height from the pavement surface. To prevent thermal distortion of the steel measurement beam, a climate control system maintains the trailer temperature at a constant 20°C (68°F). Two prototypes had been developed at the time of the evaluation by the manufacturer, Greenwood Engineering A/S of Denmark. One is owned and operated by the Danish Road Institute (DRI); the other is owned by the U.K. Highways Agency (HA) and operated on their behalf by the U.K. Transport Research Laboratory (TRL). Newer production devices have incorporated more Doppler laser sensors.

The lasers are mounted at a small angle to measure the horizontal vehicle velocity, the vertical and horizontal vehicle suspension velocity, and the vertical pavement deflection velocity. Due to its location midway between the loaded trailer axle and the rear axle of the tractor unit, the reference laser is expected to measure very little vertical pavement deflection velocity, and its response can therefore be used to remove the unwanted signals from the three measurement lasers. When accurately calibrated, the TSD produces measurements of deflection velocity that depend on driving speed. To remove this dependence, the deflection velocity is divided by the instantaneous survey speed to give a measurement of deflection slope, as illustrated in Figure 3.10. Deflection velocity is measured in mm/s while survey speed is measured in m/s; therefore, deflection slope measurements are given in units of mm/m (Ferne et al., 2009b).

The DRI Machine

The DRI and Greenwood jointly developed the TSD, initially called the high speed deflectograph (HSD), and have published a number of papers on this work. An early independent

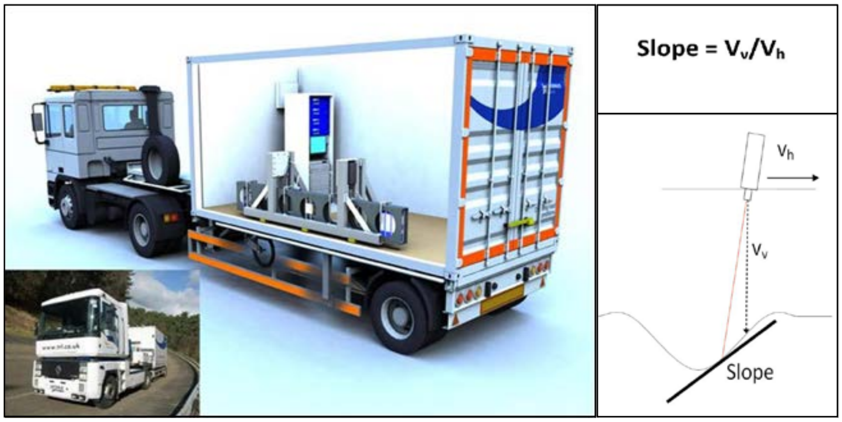


Figure 3.10. Computer render of the TSD, with the TSD in operation (inset).

Figure 3.11. DRI device measuring side by side with the U.K. TSD at TRL in 2008.

evaluation by the Laboratoire Central des Ponts et Chaussées (LCPC) in 2003 (Simonin et al., 2005) showed that even though the early prototype had limitations, it demonstrated good repeatability in the short term and a good degree of correlation with the maximum deflection recorded by other devices such as the FWD and the deflectograph. Other DRI publications confirm some aspects of this work when assessing a developed version of this device that they currently own and operate. The DRI (Figure 3.11) also have practical experience operating the device on their network, having covered their main network from 2005 to 2007. Based on this experience, Baltzer (2009) reported the DRI daily survey coverage for the device of around 170 to 225 km (105 to 140 mi).

The Highways Agency TSD

The second prototype TSD currently in operation is owned by the U.K. Highways Agency (HA) and operated by the U.K. Transport Research Laboratory (TRL). The TRL has reported its development and performance in recent conference papers (Ferne et al., 2009a and 2009b). An example of typical survey results expressed over 10-m (33-ft) and 100-m (1/16-mi) lengths are provided in Figure 3.12.

Equipment Status

At the time of completion of the Phase I evaluation (February 2010), the RWD was a working prototype, with only one such prototype in existence. This prototype has been recently upgraded by adding an additional laser sensor and providing temperature control to the beam that supports the lasers. There were also two working TSDs with new models (with more sensors) under construction. At the time of the current report, two additional TSDs have been constructed, for agencies in Italy and Poland. A fifth device is currently under construction for the South African Highway Administration. The latter three devices incorporate improvements to the

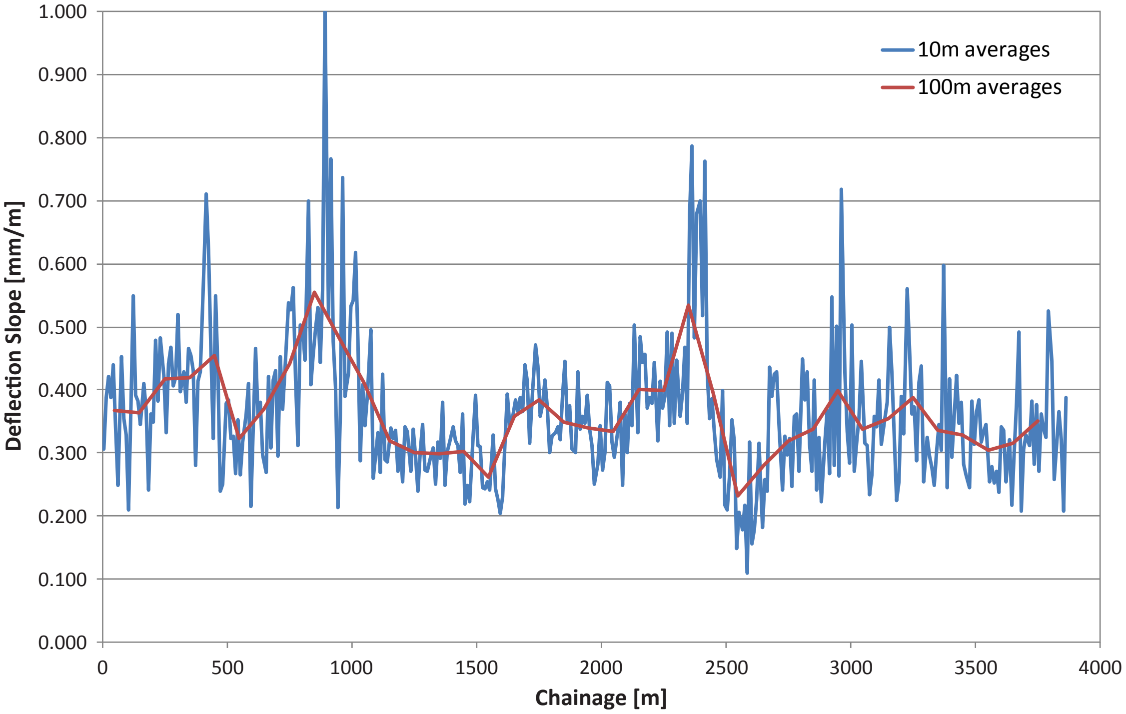


Figure 3.12. TSD deflection slope at 10 m (33 ft) and 100 m (330 ft) means against distance.

earlier two prototypes, such as additional velocity sensors and improved calibration facilities. The website of the manufacturer, Greenwood Engineering A/S, currently designates the TSD as a production model and gives details about some features added to the equipment.

Available Data Interpretation Methods

Fully developed methods of data interpretation are not available specifically for either device. In principle, the RWD deflection should be usable as an input for any procedure that requires only a maximum deflection response as its pavement response input. It has been proposed that the velocity measurements from the Danish device configuration can be used to produce surface curvature index values that are akin to those measured by an FWD. Therefore, they should be viable as input for procedures that require only surface curvature index (SCI) as a pavement response input.

Greenwood Engineering has developed a method to interpret the deflection velocity from the TSD by using a beam on elastic foundation approach. The model builds a full deflection basin using a two-parameter function and information from three deflection slope measurements. The model proposed for the deflection basin is given below (Krarup et al., 2006):

$$d(x) = \frac{-A}{2B}\left(Cos(Bx) + Sin(Bx)\right)e^{-Bx} \tag{3.1}$$

Where:

$d(x)$ = deflection at any point within the basin,
x = distance of deflection from center of load, and
A and B = constants to be optimized.

The implications of the model are that the deflection slope directly under the load is zero. This can be seen directly by differentiating the model with respect to the variable x, and evaluating it at zero.

In the United Kingdom, the main method for interpreting pavement deflection response uses the maximum deflection measured by a slow-moving deflectograph to estimate residual lives and strengthening requirements. Research in the United Kingdom, reported earlier in this section, has shown that equivalent deflectograph values can be estimated from TSD measurements, thus providing an approximate interpretation methodology for the English strategic road network. Routine network surveys of this network started in November 2009, and the measurements are being converted to one of four structural condition categories before being stored in the Highways Agency Pavement Management System for use by the agents responsible for the various parts of the network to assist them with their management of the network.

The above information refers to just flexible pavements. For rigid and unpaved roads, there is as yet no explicit interpretation method for either device although recent research has suggested that the TSD equipment may have a role in the preliminary evaluation of the joint condition of rigid pavements.

Use

Table 3.10 and Table 3.11 summarize the status of survey coverage for each type of device as of February 2010. For the RWD, most of this testing was conducted on flexible pavements with a total survey length of more than 12,100 km (7,500 mi). For the TSD, close to 100% is of flexible construction with a total surveyed length of more than 21,000 km (13,000 mi) in the United Kingdom.

The Danish device has covered well over 10,000 km (6,500 mi) in Denmark. In 2010 the device was commissioned to cover 20,000 km (12,500 mi) of the road networks in two Australian states, as described by Baltzer et al. (2010). To date, little data have been explicitly used for specific pavement management activities, so it is not possible to determine the appropriate use of data such as screening structurally deficient sections, defining rehabilitation strategies, or designing rehabilitation treatments.

Phase I Assessment

The devices were further evaluated to determine their capabilities based on existing data found in the literature review and obtained from interviews with DOT officials. Both candidate devices have been used in pilot projects over multiple locations, and evaluation of accuracy and repeatability has been conducted and reported. This section presents the past research conducted on the devices.

Accuracy

Equipment accuracy has many interpretations, whether considering individual measurement accuracy or the overall accuracy of the device. Therefore, accuracy is considered under a number of factors: choice of averaging length, short-term repeatability, long-term repeatability, effect of external variables, comparability, and comparison with other deflection measures. The term “short-term repeatability” indicates that the surveys have been repeated as quickly as possible in order to minimize the effect of external environmental conditions such as temperature changes on the results. When assessing long-term repeatability, the surveys were carried out over a period of several days or even weeks, so the results could potentially include the external effects. For each factor, the capability of the two devices is considered on the basis of available information collected in Phase I of this study and is detailed in this section. This section presents preliminary

Table 3.10. Summary of Tests Conducted in the U.S. as of February 2010

Location	Date	Lane-mi	FWD Data Availability	FWD Sampling Frequency	Repeat Runs	Road Functional Class
Louisiana	2009	NA	Good	NA	No	NA
Kansas	2008	466	Good	0.1	No	U.S. and state
New Mexico	September 2008	443	Good	0.1	No	U.S.
Colorado	October 2008	230	Partial	0.1	No	Int., U.S., and state
New Hampshire	July 2007	712	NA	NA	No	Int., U.S., and state
Connecticut	September 2007	204	NA	NA	No	Int., U.S., and state
Kansas	July–August 2006	506	Good	0.1	Research sites	U.S. and state
Iowa	July 2006	278	Good	0.1	No	Int., U.S., and state
Oregon	June–July 2006	579	Partial	0.1	No	Int., U.S., and state
California	June–July 2006	685	NA	NA	Research sites	Int., U.S., and state
Virginia	October 2005	488	Partial	0.1	3 interstate, 2 primary	Int., U.S., and state
New Jersey	October 2005	803	Partial	Varied	No	Int., U.S., and state
Minnesota	September 2005	NA[a]	Partial	0.1	MnRoad sites	U.S., state, and county
Kentucky–Ohio–West Virginia	September 2005	437	Good in OH	0.1	No	Int., U.S., and state
Indiana	September 2004	688	NA	NA	Yes	U.S. and state
Natchez Trace	November 2004	800+	NA	NA	No	U.S. park service
NCAT	July 2005	NA[b]	NA	NA	Yes	Test track
Texas	July 2003	264	Good	NA[c]	Yes	38 test sections; U.S. and state routes
Total		7,583+				

Note: NA = not available; Int. = Interstate.

[a] Testing on county roads and MnRoad facility; mileage not recorded.

[b] Testing at varying speeds on 1.3-mi test track; mileage not recorded.

[c] FWD, MDD, and RDD testing on specific spots (*see* FHWA, 2009).

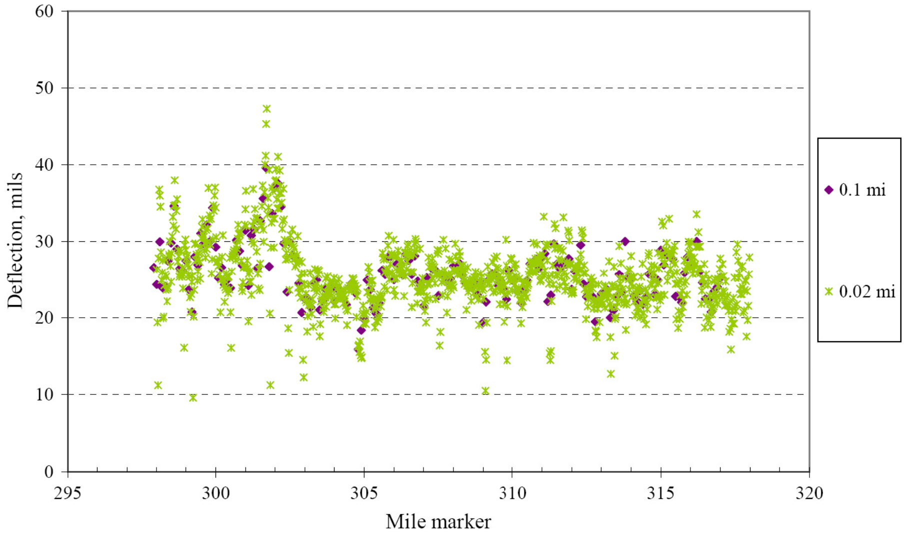
Table 3.11. Lane Lengths Surveyed by U.K. HA TSD by Survey Type (September 2005 to February 2010)

Survey Type	Approximate Length Surveyed	
	km	mi
European continent	350	220
TRL track	1,300	800
Local roads	10,400	6,500
Scottish road network	800	500
English trunk road and motorway network	8,200	5,100
Total	21,050	13,100

values based on a limited dataset collected for previous studies; a more rigorous calculation based on a larger dataset is given later.

Choice of Averaging Length

The RWD demonstration at the Eastern Federal Lands Highway Division (EFLHD) included a comparison using 160- and 32-m (0.1- and 0.02-mi) intervals for averaging the results. Figure 3.13 illustrates the effect of a shorter averaging interval on one of the tested sections. The figure suggests that decreasing the sample unit length does not significantly affect the overall trend (or the mean deflection for the overall section), but it does increase variability over the section length. On the basis of these limited results, the manufacturer has cautioned against using a sampling interval that is too small to reduce random error sufficiently (ARA, 2005b).



Source: ARA, 2005b.

Figure 3.13. Effect of sample unit length on RWD deflections.

The TSD collects raw data at around 1000 Hz, but there is significant random noise in this raw signal. Even when averaged over a 0.1-m (4-in.) length, this noise is noticeable, as illustrated by the black line in Figure 3.14. Also shown in this figure are 1-m (40-in.), 10-m (33-ft), and 100-m (330-ft) contiguous averages. This site is generally of a very variable and weak composite construction with corresponding very variable deflections. The figure illustrates how some features of the true deflection profile are probably suppressed as the averaging length increases from 1 m to 100 m (3.3 ft to 333 ft). Therefore, in the United Kingdom, it has been decided to store results at 1-m (3.3-ft) intervals and generally report results as 10-m (33-ft) averages. From chainage (distance) 215 m to 250 m (705 ft to 820 ft) the construction changes to a rigid concrete construction, which has a relatively low and uniform deflection response. This is demonstrated in Figure 3.15, which

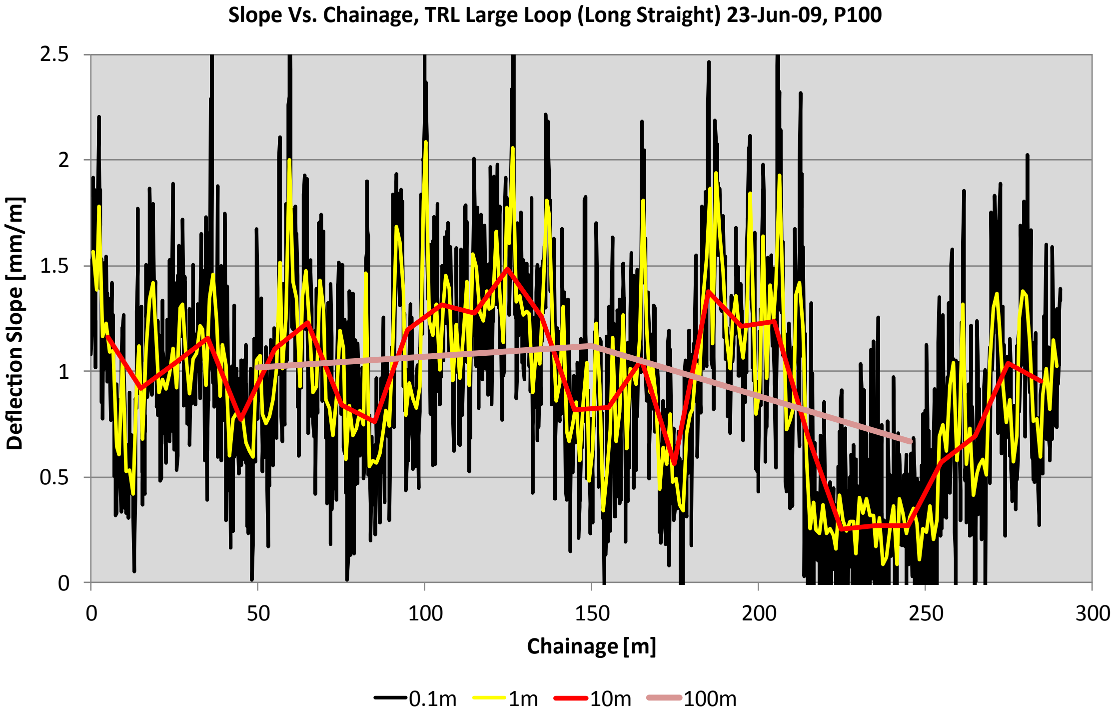


Figure 3.14. TSD deflection slope profile for Transport Research Laboratory track with various averaging lengths.

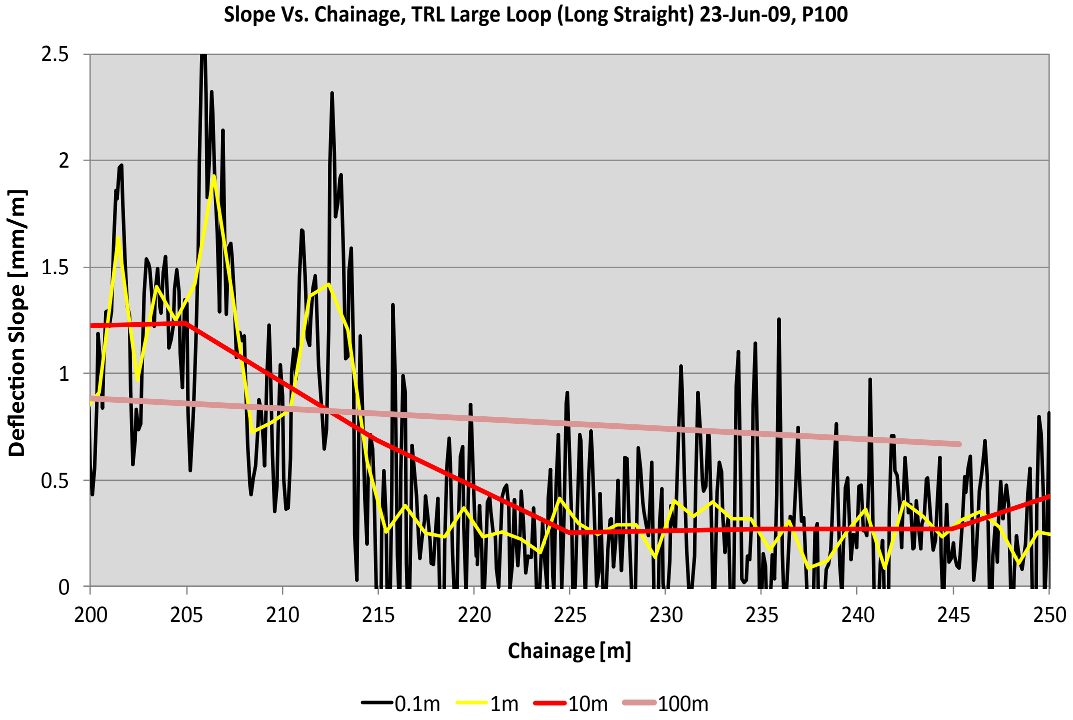


Figure 3.15. TSD deflection slope profile for TRL track with various averaging lengths: rigid section and transition.

shows a 50-m (165-ft) section of Figure 3.14 covering from 200 m to 250 m (655 ft to 705 ft). This exaggerated scale suggests that on weak composite pavement even a 10-m average length hides some true deflection variations. This is discussed further in the following repeatability section.

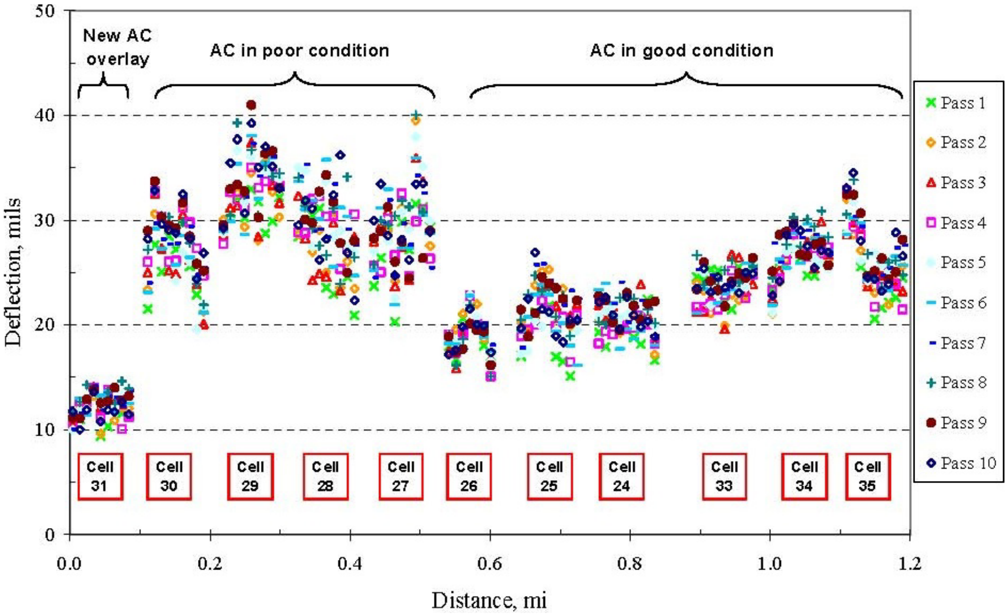
Short-Term Repeatability

Several of the RWD demonstration projects included multiple runs. Figure 3.16 shows the results of conducting multiple runs at the MnRoad test facility. RWD deflections are averaged over 15-m (50-ft) intervals. Figure 3.16a shows 10 repeat passes on the inner lane of the low-volume road loop. This loop included 11 asphalt concrete (AC) test sections with different pavement structures. The sections included 4 cells (Nos. 27 through 30) in very poor condition and one cell (No. 31) that had been recently overlaid and was in excellent condition. These conditions were reflected in the deflection profile. The repeatability standard deviations considering the individual 160-m (0.1-mi) segments ranged from about 25 microns (1 mil) for the section recently overlaid to approximately 100 microns (4 mils) for the cells in poor condition. Figure 3.16b presents three repeated runs on the outer (driving) lane of the mainline experiment, which included AC test cells of variable ages and AC layer thicknesses ranging from 100 to 380 mm (6 to 15 in.). Deflections were very uniform within the majority of cells, with standard deviations typically ranging from 50 to 75 microns (2 to 3 mils) (ARA, 2006).

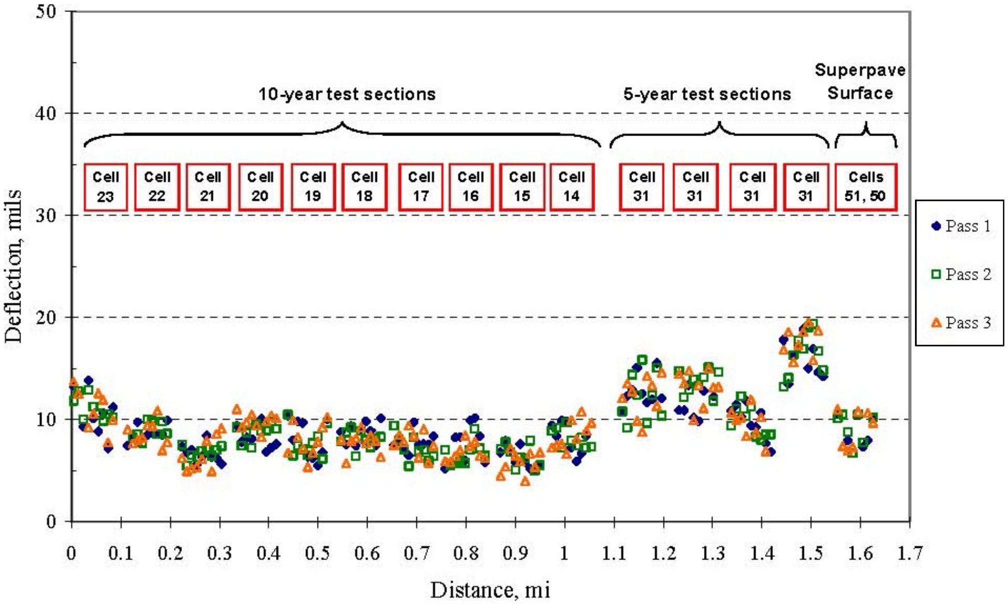
In general, the various evaluations showed relatively good repeatability that seemed to be appropriate for network-level analysis. On the other hand, Diefenderfer (2010) conducted statistical testing of RWD repeatability by use of a non-paired t-test assuming equal variances and the results showed that the RWD data were repeatable for only 8 of 15 trials. Of the non-interstate test sections, 100% of the trials were found to be repeatable. This raised some questions about the applicability of the system for detailed (e.g., project-level) evaluations, especially in areas where low deflection ranges are expected. Figure 3.17 shows an example of three repeated runs on a stretch of interstate highway in Virginia.

The repeatability standard deviation for the average 0.1-mi segments is shown at the bottom of the chart; the average standard deviation was 20 microns (0.79 mils), or 17% of the mean deflection. However, the repeatability standard deviation for the average values for the entire tested sections showed good repeatability (Table 3.12).

For the U.K. Highways Agency TSD, Ferne et al. (2009b) reported the results of testing conducted to investigate the effect of testing speed. Measurements were taken on the TRL track over a range of speeds, and the results showed that as the speed increased, a slightly lower value of deflection slope



(a) Low-volume road (10 passes)



(b) Mainline experiment (3 passes)

Source: ARA, 2006.

Figure 3.16. RWD deflections at 50-ft intervals at MnRoad.

was recorded. This being the case, the testing speeds used during further tests were strictly controlled to enable repeatable results to be obtained. Figure 3.18 shows a sample of the results of 6 runs on a 440-m (0.25-mi) length of the TRL track, which had mainly a composite pavement but included a 50-m (165-ft) length of jointed concrete at a nominal speed of 70 km/h (45 mph). The data showed reasonable short-term repeatability, with a relatively low standard deviation despite the relatively wide range of deflection slopes measured (i.e., changing by a factor of over seven).

Both the LCPC assessment of the first DRI prototype and TRL's assessment of the HA TSD suggest that the level of repeatability is not particularly dependent on the mean level of the slope. Therefore, in this section of the report they are given in absolute, not proportional, terms.

The consistency of the latest version of the HA TSD has been assessed on a small number of U.K. roads. Results of these tests in terms of the standard deviation of the mean values of each of five runs of various lengths have been summarized in Table 3.13 for the P100 and P300 TSD sensors.

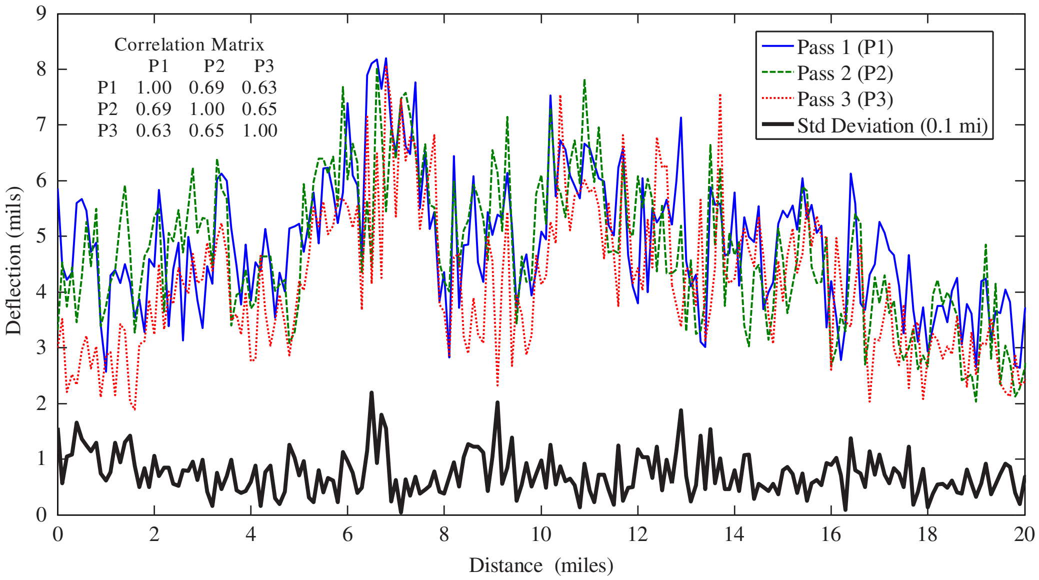


Figure 3.17. Repeated runs of the RWD on I-64 in Virginia.

This good level of short-term repeatability of the TSD that is achievable under controlled conditions can also be observed graphically. Figure 3.19 shows a 20-m (66-ft) sample length of the TRL track with the TSD P100 sensor results calculated at 1-m (3-ft) intervals plotted against distance for all five repeat runs. The repeated identification of weak spots at the same location (i.e., stations 187 to 188 m [613 to 617 ft] and 197 to 198 m [646 to 650 ft]) is clearly seen.

Long-Term Repeatability

Figure 3.20 shows a sample of five runs recorded over 5 months (September 2009 to February 2010) on 4 km (2.5 mi) of a U.K. site, which is of flexible composite construction, with a nominal testing speed of 70 km/h (45 mph). The data shown has been averaged into 100-m (330-ft) lengths so that the change in deflection slope is more visible.

Table 3.14 shows that the standard deviations of the mean values of each of the five runs are very similar to those in Table 3.13, meaning that repeatability apparently changed little when assessed over longer periods of time. This suggests that changes in pavement temperature have only a small effect on the measured slope as surface temperature changed from 4°C to 19°C (40°F to 66°F) during these surveys. This is not unexpected as the pavement is of flexible composite construction. In the United Kingdom, deflection surveys on strong flexible composite pavements are left uncorrected for pavement temperature.

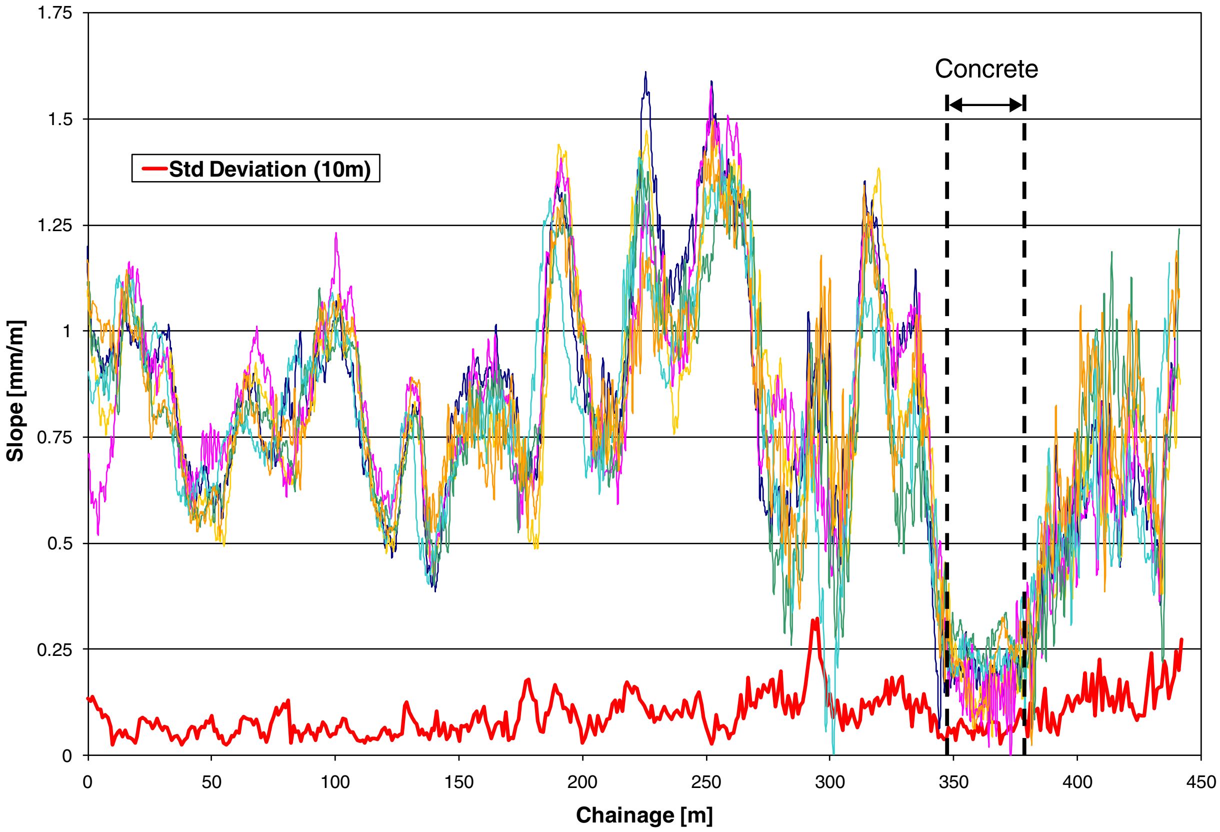
Figure 3.21 shows a 500-m selected section of the same U.K. Site B as in Figure 3.20 but with 10-m (33-ft) averaging used. Although the runs were performed over 5 months, all five surveys identify the weaker section in the same location, that is, from 2,350 m to 2,400 m (7,710 ft to 7,874 ft).

Comparability

The comparability of the RWD cannot be assessed because only one such device has been produced. Even with two devices, an assessment of true device reproducibility, such as with the TSD, is not possible. However, some limited comparisons have been made but not published. One such comparison was made in September 2008 in the United Kingdom.

Table 3.12. Summary Statistics for Average Section RWD Deflections of I-64 and I-81

Highway	Average (mils)	Repeatability Std. Dev. (mils)	Average (microns)	Repeatability Std. Dev. (microns)
Eastbound I-64	4.53	0.28	115.1	7.3
Westbound I-64	4.7	0.26	119.4	6.6
Northbound I-81	7.77	0.14	197.4	3.5
Southbound I-81	5.08	0.59	129.0	15.0



Source: Ferne et al., 2009a.

Figure 3.18. Repeatability of deflection slope at 70 km/h (45 mph) on the TRL track.

Figure 3.22 illustrates the consistency between these two devices when operating on the same 11-km (7-mi) length of varying construction and deflection response, bearing in mind that the two devices measure in different wheelpaths.

Figure 3.23 illustrates differences between the wheelpaths as revealed by surveys conducted by a slow-speed deflectograph that records peak deflections in both wheelpaths at the same time. Comparison of the two figures confirms that any differences between the two devices are likely explained by the different deflection responses of the two wheelpaths.

Table 3.13. Repeatability Standard Deviation of TSD for Five Runs in Terms of TSD Slope for Short-Term Repeatability

			Repeatability Standard Deviation (mm/m)		
			Averaging Length		
Site	Overall Length	Sensor	10 m (33 ft)	100 m (330 ft)	160.9 m (1/10 mi)
TRL track	291 m/ 0.2 mi	P100	0.071	0.046	0.040
		P300	0.053	0.038	0.034
U.K. Site A	1,080 m/ 0.7 mi	P100	0.037	0.012	0.010
		P300	0.037	0.013	0.011
U.K. Site B	3,871 m/ 2.4 mi	P100	0.054	0.025	0.023
		P300	0.071	0.052	0.051

Comparison with Other Deflection Measures

Investigations have been conducted comparing the RWD and TSD to other deflection measuring equipment, in particular the FWD. However, since the FWD and rolling wheel devices load the pavement in different ways, the relationship between them will not necessarily be one of equality.

Several of the RWD demonstrations included FWD measurements on at least some sections; however, not all were conducted at the same time that the RWD measurements were obtained. Figure 3.24 presents examples of section-level comparisons between RWD and FWD maximum deflections. In general, the RWD reports collected during follow-up interviews suggest that the average results of the RWD deflection measurements (normalized to a standard temperature) correlate relatively well with the average maximum FWD deflection when aggregated by homogeneous sections. The example from Texas (Figure 3.24d) suggests

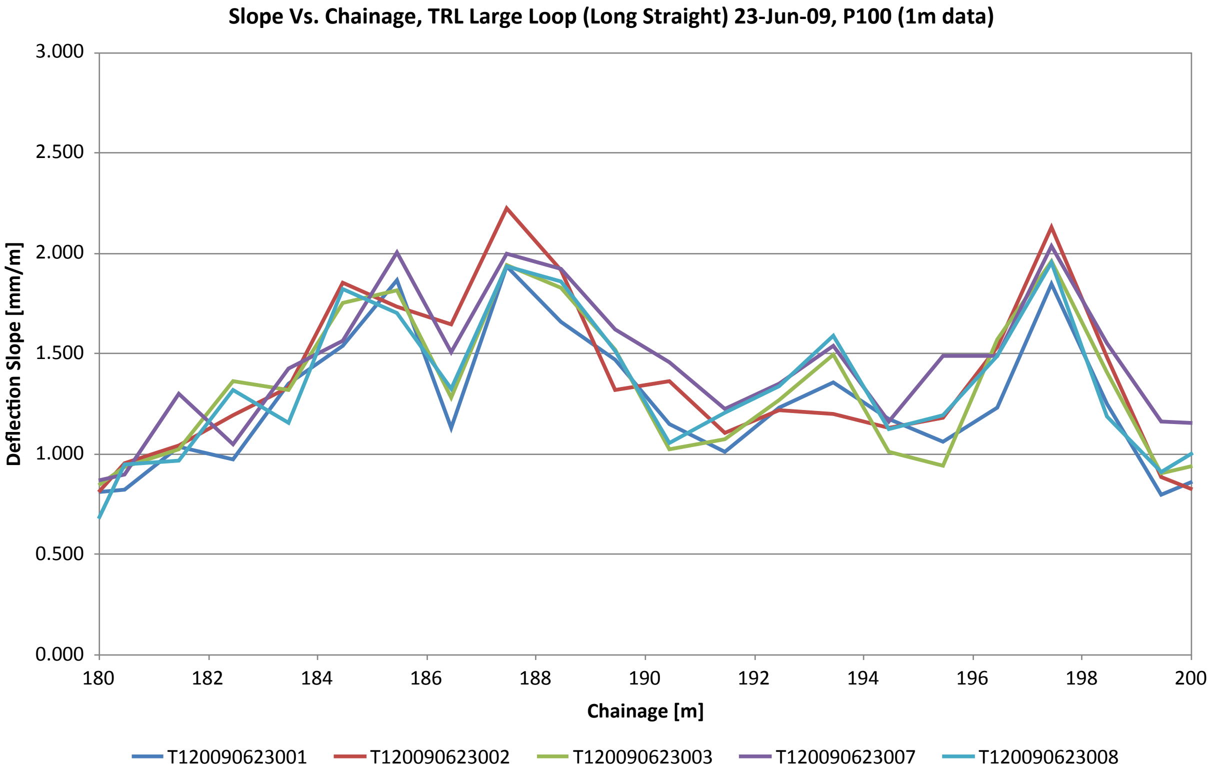


Figure 3.19. Selected 20-m (66-ft) length of TSD slope data as 1 m (3.3 ft) means on TRL track.

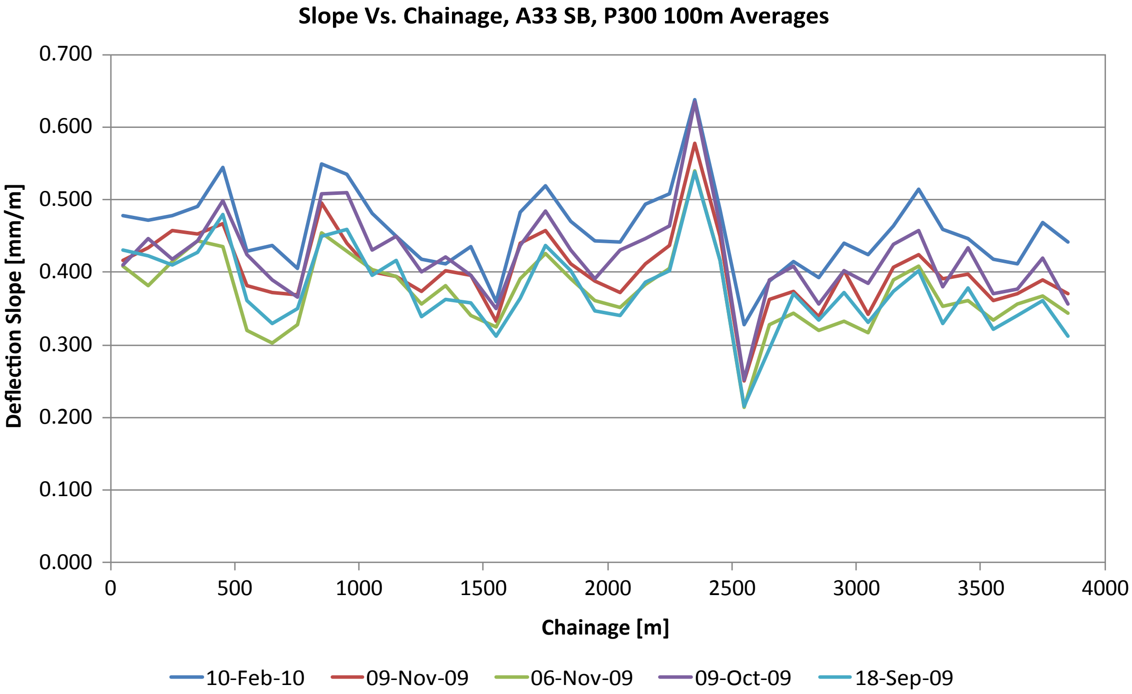


Figure 3.20. Long-term repeatability of deflection slope (P100) at 70 km/h (45 mph) on U.K. Site B, 100-m (330-ft or 0.06-mi) averages.

Table 3.14. Repeatability Standard Deviation of TSD for Five Runs in Terms of TSD Slope for Long-Term Repeatability

Site	Overall Length	Sensor	Repeatability Standard Deviation of TSD Slope (mm/m)		
			Averaging Length		
			10 m (33 ft)	100 m (330 ft)	160.9 m (0.1 mi)
U.K. Site B	3871 m (2.4 mi)	P100	0.065	0.040	0.039
		P300	0.063	0.038	0.038

that the correlation is better on sections with high deflections (having "weak" structural capacity). This is expected because a wider range of the dependent variable increases the correlation coefficient, as is discussed later in this report.

Additional analysis was performed on the New Mexico data that were provided for this project and is presented in the comparability section of the report. The data were collected on U.S. Route 550 in New Mexico and were provided by ARA for this project.

Many comparisons have been made between the TSD and other deflection measuring devices. The early independent evaluation by the LCPC in 2003 (Simonin et al., 2005) of the first Danish Research Institute (DRI) prototype showed a strong correlation ($R^2 = 0.86$) between the slope measured by the DRI TSD and the peak central deflection measured by an FWD over a range of sites in France.

Comparisons in the United Kingdom between the HA TSD and FWD measurements have been less common to date because the main emphasis has been on comparison with the deflectograph, the prime deflection measuring device used in the United Kingdom. However, some comparisons of deflection profiles on specific sites have been made. For example, Figure 3.25 shows a comparison between an FWD central deflection profile at 2-m (6.6-ft) intervals compared with a TSD deflection slope profile averaged over the same intervals on a 400-m (1,300-ft) section of the TRL track. The pavement structure includes both weak flexible composite materials and rigid concrete. Similarities in the shapes of the two profiles are very encouraging despite the 4-year interval between the surveys. It should be noted, however, that the vertical scales of the two parameters are relatively arbitrary and have been adjusted to approximately align the two profiles vertically.

In the United Kingdom, extensive comparisons have been made between the TSD slope and peak deflection measured by a U.K. deflectograph. Figure 3.26 illustrates the average relationship, together with 95% confidence limits, between deflectograph (DFG) values and TSD slope values for the P300 sensor, which is located 300 mm (1 ft) from the center

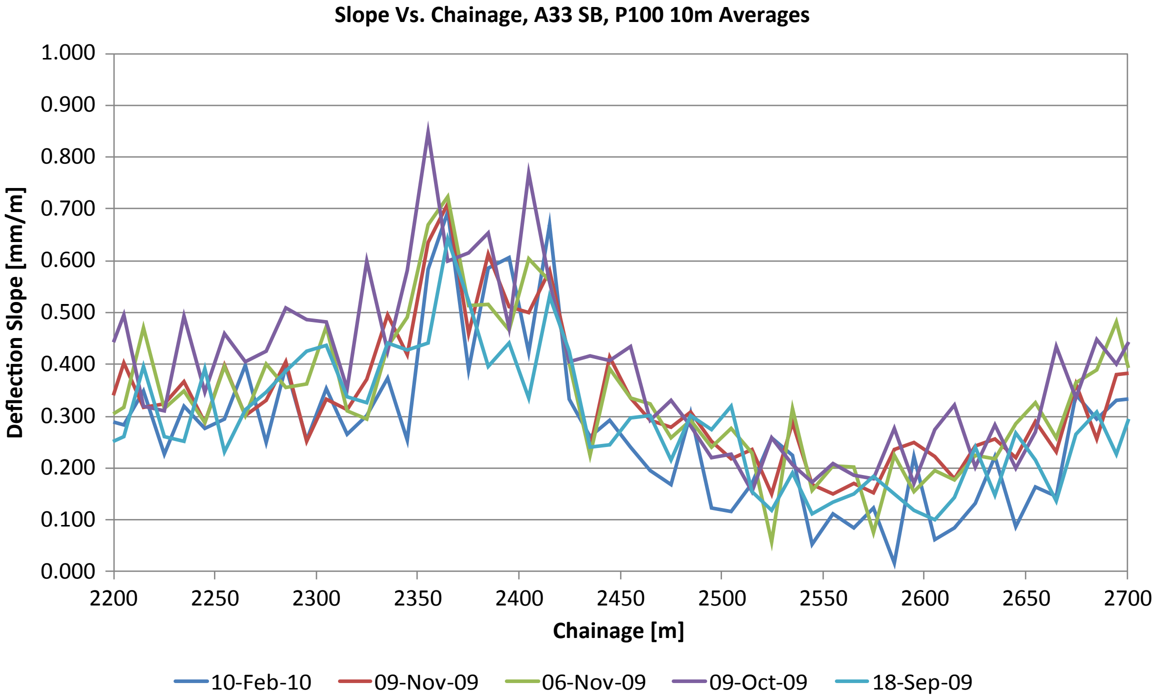


Figure 3.21. TSD slope data, as 10 m (33 ft) means, for five repeat runs over a 5-month period on U.K. Site B.

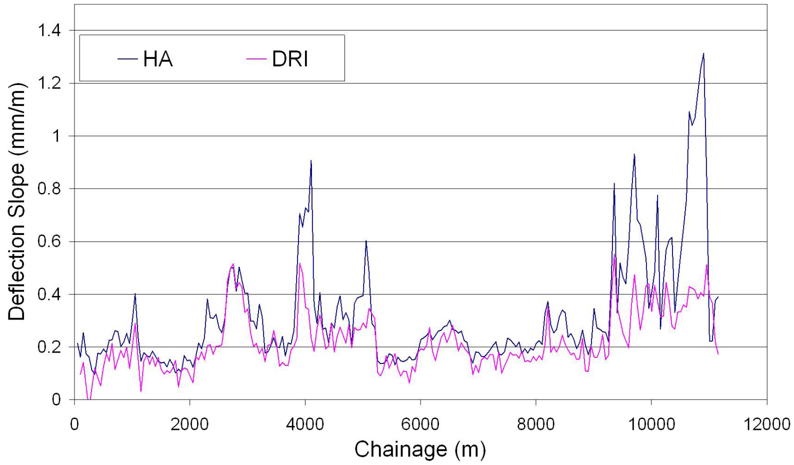


Figure 3.22. Comparison of Highways Agency TSD and Danish Research Institute TSD on a major U.K. road (70-km/h [45-mph], 50-m [165-ft] averages).

of the load. The analysis covered almost 5,000 10-m (3.3-ft) segments on a wide range of U.K. roads.

Phase II Assessment

The data obtained in Phase I and collected in the field trials were analyzed to evaluate the repeatability of the TSD and RWD and the comparability of both devices by comparison with the FWD. In the Detailed Description of the Selected Equipment section, results of different studies that evaluated RWD (conducted in the United States) and TSD (conducted in Europe) were analyzed. It was noted in this analysis that repeatability and comparability were not uniformly defined across all those studies. Measures and methodologies used to evaluate the devices included correlation, regression analysis, standard deviation, and in some cases subjective visual inspection of plots. Most studies also suggested that data averaging length affected repeatability. For example, ARA recommends that RWD results be averaged over 160 m (0.1 mi) but, in the United Kingdom, TSD test results are stored at 1-m (3.3-ft) averages and reported at 10-m (33-ft) averages. This section first discusses, evaluates, and highlights some of the drawbacks associated with the use of correlation and regression analysis to evaluate repeatability and comparability. Then, repeatability and comparability analysis based on the limits of agreement (LOA) method suggested by Bland and Altman (1986) is recommended and used to evaluate the continuous deflection devices. A method of evaluating repeatability from one run is also presented and compared to the method based on the LOA. Finally, the use of smoothing splines as a tool to

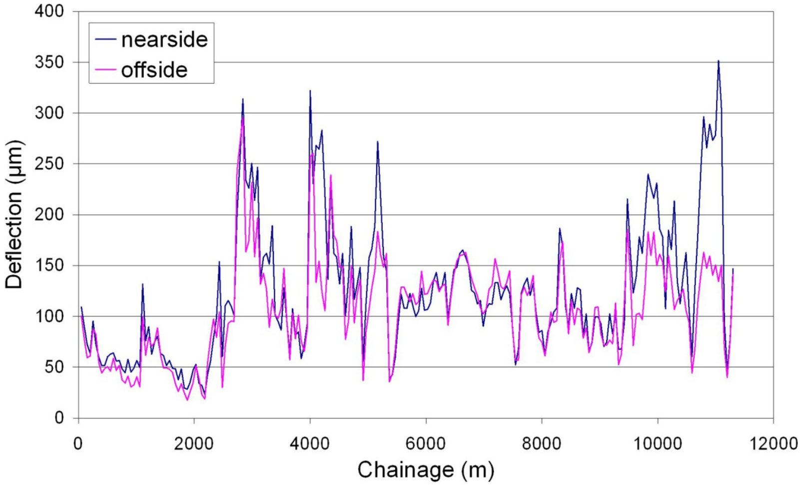
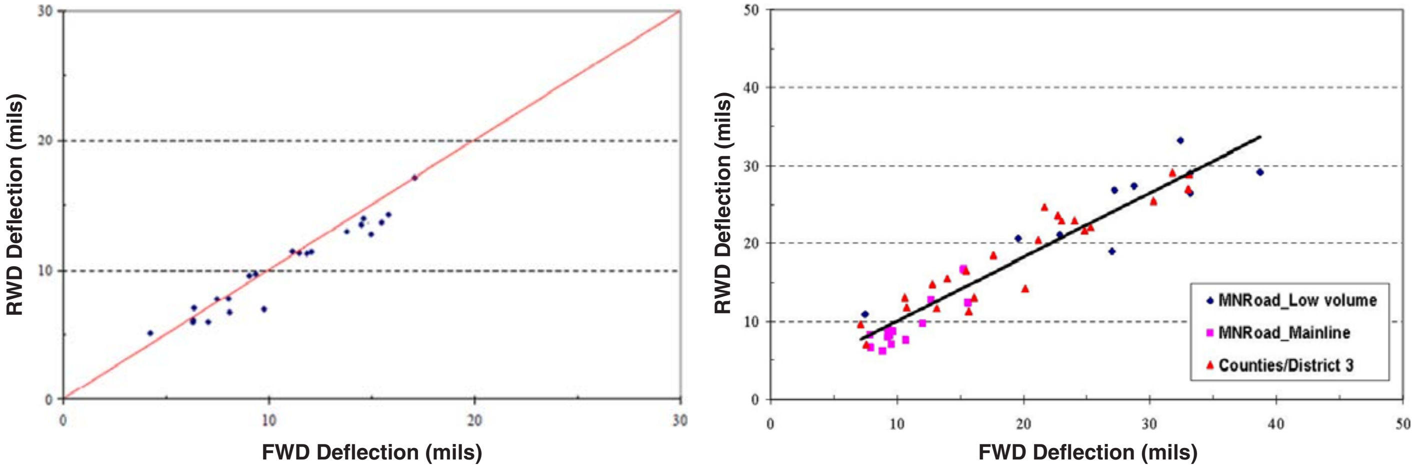
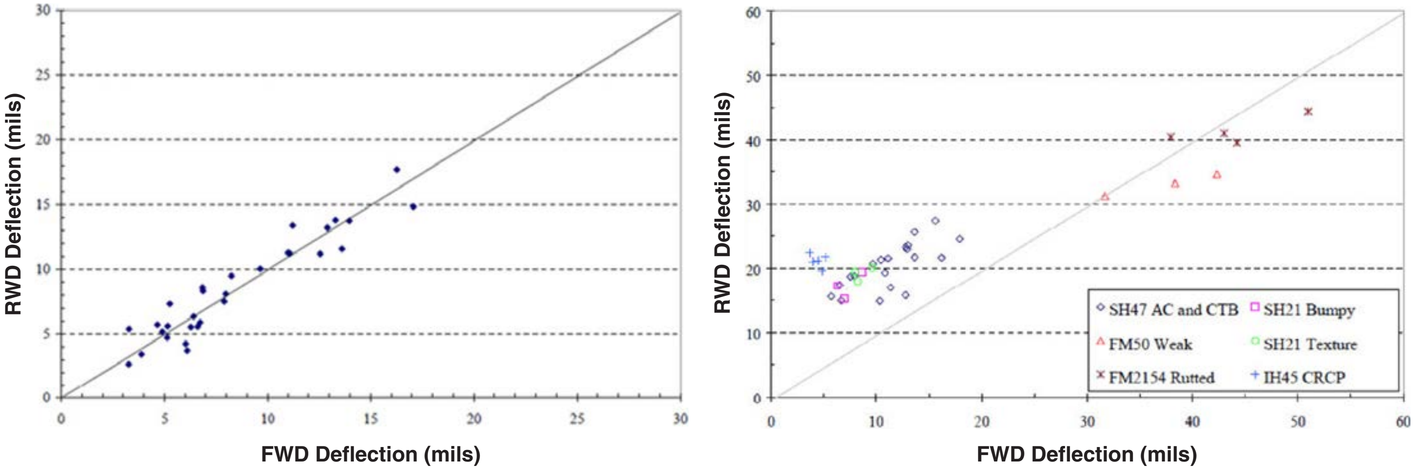


Figure 3.23. Deflectograph data for a major U.K. road at 50-m (165-ft) averages (nearside indicates outside wheelpath, offside indicates inside wheelpath).



(a) Kansas

(b) Minnesota



(c) Iowa

(d) Texas

Source: FHWA, 2009.

Figure 3.24. Examples of RWD versus FWD comparisons.

remove the noise from TSD deflection slope measurements is investigated. This smoothing splines denoising methodology shows potential to improve the frequency at which useful information can be obtained (i.e., data averaging distance).

In this report, repeatability (comparability) is defined as the 95% confidence interval of the difference between repeated measurements (difference between measurements of TSD and FWD or RWD and FWD). Correlation, cross-correlation, and regression are widely used to evaluate repeatability and comparability in many pavement engineering applications such as profile or friction measurements.

Regression Analysis

For regression, the following example uses computer-generated data that simulate repeated measurements. Because the correct answer is known, it illustrates how regression analysis can lead to wrong conclusions. This argument about regression analysis follows closely the one presented by Bland and Altman (2003). The reason it is included in this report is because the use of correlation and regression is so pervasive in the pavement field that their shortcomings (as will be illustrated) are often ignored. The example supposes the true value of any measurement at 600 different locations (for example, pavement deflection) is known to be a sinusoidal wave varying between a minimum of 4 and a maximum of 6 units (Figure 3.27). Repeated measurements, m_1 and m_2, are obtained using an instrument that is known to produce measurements that are contaminated with Gaussian (from a normal distribution) noise with mean zero and standard deviation of 0.5 units (Figure 3.28). Since the relationship between m_1 and m_2 is known to be $m_1 = 1.0m_2 + 0.0$ (i.e., the line of equality), it is desirable that an appropriate statistical analysis can suggest with some confidence this one-to-one relationship.

Figure 3.29 shows m_2 versus m_1 with the true relationship (line of equality) and the regression line. The slope of the

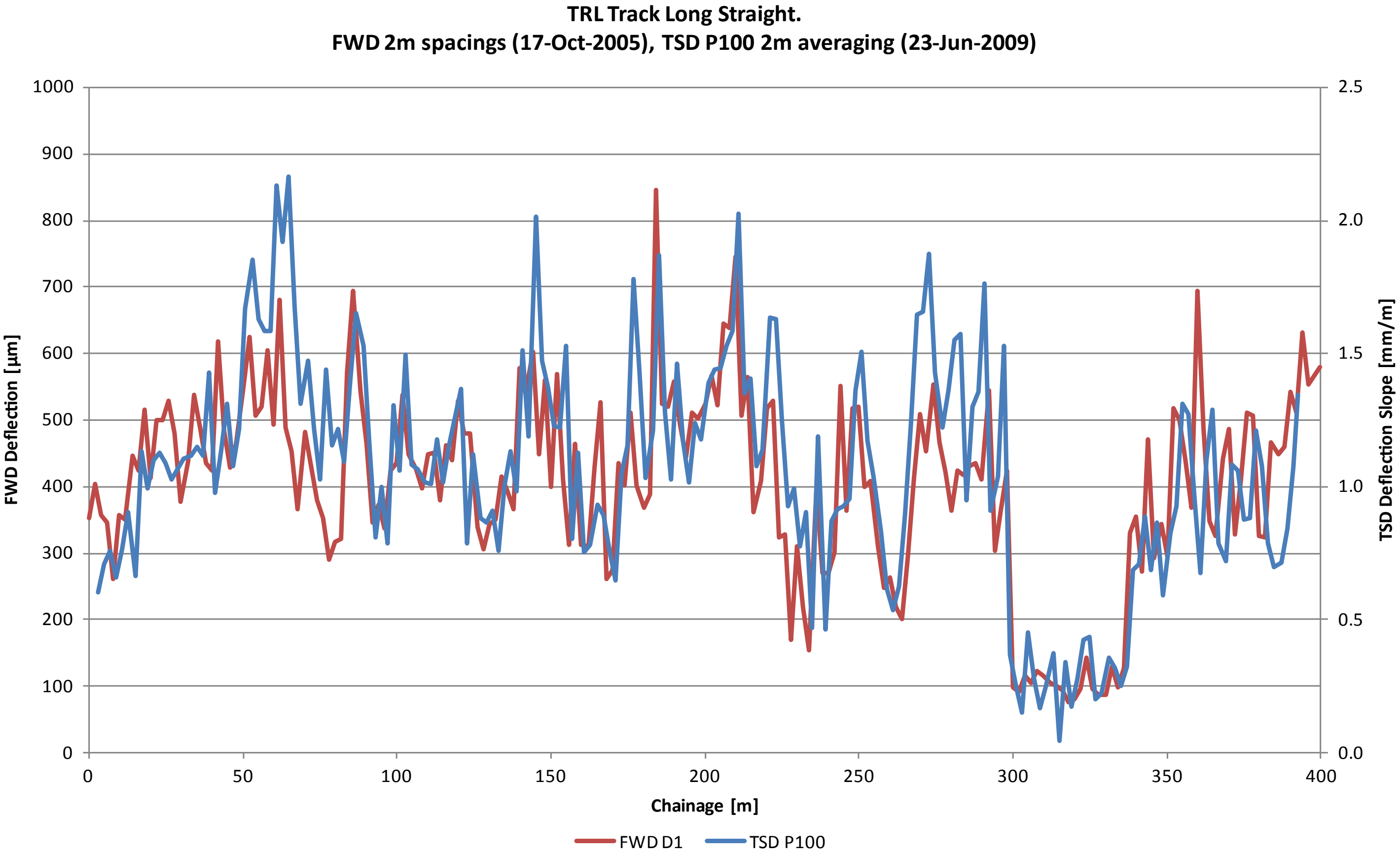


Figure 3.25. Comparison of HA TSD slope and FWD central deflection profiles on flexible composite pavement.

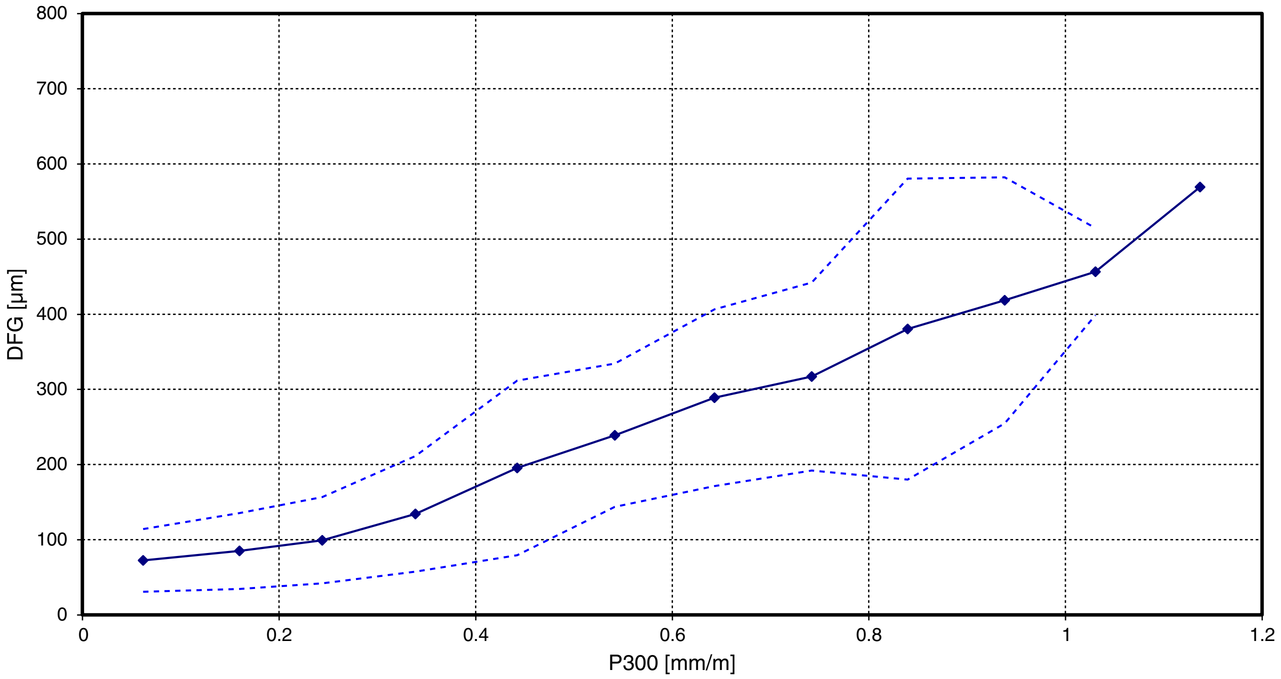


Figure 3.26. Deflectograph versus P300 with 95% confidence intervals.

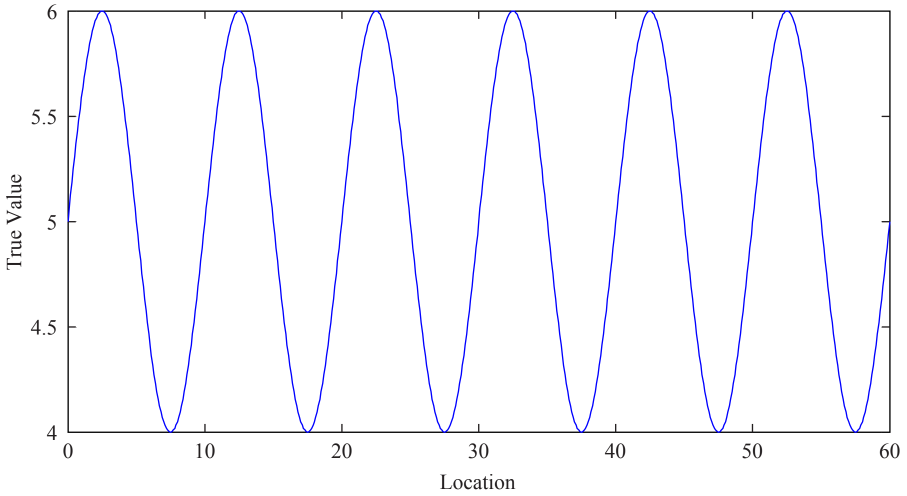


Figure 3.27. Sinusoidal function example for regression analysis.

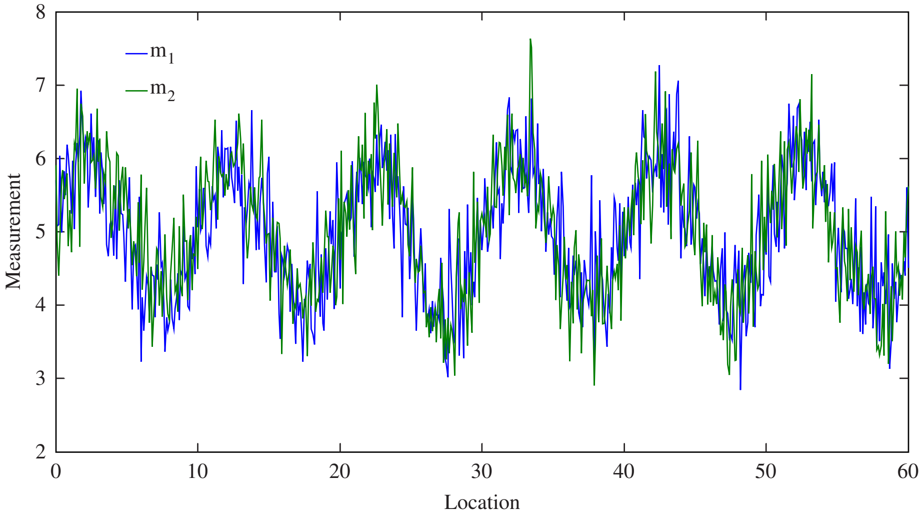


Figure 3.28. Sinusoidal signal with added Gaussian noise.

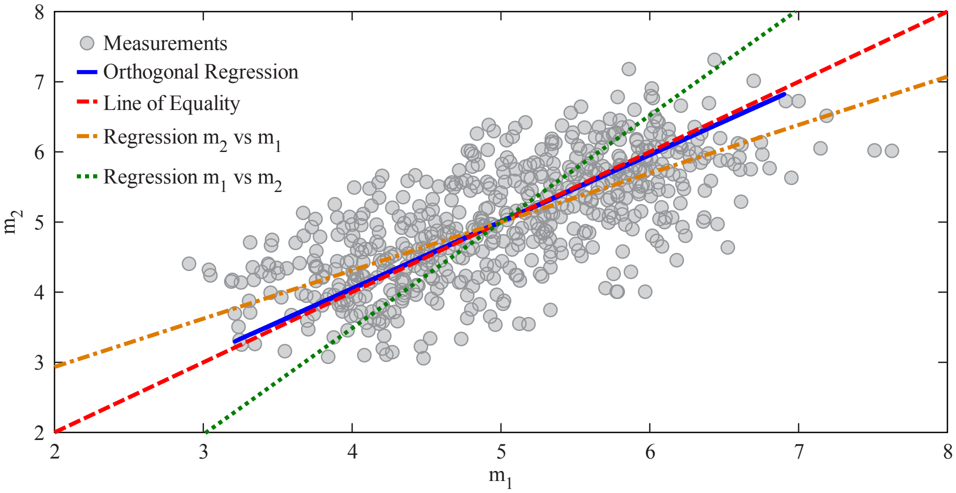


Figure 3.29. Limitation of linear regression when errors are present in the regressor. The relationship between m_1 and m_2 should be the line of equality.

regression line is 0.69, which is different from 1.0, and the intercept is 1.55, which is different from zero. The 95% ($\alpha = 0.05$) confidence interval on the slope is [0.63; 0.75], while the 95% confidence interval on the intercept is [1.08; 2.03]. Both slope and intercept are statistically different from 1.0 and 0, respectively, suggesting that the relationship between the two measurements does not follow the line of equality (which we know it does). Therefore, ordinary regression analysis is leading to the wrong conclusion. The cause for the failure of regression analysis in this case is the presence of error in the regressors (errors in m_1), which violates the conditions of the Gauss-Markov theorem. This violation leads to the least-squares regression coefficients to be biased (Myers, 1990). The irony of this is that the more measurements that are obtained, the narrower the confidence interval on the biased slope, which strengthens the wrong conclusion that the relationship between the two measurements does not follow the equality line.

The alternative to linear regression when errors are present in both variables is the total least-squares regression (Van Huffel and Wandewalle, 1991). When errors in both variables have the same variance, total least-squares regression is equivalent to orthogonal regression. The difference is that while ordinary least squares minimizes the squared distance from the dependent variable to the fitted function, orthogonal regression minimizes the square of the perpendicular distance to the fitted function. The orthogonal regression for m_1 and m_2 is presented in Figure 3.29. The slope of the orthogonal regression line is 0.96, which is very close to 1.0 (the 95% confidence interval is [0.92; 1.00]). More information on this procedure can be found in Leng et al. (2007).

Another way to look at this example is using the relationship $m_2 = 0.69m_1 + 1.6$, calculate $m_1 = 1.45m_2 - 2.32$. Since there is no specific reason to do the regression with m_1 as the x-variable, it could be done with m_2 as the x-variable. In this case, the relationship $m_1 = 0.66m_2 + 1.7$ is obtained, which is different from $m_1 = 1.45m_2 - 2.32$. The two regressions, using m_1 or m_2 as the x-variable, are presented in Figure 3.29. The relationship between m_1 and m_2 is not the same in each case. There is no reason to favor the use of m_1 as the x-variable to the alternative of using m_2 as the x-variable. This clearly illustrates the inadequacies of linear regression to evaluate the repeatability of a given device.

Data Analysis Using Correlation

The drawbacks of using correlation are similar to the drawbacks of regression analysis (although they are not completely the same). Here, instead of using artificial data, the actual repeated TSD slope measurements obtained on different pavement sections are used to illustrate the drawbacks of correlation.

Correlation measures have been extensively used to evaluate repeatability or "accuracy"—with respect to FWD—of measures of continuous deflection data. This use of correlation is also prevalent in the analysis of pavement profile and friction data. However, the use of correlation can be very misleading, as discussed by Bland and Altman (1986, 2003). Correlation does not give agreement between repeated measures. For example, two measures that vary exactly by any factor give a correlation of 1 (or −1, if the factor is negative). A measuring device that gives repeated measurements that can vary by some factor is not one that is described as repeatable. Another drawback of correlation is that it depends on the range of the true measurement; the wider the range, the greater the correlation. In the extreme case, a pavement that is perfectly homogeneous (i.e., strength is constant) will practically result in a zero correlation no matter how repeatable the device is. This is because the calculated correlation in this case is that of the error terms, which are randomly uncorrelated. Correlation should therefore be used with caution when evaluating repeatability. This is not to say that correlation should never be used. For example, the proposed method of taking differences is not applicable when comparing devices that measure two different physical quantities (such as TSD and FWD). In this case, unless the two measurements can be converted to the same quantity, correlation (or for that matter, linear regression) might be a better choice.

The average correlations between the different repeated TSD measurements obtained in this study for each section are presented in Figure 3.30. The correlations are not the same for the different sections. Interpreting the correlation as a measure of repeatability would give significantly different repeatability results depending on the tested section. As seen in Figure 3.30, for an averaging distance of 1 m, the correlation varies from under 0.10 to almost 0.90. Which correlation value in this range gives the repeatability of the device? The tested sections had a significant effect on the correlation. As expected, sections with low correlations are those that had low variation in the measured slope, and sections with high correlations are those that had high variation in the measured slope. For example, section F1 resulted in a significantly higher correlation than did all the other sections; especially for sensor 100 and 1-m averaging length. It can be concluded that correlation is a good indicator of the variability in the pavement section rather than in the repeatability of the device. This sentiment was somewhat echoed, in more technical terms, by Bland and Altman (2003): "[T]he correlation coefficient is a measure of the information content of the measurement." This clearly shows how correlation can lead to false conclusions when evaluating a device.

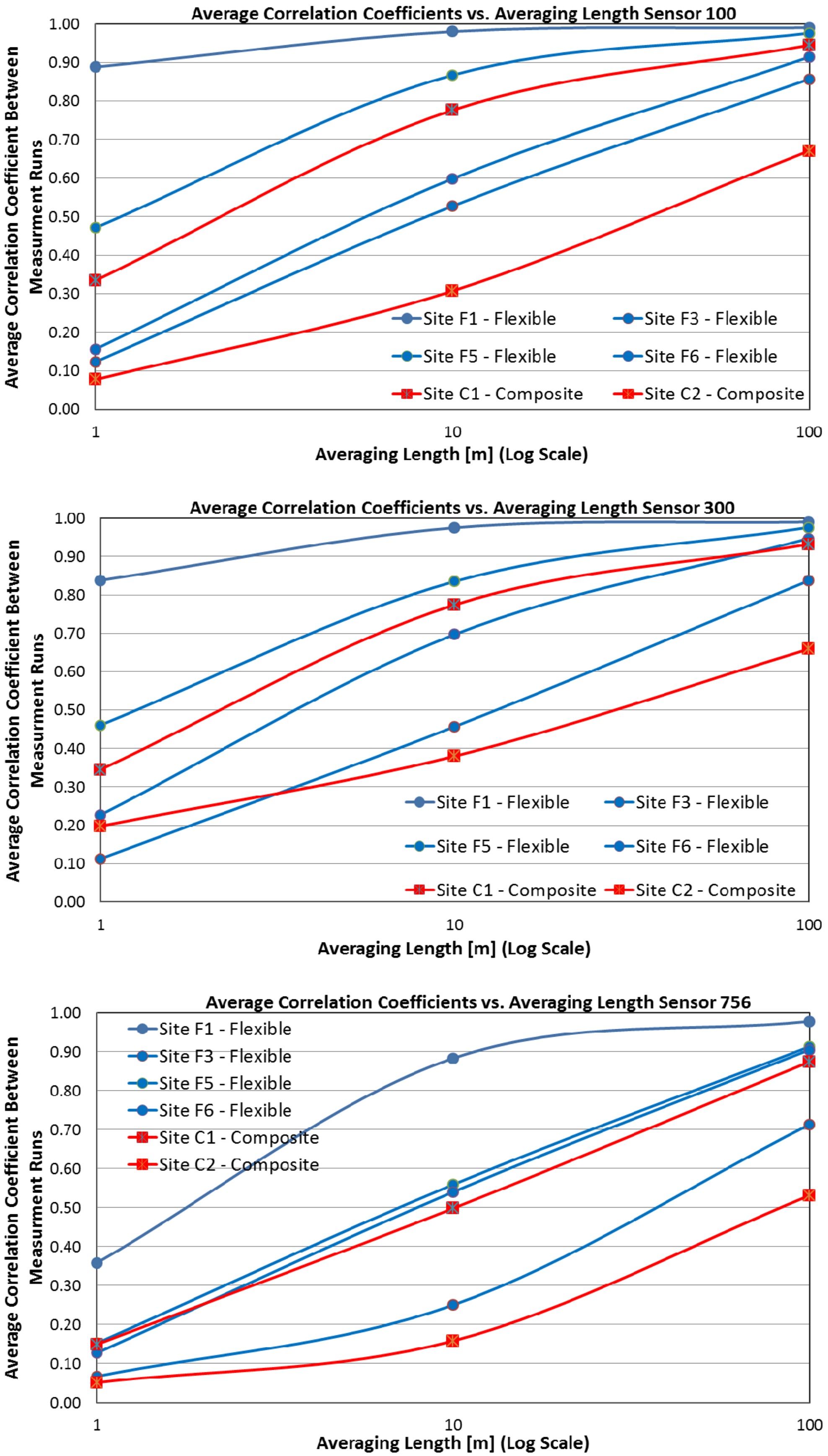


Figure 3.30. Correlation coefficient versus averaging length for three TSD sensors.

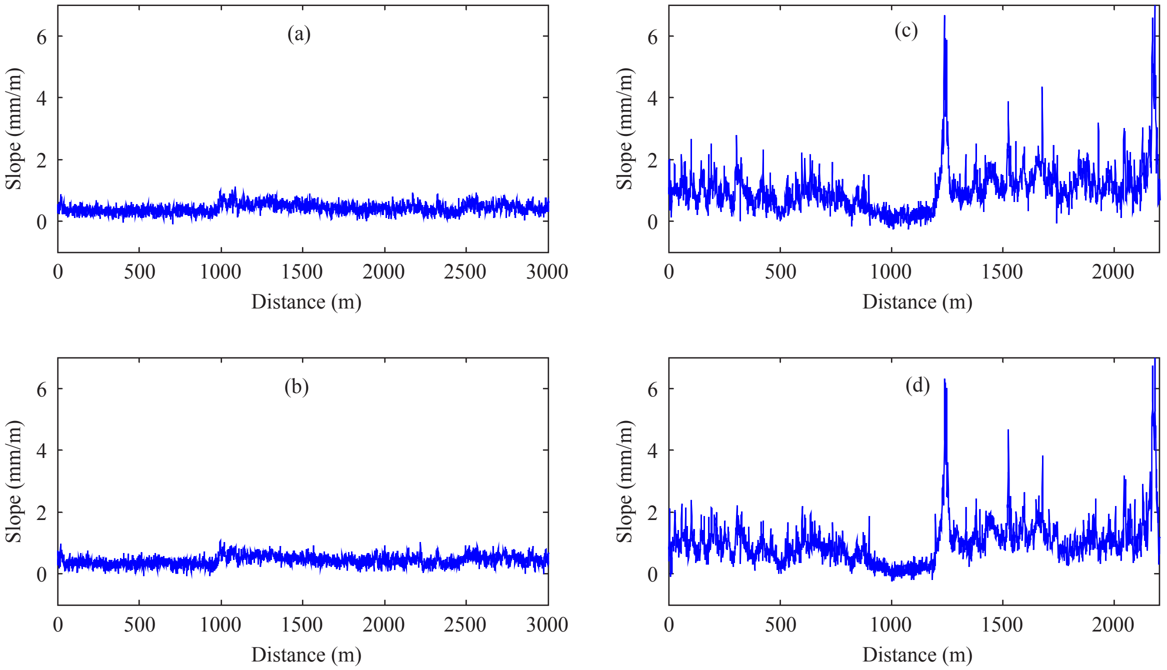


Figure 3.31. Measured deflection slope on two different flexible pavement sections: (a) first run on Section UK_F5, (b) second run on Section UK_F5, (c) first run on Section UK_F1, and (d) second run on Section UK_F1.

Figure 3.31 shows two different flexible pavement sections, one with high variation in the deflection slope (UK_F1) and another with low and uniform deflection slope (UK_F5). The correlation between repeated runs is significantly different for each section; UK_F1 had a high correlation (close to 0.9), while UK_F5 had a much lower correlation (less than 0.5). However, the measurements' noise levels are comparable, as can be observed from visual inspection of the plots.

Another observation is that the correlation varies with the distance between the sensor and the applied load. This results from the fact that sensors closer to the loaded area measure higher slopes, which increases the correlation. As a summary, correlation depends on the tested pavement (or range of measurements), the instrument location (again, partly caused by different range of measurements), and averaging length. In many cases, these factors have a much more significant effect on the correlation than does the effect of errors in the measurements.

However, a device repeatability measure should be, as much as possible, independent of the tested pavement. Not having this independence can lead to significantly different opinions about the suitability of the device. For example, somebody evaluating the device on the F1 section would be very pleased with the performance based on the correlation and somebody evaluating the device on the C2 section would be very disappointed in the device. The repeatability measure adopted in this study, in contrast, gives comparable results and is therefore much less affected by the tested pavement section.

Repeatability

The definition of repeatability given by the British Standard Institution (1979) was adopted in this report. It is defined as "the value below which the difference between two single test results . . . may be expected to lie with a specified probability." The specified probability was set at 95%, and repeatability was calculated using the procedure suggested in a series of papers by Bland and Altman (Altman and Bland, 1983; Bland and Altman, 1986, 2003, 2007). The main idea is to estimate the standard deviation of the difference between repeated measurements from the same device (repeatability) or difference between measurements from two different devices (comparability) and construct the 95% confidence interval using $1.96\sigma_d$, where σ_d is the standard deviation of the difference. In the case of comparability, this 95% confidence interval is referred to as the limits of agreement (LOA) between the two devices. In their procedure, Bland and Altman also specified calculating the bias between two different devices, while for the same device they incorporated this bias in the repeatability measure. This report shows the results of incorporating or not incorporating the bias in the repeatability measure. For all practical purposes, the two methods resulted in the same repeatability because the bias was negligible. For repeatability

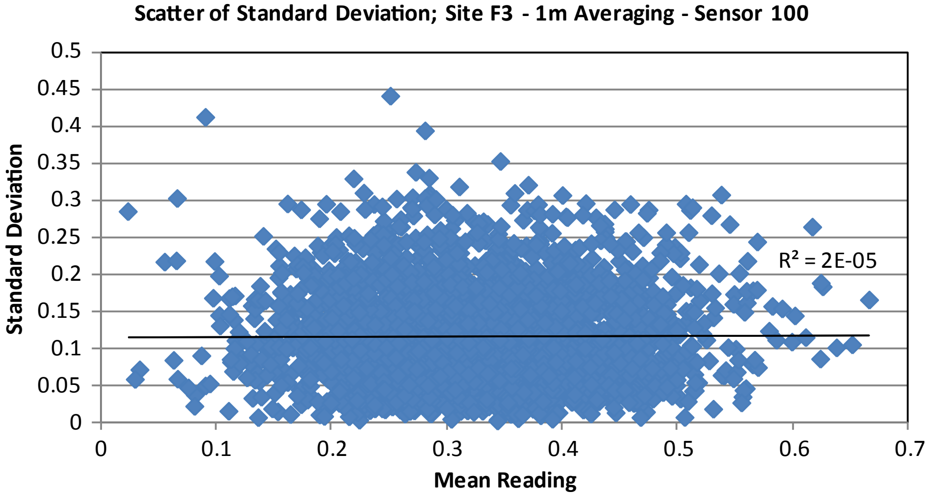


Figure 3.32. Scatter of standard deviation versus mean for low average readings.

measures between the FWD and TSD or the FWD and RWD, the bias was not incorporated.

TSD Repeatability

The analysis of TSD repeatability was performed for measurements averaged over 1-m, 10-m, and 100-m distances. Five runs were obtained for each test section (except for Section F1, which had four runs, and for Sections F3 and R2, each which had three runs) resulting in five sets of slope measures at each location.

For repeatability (or comparability) analysis, it is important to check whether measurement repeatability depends on the actual measurement level (in other words, the measurement error depends on the actual measurement). In the case of two repeated measures, Altman and Bland (1983) suggested plotting $|x_1 - x_2|$ against $(x_1 + x_2)/2$. For the case where three or more repeated measures were obtained, the plot shows the standard deviation of the measurements at each location against the average of the measurements at each location (both plots give the same qualitative view). Figure 3.32 shows the standard deviation as a function of average slope for a relatively strong flexible pavement test section labeled F3 for slope measurements averaged over a 1-m interval. The figure suggests the standard deviation (and therefore equipment repeatability) is independent of the measured slope in the range of measurements.

The observation was consistent for all other tested sections except for the flexible section labeled F1 shown in Figure 3.33, and the rigid section labeled R2. Both sections included

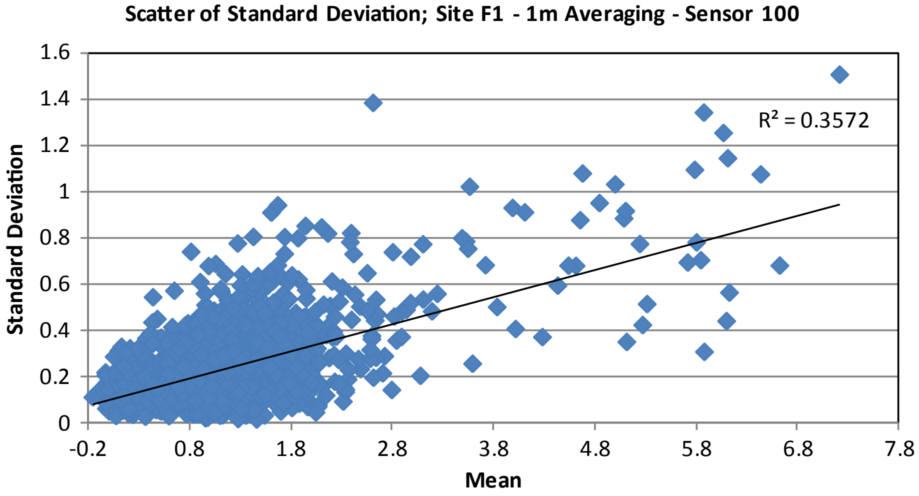


Figure 3.33. Scatter of standard deviation versus mean for high average readings.

relatively very weak spots, with significant deterioration. In Figure 3.33, the standard deviation is dependent on the associated measured slope. A possible explanation for this dependence could be that there are two main sources of variation in the slope measurement. The first source is due to the error from the sensors, vehicle dynamics, and any other factors that can affect the TSD (temperature, moisture, etc.). This source of variability is expected in most cases to be independent of the associated measurement. The second source of variability is due to the spatial variability in the pavement strength. Weaker pavements tend to have more distress factors, such as cracking, which result in a greater spatial variability on the strength and, therefore, the deflection measurements. It is important to note that this source of variability is not caused by the device.

Repeatability is closely related to the estimation of error in measurements obtained from a device. This error is composed of variance and bias. Therefore, repeatability can be defined by either the variance or the error (variance and bias). The advantage of defining repeatability in terms of variance and keeping bias as a separate measure is that causes of bias can often be identified and corrected. For example, in measurements on flexible pavement, bias can be the result of a temperature difference between repeated tests. More commonly, bias is caused by different operational characteristics or the equipment getting out of calibration. Table 3.15

Table 3.15. Consistency of TSD Measurements over Repeated Runs: Incorporating Bias in Standard Deviation

		Sensor 100			Sensor 300			Sensor 756		
Road Section	**Data Averaging (mm/m)**	**Average Reading (mm/m)**	**Std. Dev. (mm/m)**	**cov**	**Average Reading (mm/m)**	**Std. Dev. (mm/m)**	**cov**	**Average Reading (mm/m)**	**Std. Dev. (mm/m)**	**cov**
F1	1	1.0468	0.2661	0.2542	0.6198	0.1918	0.3095	0.3169	0.144	0.4544
	10		0.1054	0.1007		0.0717	0.1157		0.0383	0.1209
	100		0.0625	0.0597		0.038	0.0613		0.0146	0.0461
F3	1	0.3226	0.1305	0.4045	0.2202	0.1376	0.6249	0.2279	0.1281	0.5621
	10		0.0407	0.1262		0.0415	0.1885		0.0412	0.1808
	100		0.0155	0.048		0.0139	0.0631		0.0137	0.0601
F5	1	0.4356	0.1166	0.2677	0.3691	0.1123	0.3043	0.3767	0.1096	0.2909
	10		0.0401	0.0921		0.0383	0.1038		0.0367	0.0974
	100		0.0147	0.0337		0.0128	0.0347		0.0111	0.0295
F6	1	0.4176	0.1254	0.3003	0.3252	0.121	0.3721	0.4316	0.1169	0.2709
	10		0.0406	0.0972		0.0382	0.1175		0.0373	0.0864
	100		0.0139	0.0333		0.0124	0.0381		0.0119	0.0276
C1	1	0.4786	0.1466	0.3063	0.3779	0.1398	0.3699	0.4386	0.1355	0.3089
	10		0.0519	0.1084		0.0489	0.1294		0.0498	0.1135
	100		0.0306	0.0639		0.0292	0.0773		0.0276	0.0629
C2	1	0.3469	0.1222	0.3523	0.2811	0.1226	0.4361	0.2949	0.1146	0.3886
	10		0.0408	0.1176		0.0398	0.1416		0.039	0.1322
	100		0.0142	0.0409		0.0146	0.0519		0.0143	0.0485
R2	1	0.5859	0.2072	0.3537	0.3972	0.1671	0.4207	0.3511	0.1217	0.3466
	10		0.0643	0.1098		0.0558	0.1405		0.0512	0.1457
	100		na	na		na	na		na	na
R3	1	0.343	0.1483	0.4322	0.2356	0.1378	0.5846	0.3441	0.1419	0.4122
	10		0.0432	0.1258		0.0404	0.1716		0.0433	0.1257
	100		0.0153	0.0446		0.0136	0.0579		0.0148	0.0431

Note: cov = coefficient of variation. F = flexible; C = composite; R = rigid (road types); and na = not applicable.

presents results with the bias incorporated in the standard deviation calculation. Table 3.16 presents results with the bias taken out of the standard deviation.

A comparison of the results presented in both tables suggests that the effect of bias in the obtained measurements is negligible. This is confirmed by the bias results presented in Table 3.16, which shows the bias to be small compared to the standard deviation. However, the effect of the bias becomes more significant for measurements averaged over longer distances (for example, when averaging over 100 m [330 ft] compared to 1 m [3.3 ft]). This is because averaging over longer distances reduces the variance while keeping the bias constant. Therefore, the relative effect of the bias becomes more significant.

This effect was observed in the section labeled C1. In this case, incorporating the bias into the standard deviation of measurements averaged over a 100-m (330-ft) distance resulted in a standard deviation that is twice as large as the standard deviation calculated by not incorporating the bias (compare Table 3.15 and Table 3.16 for C1). Figure 3.34 shows that one of the runs has a significant systematic bias and is shifted up compared to the others. Note that the effect of the bias is much less pronounced for averaging distances of 1 m (3.3 ft) and 10 m (33 ft) for which the standard deviation

Table 3.16. Repeatability of TSD Measurements over Repeated Runs: Excluding Bias from Standard Deviation

		Sensor 100			Sensor 300			Sensor 756		
Road Section	**Averaging Length (m)**	**Std. Dev. (mm/m)**	**Bias (mm/m)**	**Rep.[a] (mm/m)**	**Std. Dev. (mm/m)**	**Bias (mm/m)**	**Rep.[a] (mm/m)**	**Std. Dev. (mm/m)**	**Bias (mm/m)**	**Rep.[a] (mm/m)**
F1	1	0.2649	0.0328	0.5192	0.1771	0.0169	0.3471	0.1333	0.0054	0.2613
	10	0.1024		0.2007	0.0653		0.128	0.0353		0.0629
	100	0.0583		0.1143	0.0335		0.0657			0.0257
F3	1	0.1304	0.0068	0.2556	0.1376	0.0051	0.2697	0.1280	0.0055	0.2509
	10	0.0404		0.0792	0.0414		0.0811	0.0410		0.0804
	100	0.0149		0.0292	0.0137		0.0269	0.0132		0.0259
F5	1	0.1165	0.0067	0.2283	0.1122	0.0056	0.2199	0.1096	0.0026	0.2148
	10	0.0397		0.0778	0.0381		0.0647	0.0367		0.0719
	100	0.0136		0.0267	0.0122		0.0239	0.0111		0.0218
F6	1	0.1254	0.0044	0.2283	0.1209	0.0035	0.2370	0.1169	0.0035	0.2291
	10	0.0405		0.0794	0.0381		0.0747	0.0372		0.0729
	100	0.0136		0.0267	0.0122		0.0239	0.0117		0.0229
R2	1	0.2069	0.0161	0.405	0.1666	0.0186	0.3265	0.1217	0.0033	0.2385
	10	0.0634		0.1243	0.0541		0.1060	0.0513		0.1005
	100	na	na	na	na	na	na	na	na	na
R3	1	0.1482	0.0080	0.2905	0.1377	0.0062	0.2699	0.1420	0.0064	0.2780
	10	0.0427		0.0837	0.0403		0.0790	0.0431		0.0845
	100	0.0142		0.0278	0.01333		0.0261	0.0145		0.0284
C1	1	0.1430	0.0334	0.2803	0.1375	0.0262	0.2695	0.1332	0.0267	0.2611
	10	0.0446		0.0874	0.0421		0.0825	0.0432		0.0847
	100	0.0153		0.0300	0.0155		0.0304	0.0123		0.0241
C2	1	0.1221	0.0070	0.2393	0.1224	0.0103	0.2399	0.1145	0.0061	0.2244
	10	0.0404		0.0792	0.0389		0.0762	0.0386		0.0757
	100	0.0129		0.0253	0.0121		0.0237	0.0132		0.0259

Note: F = flexible; C = composite; R = rigid (road types); and na = not applicable.

[a] Rep. = repeatability or 1.96 * std. dev.

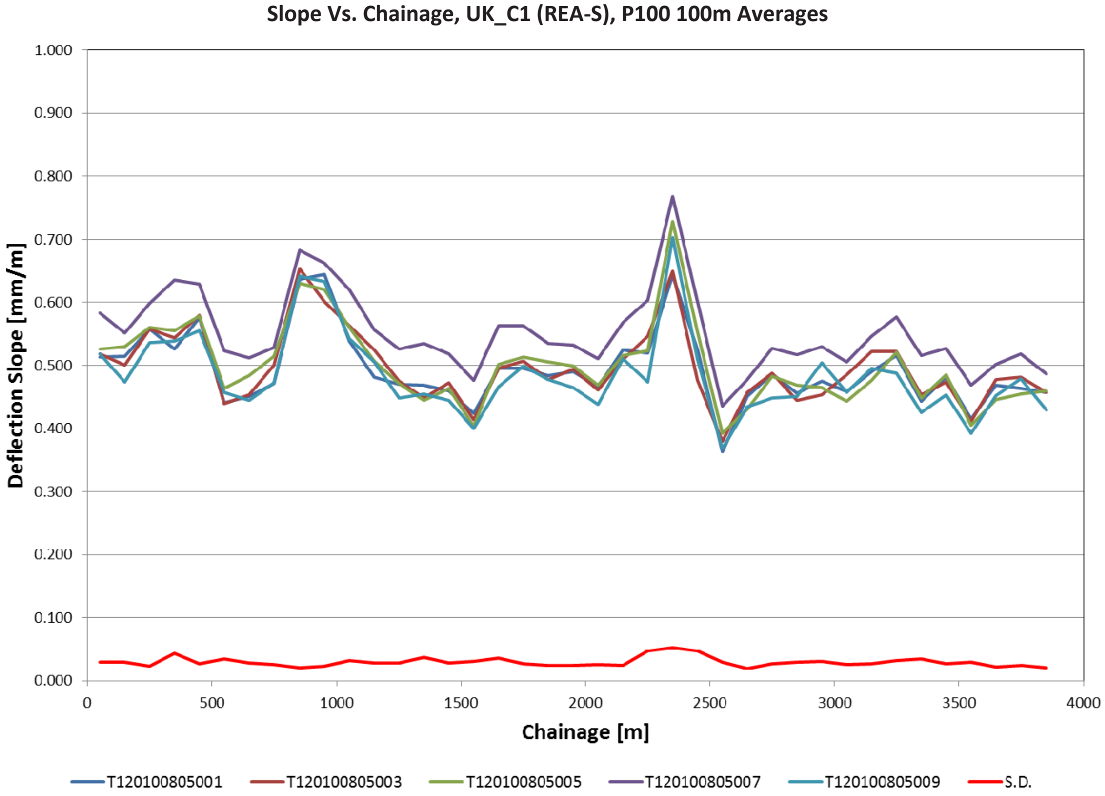


Figure 3.34. Measured slope averaged over 100-m length for Site C1.

of C1 is similar to that of the other sections. In this analysis, of all tested sections, C1 was the only one that had a statistically significant bias.

The results presented in Table 3.15 and Table 3.16 were obtained using the method of analysis of variance (ANOVA). The procedure can be illustrated using two repeated measurements. For the TSD, each slope measurement consists of the actual slope and an error term. This can be expressed as follows:

$$y_{ij} = s_{ij} + e_{ij} \tag{3.2}$$

where

y_{ij} = TSD slope measurement at location i for run j,
s_{ij} = actual (unknown) slope at location i during run j, and
e_{ij} = error in TSD slope measurement at location i for run j.

The first two runs for F5 are shown in Figure 3.35a. Figure 3.35b shows the difference between the two runs. The mean of this difference is an estimate of the bias between the two runs, while the variance of the difference represents the sum of the error variances for each run (Bland and Altman, 1986).

Assuming the variance for each run is the same, the measurement variance can be estimated by dividing the variance of the difference by two. For example, taking the difference between runs 1 and 2, the bias and variances can be calculated as follows:

$$Bias = \sum_{i=1}^{N} \frac{y_{i1} - y_{i2}}{N} \tag{3.3}$$

$$\sigma_d^2 = \sum_{i=1}^{N} \frac{\left[Bias - \left(y_{i1} - y_{i2}\right)\right]^2}{N-1} \tag{3.4.a}$$

$$\sigma^2 = \frac{1}{2} \sum_{i=1}^{N} \frac{\left[Bias - \left(y_{i1} - y_{i2}\right)\right]^2}{N-1} \tag{3.4.b}$$

where

N = total number of data points per run,
σ_d^2 = variance of the differences, and
σ^2 = variance of the measurements.

If both bias and variance are used to estimate the repeatability (see Bland and Altman, 1986), the mean squared difference (MSD) can be calculated as follows:

$$MSD = \frac{1}{2} \sum_{i=1}^{N} \frac{\left[\left(y_{i1} - y_{i2}\right)\right]^2}{N} \tag{3.5}$$

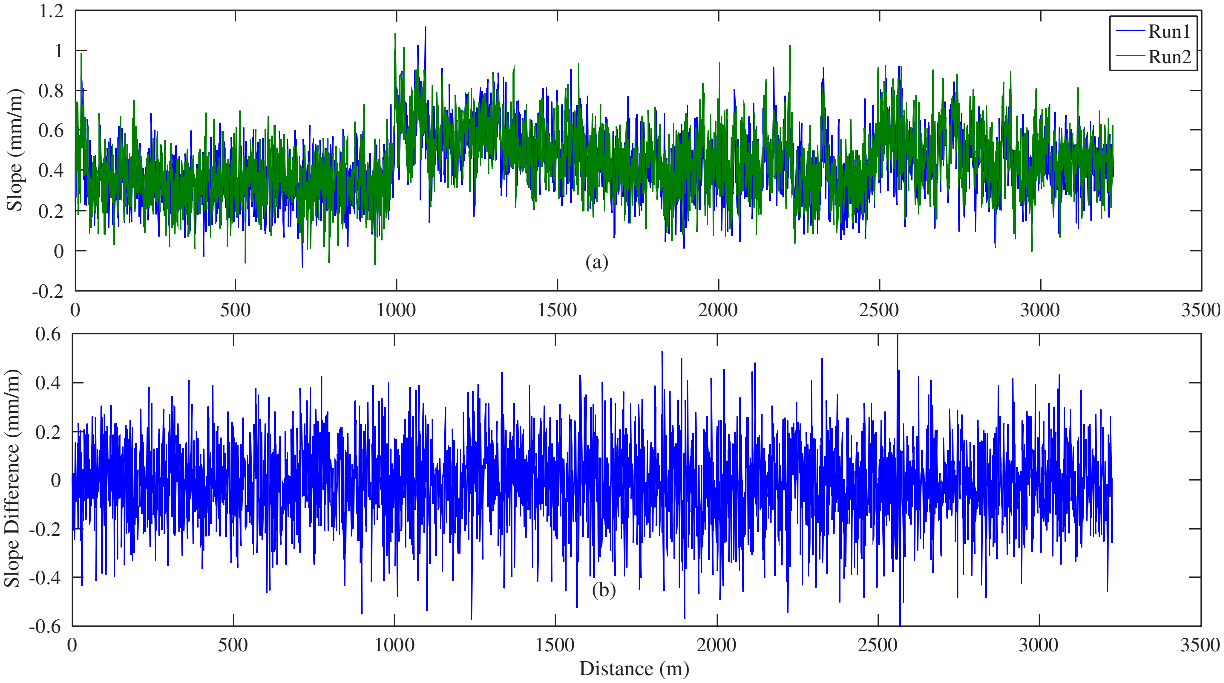


Figure 3.35. Comparison of P100 measurements of Runs 1 and 2 for Site F5 (a), and difference between the two runs (b).

The factor ½ in the calculation of the variance (or MSD) reflects that the measurement variance is half the variance of the difference. The calculated variances (in the case of Equation 3.3), using the difference between the first run and each of the remaining 4 runs for F5 for the 1-m (3.3-ft) averaging distance, were 0.0141, 0.0132, 0.0130, and 0.0135 mm/m. Levene's test of equal variance with $\alpha = 0.05$ showed that the variances are equal. Because the calculated variances using the difference between different pairs of runs are equal, the TSD error variance can be estimated as the average of the calculated variances. The TSD error standard deviation can then be calculated as the square root of the variance. The resulting standard deviation calculated for F5 and 1 m (3.3 ft) TSD measurement averaging was 0.1165 mm/m. This procedure is essentially implemented in MATLAB in the function called "anova2."

Calculation of the repeatability coefficient was performed using the $1.96\sigma_d$ estimate of confidence interval. This estimate was used after the error distribution was found to follow a normal distribution (using the Anderson–Darling test for normality). The repeatability calculated for all sections is presented in Table 3.16.

RWD Repeatability Analysis

A similar analysis (which separates the bias and variance) was conducted for the RWD using the data obtained in Phase I for Virginia. Although the device has been improved, this analysis permits the establishment of a baseline repeatability value. The analysis of repeatability was performed using three RWD repeated measurements averaged over 160 m (0.1 mi) collected over a distance of 32 km (20 mi) on I-64 for both eastbound and westbound directions. Figure 3.36 shows the test results for the eastbound direction. The difference between the first and second runs is shown in Figure 3.37.

A test of normality showed that the differences between the two measurements are normally distributed. The calculated standard deviations of the difference (σ_d) between Runs 1 and 2, Runs 1 and 3, and Runs 2 and 3 are 24.9, 27.3, and 27.2 μm (0.98, 1.07, and 1.07 mils), respectively, for the eastbound direction, and 26.1, 24.3, and 24.8 μm (1.03, 0.96, and 0.98 mils), respectively, for the westbound direction. Differences between the standard deviations were found not to be statistically significant at the 0.05 significance level using Levene's test of equal variances. Therefore, the error defined as the standard deviation of RWD measurements (σ) was calculated as 18.2 μm (0.72 mils). This standard deviation was computed by dividing σ_d by the square root of 2.

The bias between the runs is defined as the mean of the difference. For the eastbound direction, the biases between Runs 1 and 2, Runs 1 and 3, and Runs 2 and 3 are 3.93, 18.4, and 14.5 μm (0.15, 0.72, and 0.57 mils), respectively. For the westbound direction, the biases between Runs 1 and 2, Runs 1 and 3, and Runs 2 and 3 are 14.2, 6.5, and −7.7 μm (0.56, 0.26, and −0.30 mils), respectively. All these biases were found to

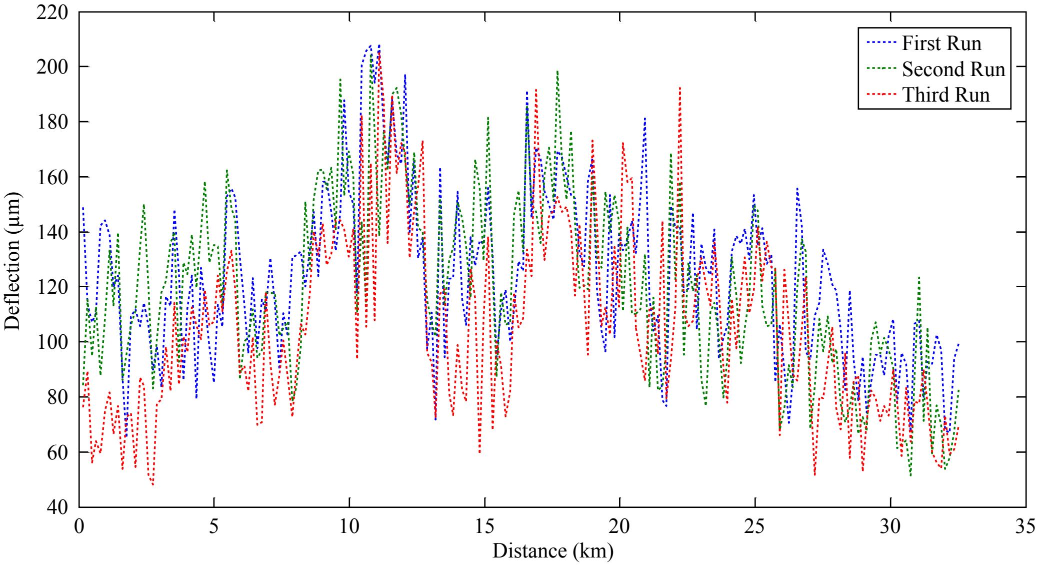


Figure 3.36. RWD deflections on eastbound I-64 in Virginia.

be statistically significant at the 0.05 significance level. Since the distances covered are relatively long, the biases could be due to differences in the testing conditions (e.g., pavement temperature). An average bias of 10.9 µm (0.43 mils) was calculated as the average of the absolute values of the biases. Finally, the repeatability of RWD was calculated as $1.96\sigma_d$, which is equal to 50.4 µm (1.98 mils). The results of RWD repeatability analysis are presented in Table 3.17.

Summary of Repeatability Evaluation

For the TSD, except for the two sites UK_F1 and UK_R2, the evaluated LOA (repeatability) was the same for all tested sites and for the three sensors (see Table 3.16). As a function of averaging length, the LOA roughly decreased (lower LOA means higher repeatability) by a factor of $\sqrt{L_2/L_1}$ going from the averaging length L_1 to the averaging length L_2. For example, going from $L_1 = 1$ m (3.3 ft) to $L_2 = 100$ m (33 ft), the repeatability roughly decreases by a factor of $\sqrt{100/1} = 10$. This occurs when measurement errors are uncorrelated and therefore suggests that measurement errors are uncorrelated.

Furthermore, it was found that there is no significant bias (systematic error) between repeated runs (except for one run on Section C1). For Sites UK_F1 and UK_R2, the repeatability was found to depend on the actual deflection slope measurement. Higher measurements resulted in larger error standard deviation and therefore larger LOA (lower repeatability). A possible reason for this is that weaker sections, which result in

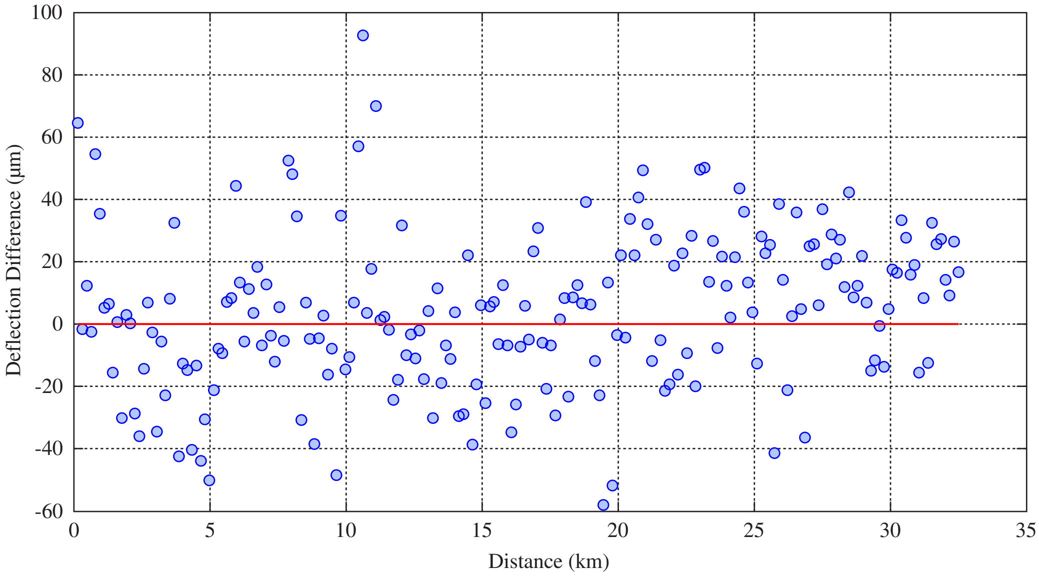


Figure 3.37. Difference of measurements versus average measurement.

Table 3.17. Repeatability Analysis of the RWD

	Westbound			Eastbound		
	1 and 2	1 and 3	2 and 3	1 and 2	1 and 3	2 and 3
Standard Deviation	24.9	27.3	27.2	26.1	24.3	24.8
Bias	14.2	6.5	–7.7	3.93	18.4	14.5
Repeatability	51.8			49.1		
	50.4					

Note: Units in table in µm.

higher measurements, are much less homogeneous because of the presence of distresses (either on the surface or in the hidden layer). This results in larger LOA.

For the RWD, the analysis was limited to three runs performed on a single section. The effect of averaging length could not be evaluated as measurements were already averaged over 160-m (0.1-mi) sections. Furthermore, there was a significant bias between the three repeated runs. The repeatability of RWD for the section evaluated was 50.4 µm (1.98 mils).

Comparability

Comparability is defined similarly to repeatability and is the level of agreement between the two devices (TSD and FWD or RWD and FWD). The difference is that comparability compares measurements from two different devices, whereas repeatability compares measurements from the same device. The FWD is used as a reference point because it has become the de facto standard for structural evaluation of pavement. Many engineering parameters and properties are obtained from FWD testing. Most state DOTs have acquired enough experience to be able to effectively interpret and use FWD test results. Therefore, the FWD can be used as the reference for evaluating any deflection measuring device (or structural capacity measuring device).

Because the TSD does not directly measure pavement deflections, the analysis first investigates the correlation between TSD slope and FWD deflection. To evaluate comparability, measurements need to be converted to the same physical quantity. The physical quantities that can be obtained from both devices are the surface curvature index (SCI) and the base damage index (BDI). The first step in the comparison is to temperature correct FWD deflections to the TSD test temperature. The reason for correcting FWD deflections and not the TSD or both devices is because the temperature-correction procedure for the TSD is still under development.

Temperature Correcting the FWD for TSD Sites

FWD deflection values were first corrected to the temperature at the mid-depth of the asphalt layer during TSD testing. The estimated temperatures near the mid-depth of the pavement (using the U.K. methodology) during FWD testing and TSD testing were included in the files. The method adopted was to correct the center deflection of the FWD first using the procedure described by the FHWA (1998). The correction assumes that deflections 900 mm (36 in.) away from the center of the load plate are not significantly affected by temperature. Thus, using the deflections at this point, along with a measured temperature, a value for asphalt stiffness, and the pavement thickness, the center deflection of the FWD can be corrected to a reference temperature. The latitude of the test site was used to account for climatic differences.

The corrected center deflection can be found with the following equations:

$$D0_{\text{Corrected}} = D0_{\text{Measured}} * TAF \tag{3.6}$$

where TAF = temperature adjustment factor calculated according to Equation 3.7.

$$TAF = \frac{\left(D36 + \text{Delta}_{36@T_{\text{ref}}}\right)}{\left(D36 + \text{Delta}_{36@T_{\text{meas}}}\right)} \tag{3.7}$$

where

$D36$ = deflection at 900 mm (36 in.) from the center of the load plate in µm,

$\text{Delta}_{36@T_{\text{ref}}}$ = basin factor calculated at the reference temperature, and

$\text{Delta}_{36@T_{\text{meas}}}$ = basin shape factor calculated at the measured temperature.

The basin shape factor is found by the following equation:

$$\begin{aligned}\log\left(\text{Delta}_{36}\right) = 3.05 - 1.13\log(ac) + 0.502\log(\text{Theta})\log(D36) \\ - 0.00487(T)\log(\text{Theta})\log(D36) \\ + 0.00677(T)\log(\text{Theta})\log(ac)\end{aligned} \tag{3.8}$$

where

ac = total thickness of the HMA in mm,

Theta = latitude of the pavement section, and

T = temperature at middepth of the HMA in degrees Celsius.

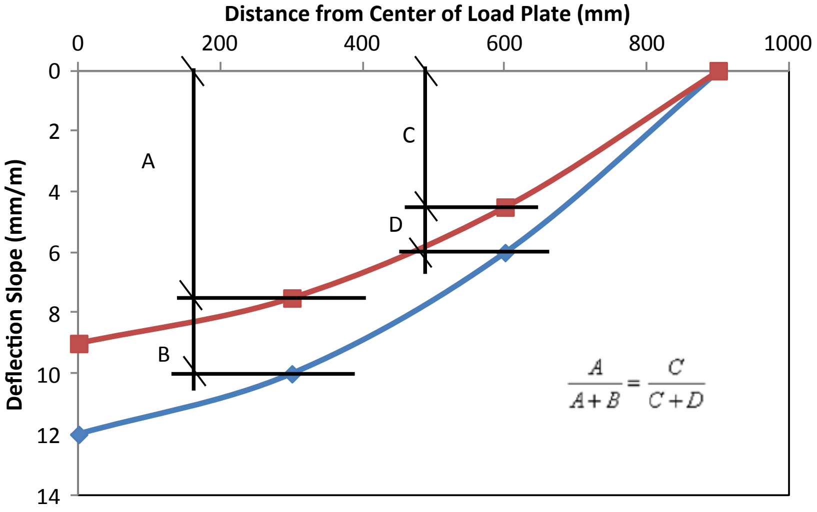


Figure 3.38. Temperature-correction technique for deflections between D0 and D36.

After the center deflections were corrected, the deflections between 0 mm and 900 mm (0 in. and 36 in.) were also adjusted for temperature. The adjustment factor was assumed to vary linearly along the distance from the applied from a maximum calculated using Equation 3.5 at 0 to 0 at 900 mm away from the applied load. Figure 3.38 illustrates how the correction factor can be obtained. The calculation can be performed according to the following equation:

$$D(x)_{\text{Corrected}}=(D(x)-D36)*\frac{(D0_{\text{Corrected}}-D36)}{(D0-D36)}+D_{36} \qquad (3.9)$$

where

$D(x)_{\text{Corrected}}$ = temperature-corrected deflection at location x,
$D(x)$ = measured deflection at location x,
$D0_{\text{Corrected}}$ = temperature-corrected center deflection, and
$D0$ = measured center deflection.

Comparison of TSD Slope and FWD Deflection

The TSD and FWD measure two different quantities; therefore, measurements obtained from the devices cannot be directly compared. To make a comparison, a relationship between measurements from the two devices needs to be obtained. The simplest relationship is the linear one. In this case, correlation is used to evaluate the strength of the linear relationship. Table 3.18 shows the correlation between TSD measurements averaged over 10 m and selected FWD measurements (*D*0 and *D*300) at 10-m (33-ft) intervals, obtained at six different sites (UK_R2, UK_R3, UK_F1, UK_F5, UK_C3, and UK_F3). The correlation ranges from very good (~0.95) for Site UK_R2 to relatively poor (~0.27) for Site UK_F3. One main drawback of correlation is that it is significantly affected by the range of measurements: the wider the range of measurements, the better the correlation. This is illustrated for the six sites in Figure 3.39 and Figure 3.40. Measurements collected on Site UK_F3 were gathered over a much smaller range than those collected on the other sites, which explains why the correlation for Site UK_F3 is lower than that of the other sites.

While correlation values suggest a relatively good linear relationship between FWD deflections and TSD slope, the figures show that this relationship is pavement-type specific, with flexible and composite pavements (F1, F3, F5, and C3) exhibiting the same relationship, and rigid pavements (R2 and R3) exhibiting a different relationship (Figure 3.39 and Figure 3.40); that is, no single linear (or any function) model

Table 3.18. Correlation Between TSD Slope and FWD Deflection

	UK_R2	UK_R3	UK_F1	UK_F5	UK_C3	UK_F3
TSD100 and *D*0	0.9492	0.2798	0.8289	0.7252	0.8007	0.3716
TSD300 and *D*0	0.9514	0.3721	0.8260	0.7164	0.7942	0.2189
TSD100 and *D*1	0.9420	0.2839	0.7984	0.6941	0.7941	0.3338
TSD300 and *D*1	0.9448	0.4002	0.8223	0.6865	0.7948	0.1906

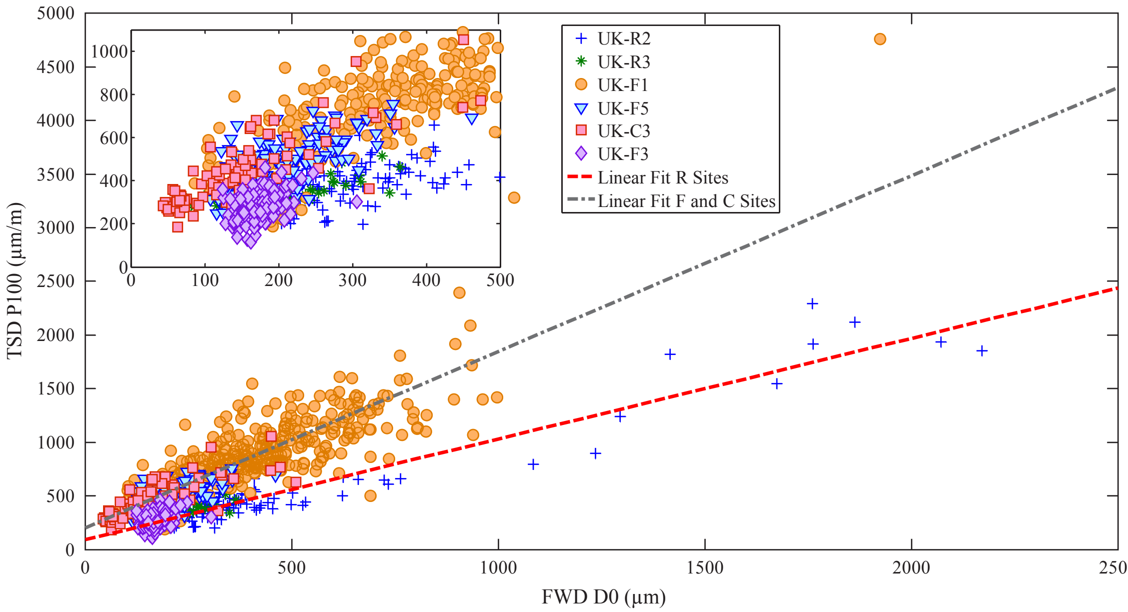


Figure 3.39. TSD P100 slope versus FWD **D0** *deflection.*

can adequately represent the relationship between FWD deflections and TSD slope for the two pavement categories.

Comparability Between TSD and FWD Test Results

To evaluate the comparability between the TSD and the FWD, the two measured quantities need to be converted to the same physical quantity. The surface curvature index (SCI) and the base damage index (BDI) were chosen because they can be calculated from both the TSD and FWD measurements. The calculated SCI is SCI300, which is defined as D0 – D300, and the BDI is defined as D300 – D600. For the FWD, D0, D300, and D600 are directly measured and calculation of the SCI is straightforward. In the following section, we present the methodology used to calculate both the SCI and the BDI from TSD slope measurements.

Converting TSD Slope to SCI or BDI

The TSD measures the slope of the deflection bowl that results from the truck traveling over the pavement. Therefore,

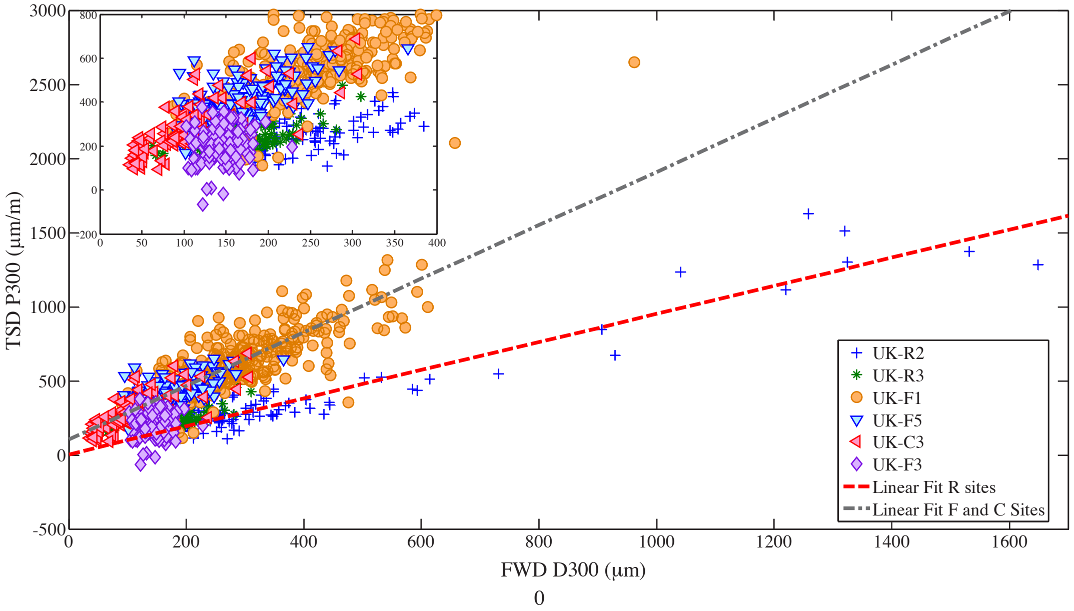


Figure 3.40. TSD P300 slope versus FWD **D300** *deflection.*

deflection can, in principle, be obtained from the TSD slope by integration if a sufficiently detailed representation of the full deflection slope bowl is available. Integration is specified only up to a constant value; therefore, the deflection cannot be recovered without a reference deflection measurement. The difference between two deflection readings can be obtained; the constant cancels out, which gives the SCI or BDI. The relationship between slope, deflections, and SCI is presented in Equation 3.10.

$$\int_a^b s(x)Dx = D(b) - D(a) = \text{SCI} \qquad (3.10)$$

where

$s(x)$ = slope at location x, and
$D(x)$ = deflection at location x.

Recent results by Thyagarajan et al. (2011) and Krarup et al. (2006) suggest that SCI values, especially SCI300, correlate very well with tensile strain at the bottom of the asphalt layer. Krarup et al. (2006) used a functional representation of the deflection and slope presented in Equation 3.11 and Equation 3.12 to perform the integration:

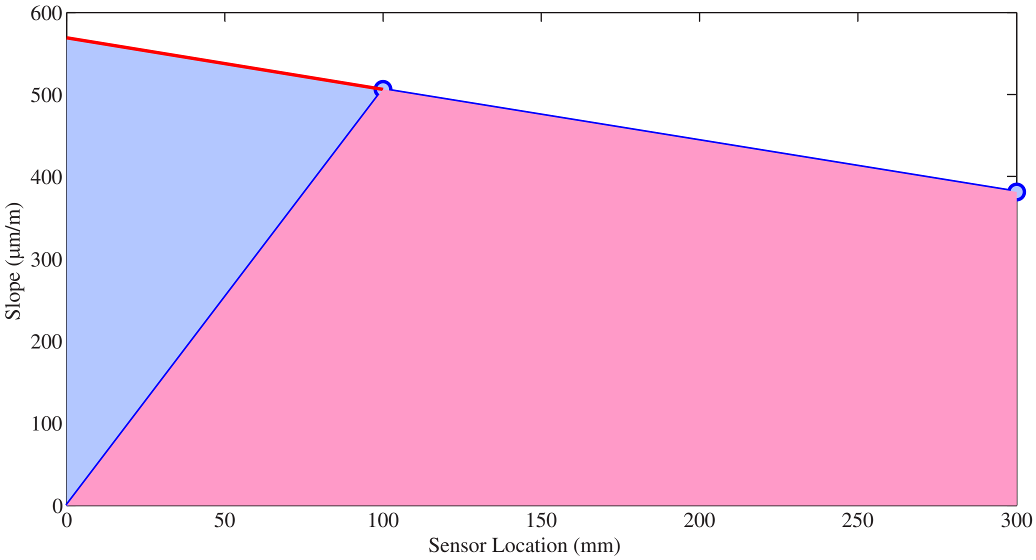
$$D(x) = -\frac{A}{2B}\left[\cos(Bx) + \sin(Bx)\right]\exp(-Bx) \qquad (3.11)$$

$$s(x) = D'(x) = A\sin(Bx)\exp(-Bx) \qquad (3.12)$$

where A and B = experimentally determined constants.

Equations 3.11 and 3.12, which were developed for a sensor configuration of 100, 200, and 300 mm (3.94, 7.87, and 11.8 inches) from the applied wheel load, were investigated to fit measured TSD slope. The results showed that the equations are not suitable to use in the sensor configuration tested (sensors at 100, 300, and 756 mm [3.94, 11.81, and 29.8 in.] from the load). Therefore, numerical integration was adopted (trapezoidal rule) to calculate the SCI and BDI.

To calculate the SCI and BDI from TSD measurements, the TSD slope was integrated numerically. Slope measurements were obtained at 100, 300, and 756 mm (3.94, 11.81, and 29.8 in.) from the applied load. The integration was performed using the trapezoidal rule. To calculate SCI300, the integration interval is [0 mm; 300 mm] ([0 in.; 11.81 in.]). In this interval, TSD slope measurements were obtained at 100 and 300 mm (3.94 and 11.81 in.) from the applied wheel load and an assumption was needed on how the slope varies between 0 and 100 m (0 and 3.94 in.). Two assumptions illustrated in Figure 3.41 were investigated. The first assumption sets the slope to vary linearly throughout the interval from 0 to 300 m (0 and 11.81 in.). This assumption is represented by the red line between 0 and 100 mm (0 and 3.94 in.) and the blue line between 100 and 300 mm (3.94 and 11.81 in.). The integration in this case results in the area comprising the red and blue areas. The second, more realistic assumption is to set the slope at 0 mm from the load equal to zero. This assumption is valid if the load is uniformly (or approximately uniformly) applied over a specific area rather than being a point load and if viscoelastic effects are neglected. The results of both calculations are presented in Figure 3.42, which suggests the second assumption (slope at 0 equals 0) works better because the calculated SCI values (from FWD and TSD)



Note: The SCI300 is the shaded area under the piecewise linear curve.

Figure 3.41. Effect of assuming the slope at 0 mm to be equal to zero on the calculated SCI300.

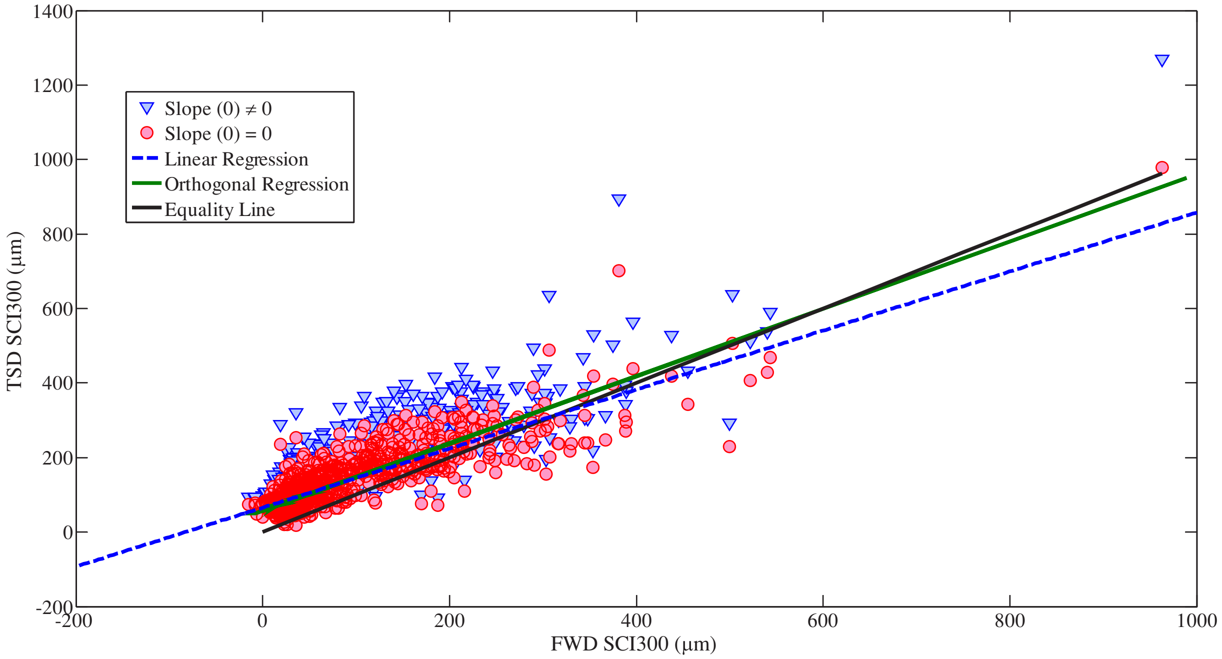


Figure 3.42. Comparison of SCI300 calculated by using various assumptions on the slope.

better follow the line of equality. The second assumption was thus adopted in the analysis.

Figure 3.42 also shows the results of the ordinary and orthogonal regressions between the SCI calculations based on the FWD and TSD measurements. Since both variables contain errors, orthogonal (or total least-squares) regression is more appropriate, as shown in the figure. The orthogonal regression line has a slope of 0.90, which is closer to the line of equality than the one obtained using the least-squares regression with FWD measurements as the independent variable, which had a slope of 0.79.

SCI Comparisons

Figure 3.43 shows the calculated SCI300 with the assumption of slope at 0 equal to 0 while Figure 3.44 shows the calculation of BDI (also known as SCI450, which is defined here as D300 – D600). The main advantage of comparing the indices

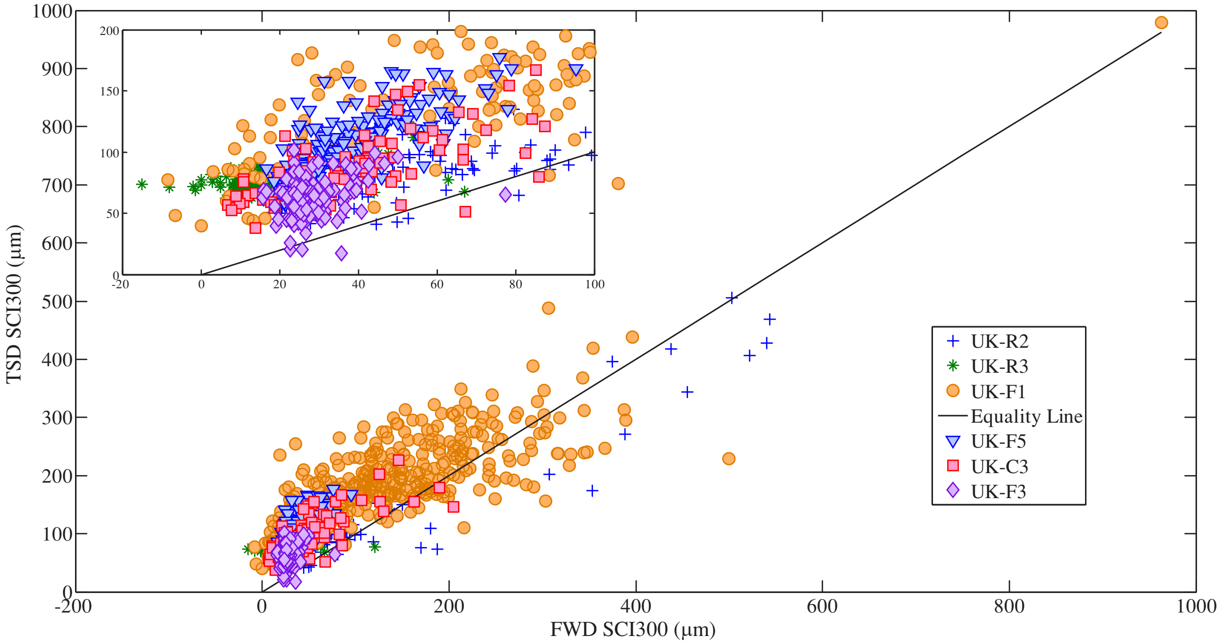


Figure 3.43. Comparison of SCI300 obtained from the TSD and FWD testing.

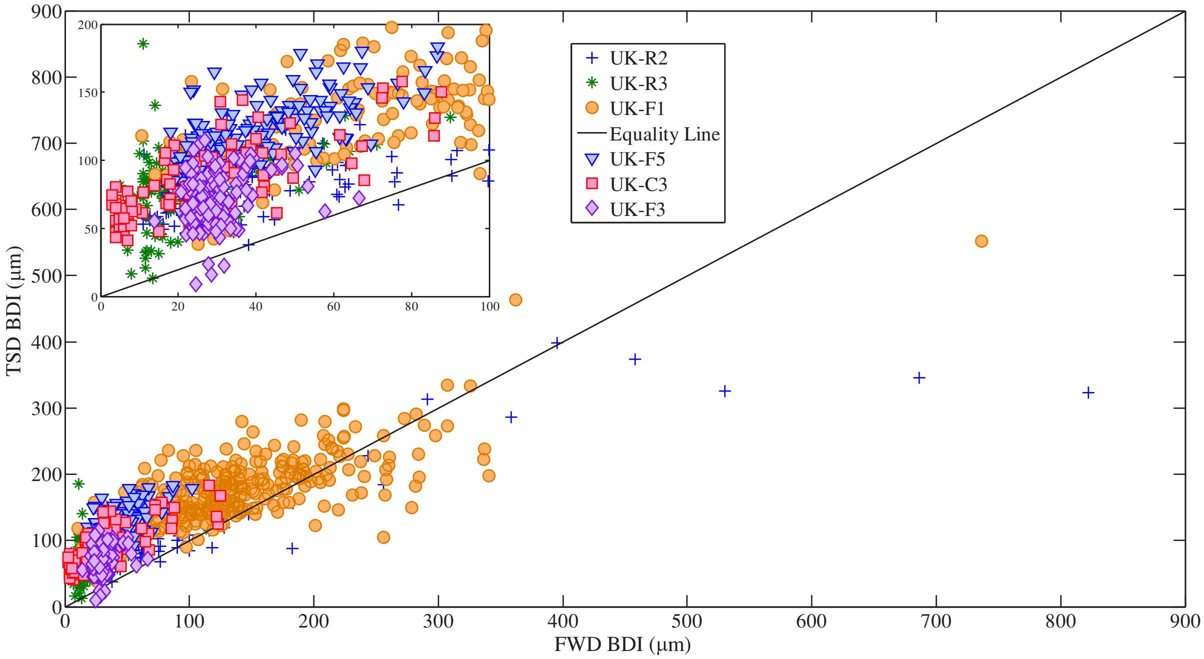


Figure 3.44. Comparison of BDI obtained from the TSD and FWD testing.

is that both quantities have the same dimensions. The first important observation is that there is no obvious indication that the relationship is not the same for all tested pavement types (Figure 3.43 and Figure 3.44). The plots also show that the results of the calculated SCI300 and BDI are comparable for both the FWD and TSD; this is reflected by the close proximity of the observed measurements to the equality line. The limits of agreement (LOA) method was then used to assess the comparability between the two devices, as is presented in the next section.

Comparability and LOA of SCI and BDI Measurements

The plots presented in Figure 3.43 and Figure 3.44 suggest a relatively good agreement between both devices; however, to compare measurements obtained from the two devices, one would need to evaluate how well they agree with each other in a quantifiable way. This is usually a judgment call, but there are some parameters that provide guidance for this problem. Generally, a discrepancy in measurement between the two devices will be accepted if it is less than a certain limit, usually referred to as the confidence limit. Confidence limits should be narrow enough to expect that the result will not affect a decision that is based on it.

To evaluate this dependence, the standard deviation of the difference as a function of the SCI measurement was calculated. This was done with the method presented by Davidian and Carrol (1987). The procedure consists of fitting a regression line with the y variable taken as the difference in the SCI and the x variable taken as the average SCI. This regression line is an estimate of the bias (as a function of average SCI) between the two methods. The variance can be estimated by using the squared residuals obtained from the regression analysis. This is done by (again) performing regression on the squared residuals. The result of this regression is presented in Figure 3.45. These results correspond to the square root of the squared residuals, and as such, the fitted lines represent the standard deviation variation as a function of average SCI. The reason for not plotting the squared residual is because taking the square root results in a clearer visual representation. The LOA presented in Figure 3.46 can be calculated by using the derived standard deviation and constructing the 95% confidence interval around the bias.

As recommended by Bland and Altman (1983), the plot of the difference of the SCI (FWD – TSD) versus the average SCI ([FWD + TSD]/2) is the first step to evaluate the LOA. This plot is presented in Figure 3.46 for both SCI300 and BDI (referred to both as SCI). The figure suggests that in both cases, the difference depends on the SCI measurements. Thus, data transformations were investigated to possibly remove this dependence. If transformation is not successful, the repeatability can be defined as a function of the size of measurement (Bland and Altman, 1983). A logarithmic transformation, as well as a coefficient of variation transformation (difference divided by average), on the data did not result in the removal of this association. The repeatability was therefore defined as a function of the size of measurements.

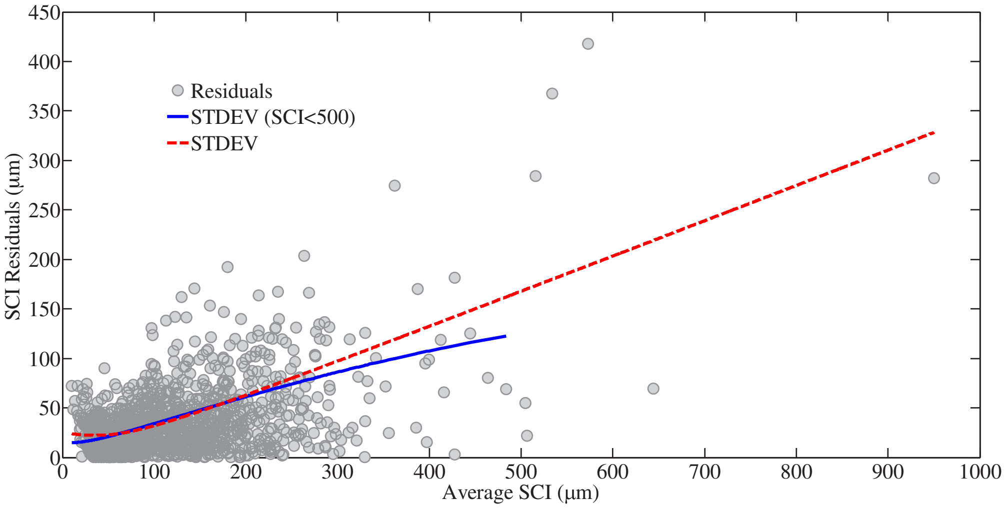


Figure 3.45. Plot of absolute value on residual and the regression on the residual squares.

Figure 3.45 and Figure 3.46 present two sets of results each. The first trend line (red dashed line, STDEV) and confidence interval used all the measurements to estimate the bias and standard deviation. However, only seven measurements were obtained for SCI values above 500 μm (19.7 mils), and the results of the analysis performed by using all measurements are highly influenced by those seven measurements. The same analysis was performed with only the set of points that resulted in an average SCI below 500 μm (19.7 mils). As can be seen in Figure 3.45 and Figure 3.46, the results of both analyses are essentially the same for average SCI values below 250 μm (9.84 mils), and differences increase with increasing average SCI values.

To interpret the results presented in Figure 3.46, the example average SCI of 300 μm (11.8 mils) can be examined. In this case, the SCI calculated from the FWD is expected to be (on average) 30 μm (1.18 mils) lower than the SCI calculated from the TSD, with values ranging from as much as 205 μm (8.07 mils) lower to 175 μm (6.89 mils) higher (for a range of 380 μm [15.0 mils]) expected to occur 95% of the time. For an average SCI of 100 μm, the values computed using the FWD measurements are expected to be (on average) 50 μm (1.97 mils) lower than the SCI calculated from the TSD, with values ranging from as much as 115 μm (4.53 mils) lower to 15 μm (0.59 mils) higher (for a range of 130 μm [5.12 mils]),

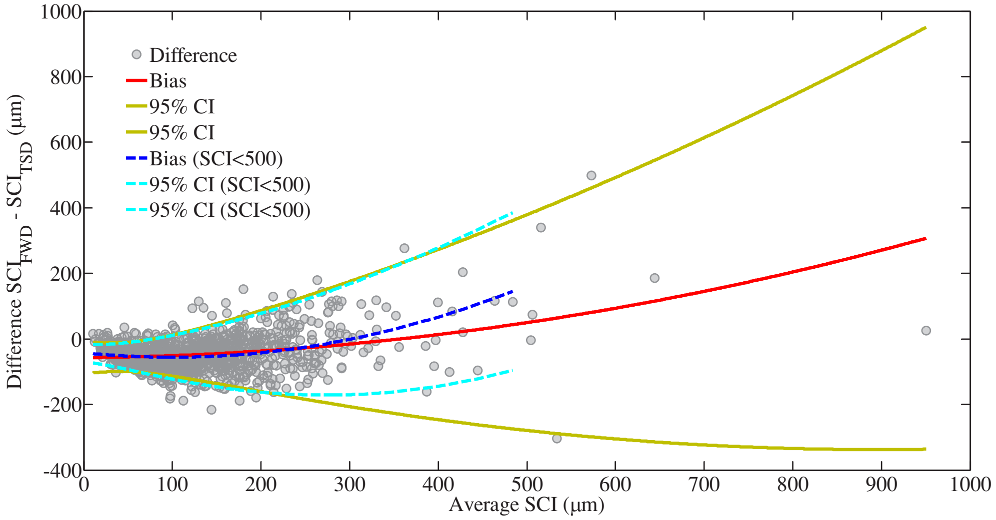


Figure 3.46. Plot of difference of SCI versus average SCI with bias and limits of agreement.

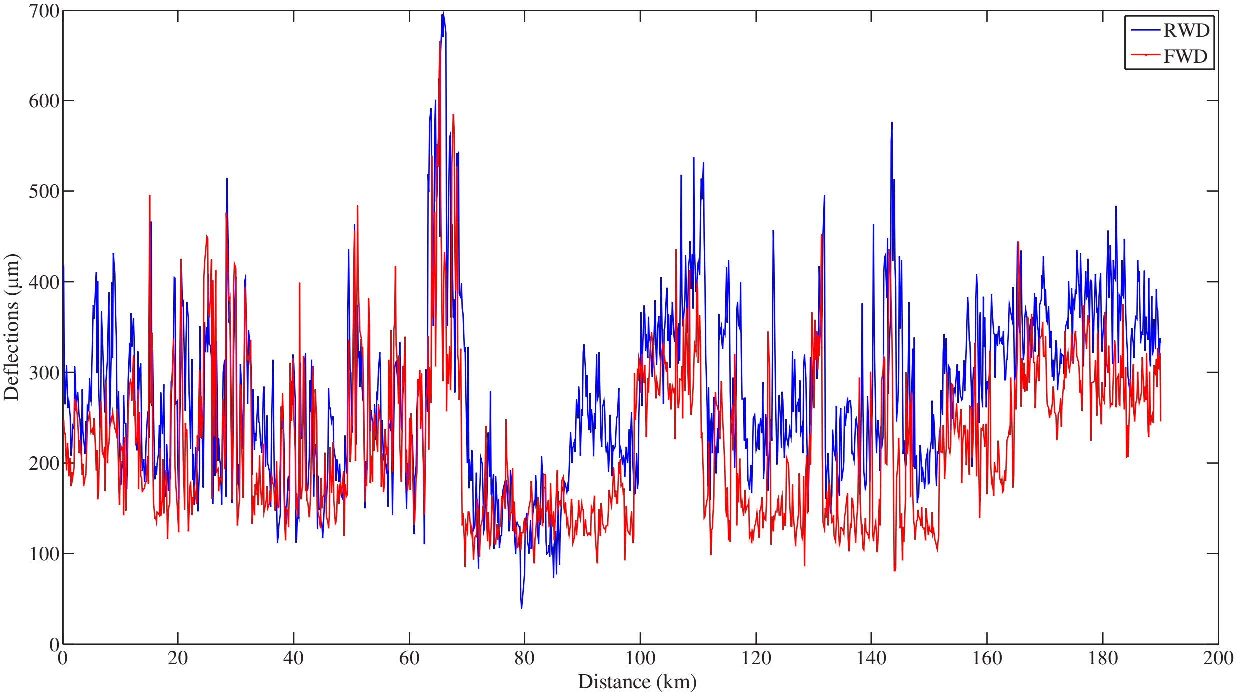


Figure 3.47. FWD and RWD measurements obtained from New Mexico.

expected to occur 95% of the time. To put these two numbers into perspective, the repeatability of TSD SCI300 measurements for Sites UK_F1 and UK_F5 was calculated as 51 µm (2.01 mils) (range of 102 µm [4.02 mils]) for UK_F1 and 25 µm (0.98 mils) (range of 50 µm [1.97 mils]) for UK_F5.

Comparability Between RWD and FWD

Comparison of RWD and FWD testing performed in New Mexico, which was provided by ARA for this project, is presented in Figure 3.47. In this case, RWD and FWD measurements were obtained at 160-m (0.1-mi) intervals. The plot of the difference, FWD – RWD, versus the average is presented in Figure 3.48. The figure suggests the measurement error depends on the associated measurement. Both logarithmic and power transformations of the data were investigated but did not result in removal of the error dependence with the associated measurement. In the end, the normalized difference calculated as $(x_1 - x_2)/(0.5x_1 + 0.5x_2)$ was found to be the error measurement parameter that was the least

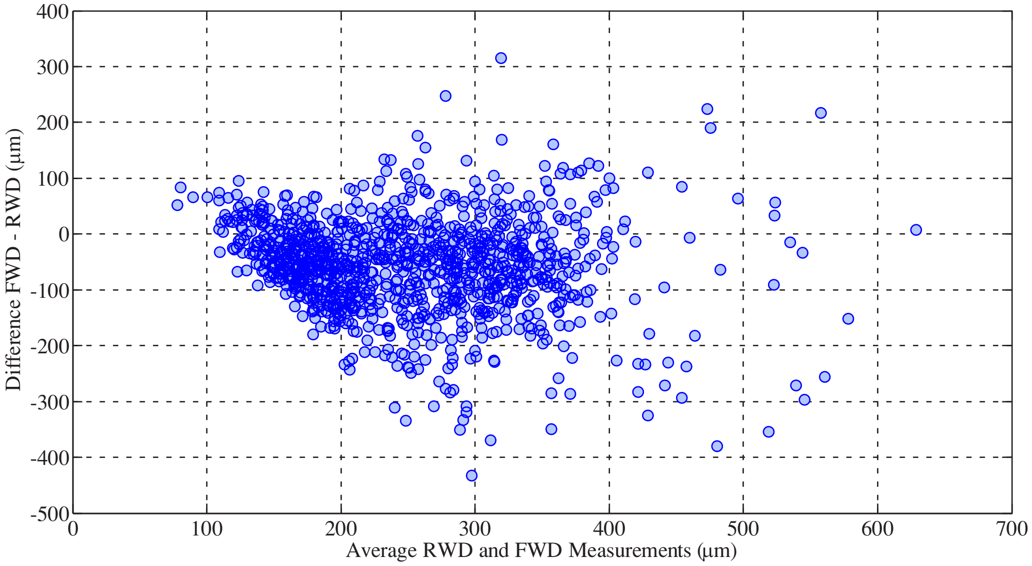


Figure 3.48. Difference versus average measurement.

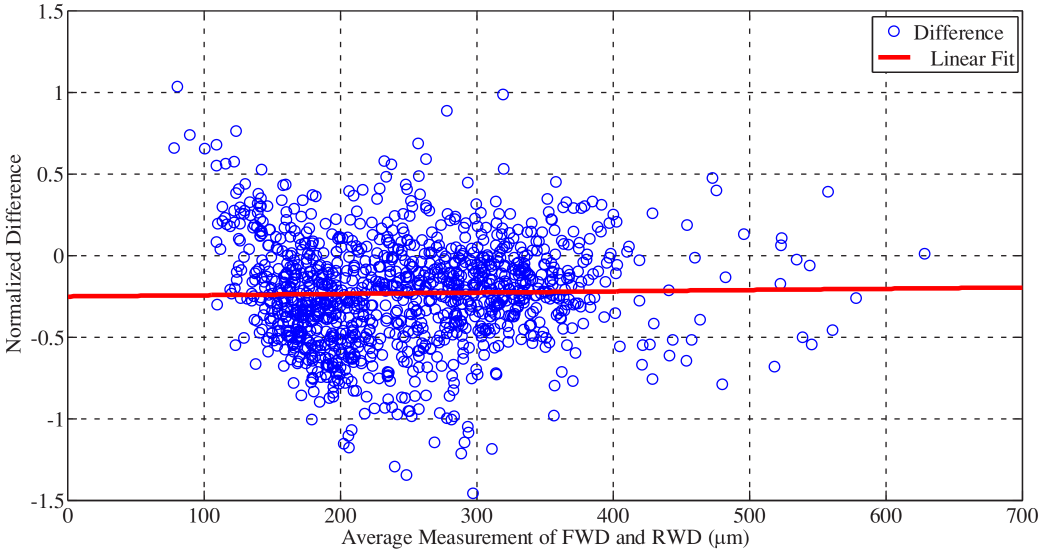


Figure 3.49. Normalized difference versus average measurement.

dependent on the associated measurement. Figure 3.49 shows the normalized difference as a function of the measurement. The dependence on the associated measurement is not completely removed; however, it is appreciably lower than the association in Figure 3.48.

The average normalized difference of the difference (FWD − RWD) is −0.2328 and the standard deviation is 0.3265. Figure 3.50 shows a distribution of the normalized difference. The Anderson–Darling test for normality showed that this distribution does not follow the normal distribution. The 95% bootstrap confidence interval of the normalized difference was calculated as [−0.8642; 0.4286]. In comparison, the 95% confidence interval using normal assumptions is [−0.8538; 0.3882]. The two intervals are close; however, the wider calculated bootstrap interval reflects the fact that the distribution in Figure 3.50 has a heavy tail.

Direct Comparison of RWD Deflections and FWD Deflections

A comparison was made directly between the RWD data and the FWD data collected. Figure 3.51 presents a more detailed analysis of the data collected on U.S. Route 550 in New Mexico.

The figure shows the entire length measured with the RWD (Figure 3.51a) and FWD (Figure 3.51b) divided into homogeneous sections. Each plot displays the average and characteristic deflections (upper 95% confidence limit) for

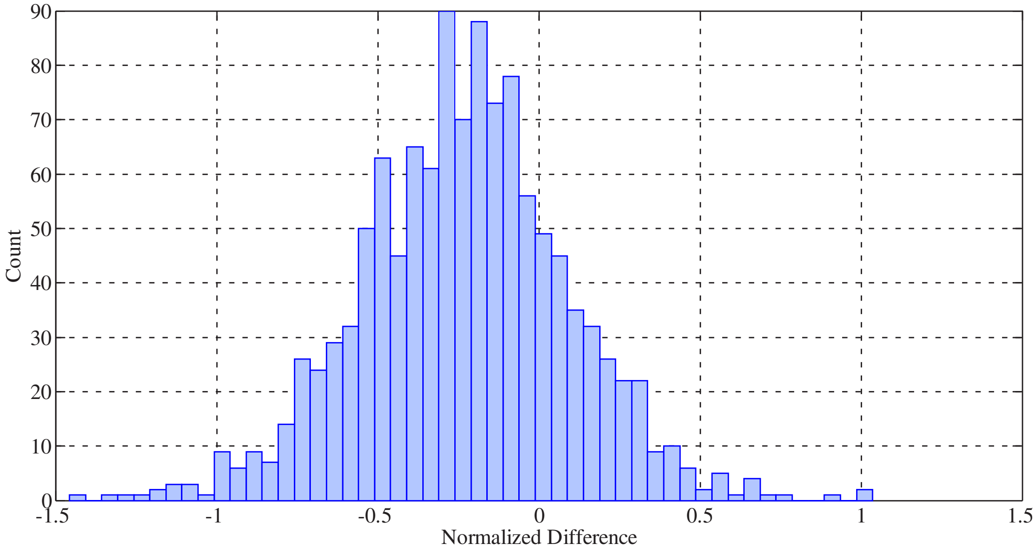
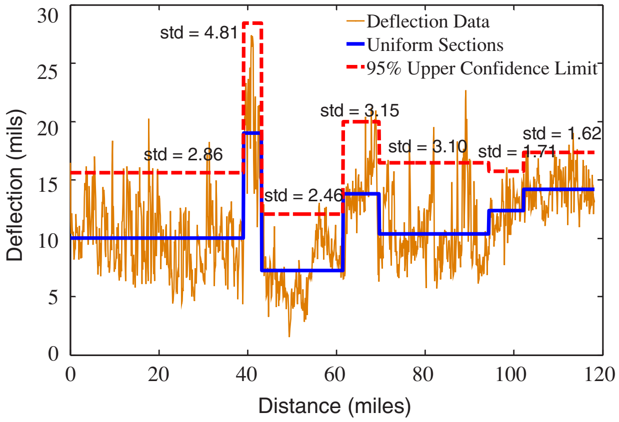
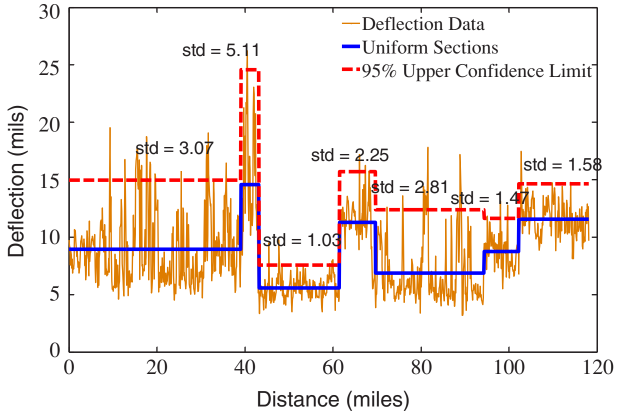


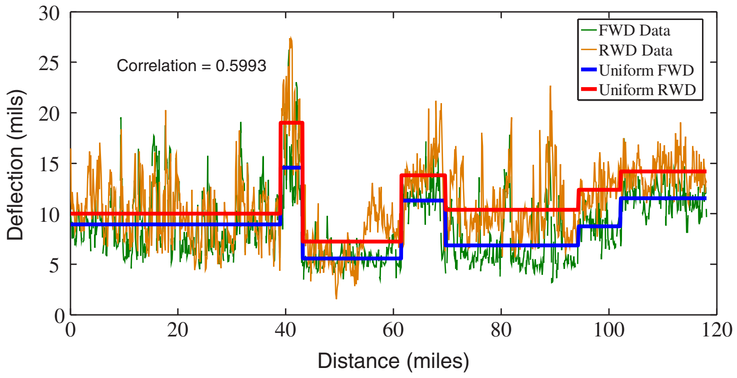
Figure 3.50. Distribution of normalized difference.



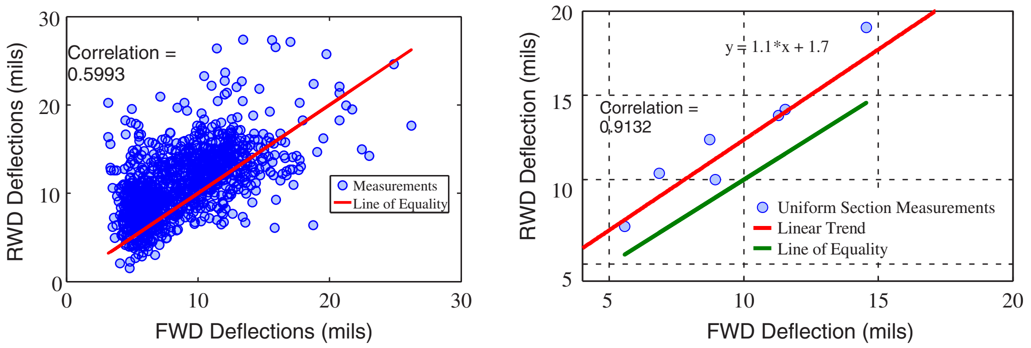
(a) RWD measurements



(b) FWD measurements



(c) Comparison of 0.1-mi averaged measurements and section averages



(d) Individual 0.1-mi segment comparisons (e) Homogeneous section comparisons

Figure 3.51. Analysis of New Mexico data.

each section. The sections were segmented visually, and the average values are compared in Figure 3.51c.

Figure 3.51d and e compare the individual 160-m (0.1-mi) averages and the homogeneous section averages, respectively. The correlation between the individual measurements is relatively weak ($R = 0.60$, $R^2 = 0.36$), but it improves significantly when the data are aggregated in homogeneous sections. The RWD deflections are consistently higher than the FWD ones, but the correlation is good ($R = 0.91$, $R^2 = 0.83$).

Summary of Comparability

To evaluate the comparability between the TSD and FWD, the TSD slope measurements and the FWD deflection measurements were converted to the SCI and BDI. This was performed because the FWD and TSD measure different physical quantities—deflection and deflection slope, respectively. Both these quantities can be used to calculate the SCI and BDI, which makes comparability evaluation between the two devices feasible. The LOA between the TSD and FWD was found to depend on the average measurement of the two devices (see Figure 3.45 and Figure 3.46). Furthermore, there is a bias between the TSD and FWD, SCI, and BDI measurements that depends on the average measurement (see Figure 3.46). To interpret the results presented in Figure 3.46, the example of average SCI of 300 μm (11.8 mils) can be examined. In this case, the SCI calculated from the FWD is expected to be (on average) 30 μm (1.18 mils) lower than the SCI calculated from the TSD, with values ranging from as much as 205 μm (8.07 mils) lower to 175 μm (6.89 mils) higher (for a range of 380 μm [15.0 mils]) expected to occur 95% of the time. For an average SCI of 100 μm (3.94 mils), the value computed using the FWD measurements are expected to be (on average) 50 μm lower than the SCI calculated from the TSD, with values ranging from as much as 115 μm (4.53 mils) lower to 15 μm (0.59 mils) higher (for a range of 130 μm [5.12 mils]) expected to occur 95% of the time. It is important to point out that the large range in the LOA between the two devices does not imply that the TSD fails to give accurate measurements. The LOA between the two devices depends on the repeatability of the TSD, the repeatability of the FWD, and the comparability between the two devices. The repeatability of the FWD was not evaluated.

The repeatability between the FWD and RWD was also found to depend on the average deflection measurement. However, the cov was found to be relatively uniform across all measurement values and was therefore used as a measure of repeatability. The average cov of the difference (FWD – RWD) was calculated as –0.2328 (or –23.28%). The 95% interval of the cov was calculated as [–0.8642; 0.4286] or, in percent, [–86.42%; 42.86%]. This means that on average, FWD deflection measurements are 23.28% lower than RWD deflection measurements, and in 95% of the cases, FWD deflection measurements will be between –86.42% lower to 42.86% higher than RWD deflection measurements. This difference seems to be high however, and as in the case of the TSD comparison with FWD, the repeatability of the FWD was not evaluated. Therefore, it was not possible to quantify how much of this large range resulted from repeatability of the FWD.

TSD Repeatability from Single Measurement Run

The calculation of repeatability requires at least two runs of the TSD repeated on the same pavement section. Ideally, these runs should be performed under the same conditions. For example, for flexible pavement sections, the test temperature should, as much as possible, be the same. This section presents a method to evaluate TSD repeatability from measurements obtained from a single run. Such a method can be very useful in cases where repeated runs performed under the same conditions are not practically or economically feasible. This probably includes the majority of applications of continuous deflection devices, specifically the TSD.

Difference Sequence Method for Standard Deviation Estimation

Difference sequence methods (DSMs) arose from the need to estimate the error standard deviation in nonparametric regression models. The calculated standard deviation can be used, among other things, for the computation of confidence bands or the optimal choice of smoothing parameter (Munk et al., 2005; Brown and Levine, 2007). The general procedure is summarized in Hall et al. (1990), who introduced difference-based estimators of arbitrary order r using a difference sequence d_i of real numbers as follows:

$$\sum_{i=0}^{r} d_i = 0 \tag{3.13}$$

$$\sum_{i=0}^{r} d_i^2 = 1 \tag{3.14}$$

$$\hat{\sigma} = \sqrt{\frac{1}{(n-r)} \sum_{i=1}^{n-r} \left(\sum_{j=0}^{r} d_j y_{j+1} \right)^2} \tag{3.15}$$

It can easily be verified that, except for the case of $r = 1$, different combinations of the values d_i can be used and still satisfy Equations 3.13 and 3.14. Here, the results of the best estimator for the investigated data (Katicha et al., 2012), which was the second order estimator ($r = 2$), known as the Gasser estimator

Table 3.19. Standard Deviation Calculated with Second Order Difference Sequences for Sensor P100

Site	Slope Standard Deviation (mm/m)						
	Run					Average	Difference Method
	1	2	3	4	5		
F1	0.2706	0.2623	0.2647	0.2750	na	0.2682	0.2661
F3	0.1260	0.1360	0.1226	na	na	0.1283	0.1305
F5	0.1118	0.1173	0.1096	0.1152	0.1136	0.1135	0.1166
F6	0.1181	0.1253	0.1233	0.1226	0.1213	0.1221	0.1254
C1	0.1503	0.1429	0.1510	0.1357	0.1489	0.1459	0.1466
C2	0.1214	0.1184	0.1186	0.1172	0.1241	0.1200	0.1222
R2	0.2151	0.2087	0.1921	na	na	0.2055	0.2072
R3	0.1566	0.1739	0.1501	0.1571	0.1601	0.1598	0.1483

Note: na = not applicable.

(Gasser et al., 1986), are presented. This estimator for equally spaced observations is given by the following equation:

$$\hat{\sigma} = \sqrt{\frac{2}{3(n-2)}\sum_{i=1}^{n-2}\left(\frac{1}{2}y_i - y_{i+1} + \frac{1}{2}y_{i+2}\right)^2} \qquad (3.16)$$

Calculation of Standard Deviation

Table 3.19 and Table 3.20 present the results of standard deviation estimation for the measurements averaged over a 1-m (3.3-ft) length by using the Gasser estimator for P100 and P300, respectively. These are compared with the standard deviations obtained by using repeated runs (presented in the TSD Repeatability section). In general, the two estimates of the standard deviation agree very well, which suggests that the DSM can be used to obtain the standard deviation from a single run. Note that in the DSM, the bias is not accounted for (because there is only one run investigated at a time, the bias cannot be evaluated).

Effect of Sampling Frequency on Accuracy of Standard Deviation Estimation

Although the results presented in the previous sections show that the standard deviation estimated from a single run agrees

Table 3.20. Standard Deviation Calculated with Second Order Difference Sequences for Sensor P300

Site	Slope Standard Deviation (mm/m)						
	Run					Average	Difference Method
	1	2	3	4	5		
F1	0.2053	0.2057	0.2027	0.2096	na	0.2058	0.1918
F3	0.1267	0.1363	0.1245	na	na	0.1293	0.1376
F5	0.1137	0.1153	0.1071	0.1114	0.1077	0.1111	0.1123
F6	0.1117	0.1156	0.1215	0.1164	0.1181	0.1167	0.1210
C1	0.1491	0.1325	0.1426	0.1357	0.1467	0.1415	0.1398
C2	0.1199	0.1207	0.1201	0.1212	0.1263	0.1217	0.1226
R2	0.1674	0.1617	0.1482	na	na	0.1593	0.1671
R3	0.1418	0.1550	0.1358	0.1473	0.1344	0.1431	0.1378

Note: na = not applicable.

with the standard deviation estimated by using repeated measurements, there are some limitations to the application of the DSM. For the method to be successful (which depends on how accurate the estimation of standard deviation needs to be), the variation in the true measurement (deflection slope, in this case) profile should happen relatively smoothly. In practical terms, for the most part of the profile, the difference of the true deflection between adjacent points should be small compared to the noise level in the measurements. In a pavement structure, the deflection measured at a given location is influenced by the pavement properties within a certain distance, say of radius *R,* of that location. The radius *R* depends on the pavement structure (number of layers, thicknesses, and so forth) and the mechanics that govern the deformation of the pavement (e.g., multilayer analysis). Results presented in the previous section suggest that, for all practical purposes, to obtain a good estimate of the standard deviation from a single run, a distance of 1 m (3.3 ft) is within the radius of influence *R* for the tested pavements.

To illustrate the effect of measurement distance, the standard deviation for the case of P100 measurements averaged over 10 m and 100 m (33 ft and 330 ft) were calculated by using the DSM. The results of this calculation, along with the 1-m (3.3-ft) results, are presented in Table 3.21. The table shows that the calculated standard deviation for 10-m (33-ft) averaging derived with the DSM does not agree with the calculated standard deviation derived with repeated measurements. The DSM produces wrong estimates of the standard deviation for deflection averaged over a 10-m (33-ft) section, probably because the average values can be significantly different from one point to another. The more variation there is in a tested section, the worse the estimate of the DSM. This is confirmed by the fact that Section F1 and Section R2, which had the most variation, resulted in the worse estimate of the standard deviation (see Table 3.21 and Figure 3.52).

As expected, the estimate is also worse for longer averaging distance; for example, the results for 100-m (330-ft) averaging are very different except for Site C2, which is a relatively uniform site. This shows one limitation of difference sequence methods. However, the standard deviation for different averaging distances can still be estimated from the standard deviation for 1-m (3.3-ft) averaging using the following formula:

$$\sigma_n = \frac{\sigma_1}{\sqrt{n}} \tag{3.17}$$

where

n = section length in meters,

σ_n = the standard deviation for the sections of length n, and

σ_1 = the standard deviation for 1-m averaging.

Denoising and Data Aggregation

The purpose of continuous deflection devices is to measure a physical characteristic of the pavement (e.g., deflection in the case of RWD and deflection slope in the case of TSD) at specific locations. Measurements are contaminated with noise; from these noisy measurements, the objective is to make inferences about the expected value of the true physical quantity being measured with a confidence interval on that expected value. For TSD measurements, this can be interpreted as finding out how the deflection slope varies as a function of the measurement location (i.e., along the roadway). This

Table 3.21. Calculation of Standard Deviation for Measurements Averaged over Distances (mm/m)

	1 m (3.3 ft)		10 m (33 ft)		100 m (330 ft)	
Site	Difference Sequence	Repeated Runs	Difference Sequence	Repeated Runs	Difference Sequence	Repeated Runs
F1	0.2682	0.2611	0.2548	0.1054	0.3504	0.0625
F3	0.1282	0.1305	0.0436	0.0407	0.0256	0.0155
F5	0.1135	0.1166	0.0578	0.0401	0.0544	0.0147
F6	0.1223	0.1254	0.0448	0.0406	0.0227	0.0139
C1	0.1458	0.1466	0.0659	0.0446	0.0423	0.0153
C2	0.1200	0.1222	0.0409	0.0408	0.0168	0.0142
R2	0.2053	0.2072	0.1766	0.0643	na	na
R3	0.1596	0.1483	0.0500	0.0432	0.0179	0.0153

Note: na = not applicable.

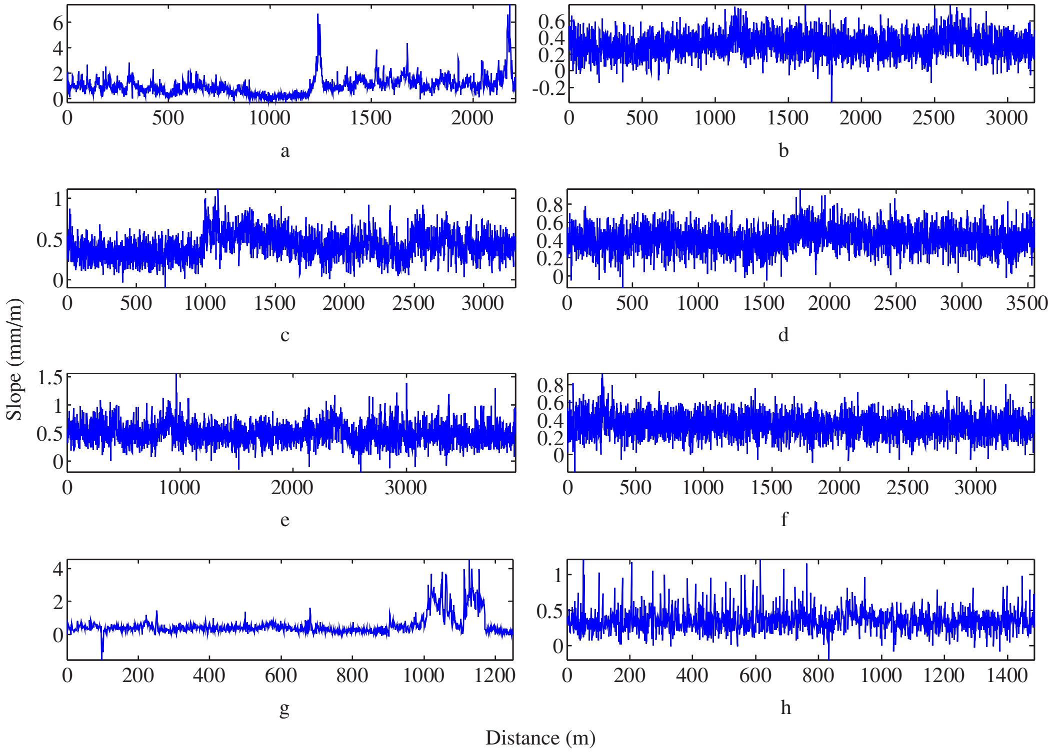


Figure 3.52. TSD slope measurements for Sensor P100 for U.K. sites: (a) F1; (b) F3; (c) F5; (d) F6; (e) C1; (f) C2; (g) R2; and (h) R3.

can be done by using nonparametric regression. Common regression analysis, which is extensively used by engineers, is parametric regression where a (parametric) model (e.g., linear model) is postulated to represent the observed behavior and model parameters are obtained using a specified criterion (e.g., least squares, maximum likelihood). In some cases, such as for continuous deflection measurements, the form of the regression curve is not known. In such cases nonparametric regression, which is not restricted to a given form (such as linear and exponential), can be used. Essentially, the collected data are used to infer on the regression function.

The three most common methods of nonparametric regression are kernel regression, smoothing spline regression, and least-squares spline regression. The familiar moving average falls under kernel regression. From a practical perspective, all three methods give very similar results, and selecting a particular one is often the result of individual preference and ease of use. In this report, the method of smoothing splines is used for its simplicity and ease of implementation. The main question in smoothing spline regression is how much smoothing should be performed. A number of objective methods have been developed to answer this question. These methods consist of optimizing a parameter that controls the trade-off between smoothness and adherence to the measurements (i.e., controls variance and bias). The method can be formulated using the following model for the TSD deflection slope measurements:

$$y_i = f(x_i) + \varepsilon_i \tag{3.18}$$

where

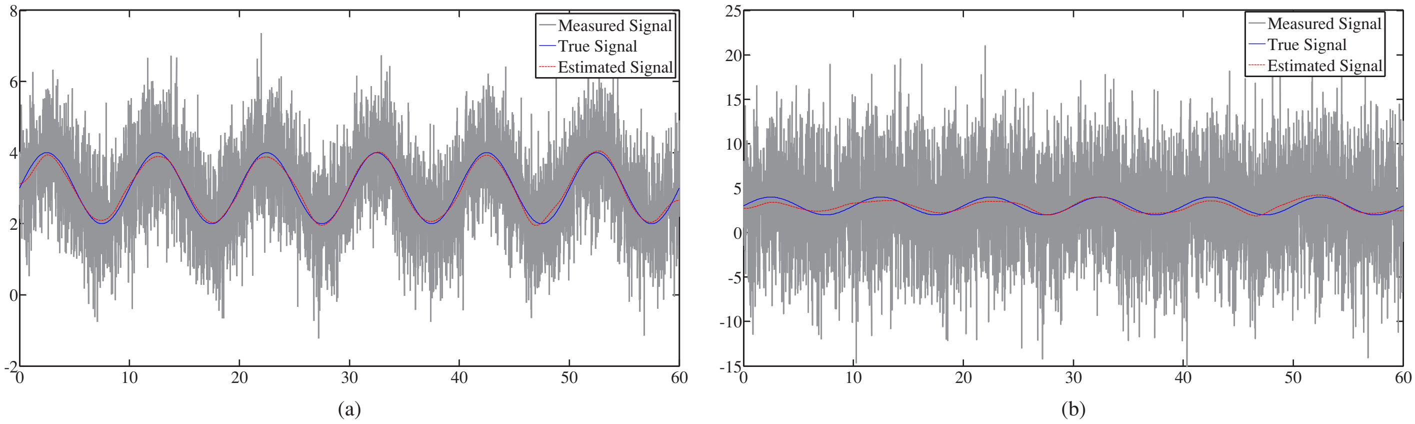
y_i = TSD deflection slope measurements,
$i = 1, 2, \ldots, n$ (the number of measurements),
$x_i \in [0, 1]$,
$f(x_i)$ = true deflection slope (which is not known and is to be estimated), and
ε_i = i.i.d random variables with mean zero and known or unknown variance σ^2.

The smoothing spline method consists of finding the function g that minimizes the following formula:

$$\frac{1}{n}\sum_{i=1}^{n}\left(g(x_i) - y_i\right)^2 + \lambda\int_0^1 \left(g^{(m)}(u)\right)^2 du \tag{3.19}$$

where $g^{(m)}$ is the mth derivative of g.

In this report, m is taken as $m = 2$ (the typical value used for m). In this case, the solution to the minimization problem, g is a cubic spline. The parameter λ (the only parameter that needs to be determined) is a smoothing parameter that controls the



(a)

(b)

Figure 3.53. Spline smoothing of sinusoidal function contaminated with (a) low and (b) high noise levels.

trade-off between the "roughness" of the solution and the fidelity to the measured data. A popular method to estimate λ, which is used in this report, is the generalized cross validation (GCV) criterion first suggested by Craven and Wahba (1979).

Illustrative Simple Examples with a Sinusoidal Function

Two simple examples of spline smoothing using a sinusoidal function are first presented. The purpose of these examples is to give an intuitive feeling on the performance of the method. The example compares synthetic measurements with relatively low noise levels ($\sigma = 1$) and relatively high noise levels ($\sigma = 5$) of a sinusoidal function given by the following equation:

$$y = \sin(2\pi \times 0.1x) + 3 \tag{3.20}$$

Measurements are obtained for x between 0 and 60 and 0.01 spacing (units are not important in the example; however, these can be meters). Figure 3.53a shows the results for the case of low noise levels ($\sigma = 1$). From the measured signal, the underlying signal is presumed to be fluctuating (such as a sinusoidal). The smoothing spline estimate (dashed red line) is very close to the actual sinusoidal signal (continuous blue line). Figure 3.53b shows the measured signal for the case of high noise levels ($\sigma = 5$). In this case, visual inspection of the plot may not by itself suggest that the true signal is fluctuating. However, even for the level of noise in the signal, the performance of the smoothing spline in estimating the true function is still very reasonable.

Application to TSD Measurements

In this section, the application of the smoothing spline is demonstrated on three sets of TSD deflection slope measurements from the P100 sensor on Sites UK_F3, UK_F5, and UK_F1. These were selected because of the different range of TSD slope variation in each site (see Figure 3.52). UK_F3 exhibited very low variation in the measured TSD deflection slope, UK_F5 exhibited some variation in the measured TSD deflection slope, and UK_F1 exhibited the most variation in the measured TSD deflection slope.

Figure 3.54 shows the measured first run on Site UK_F3, with the smoothing spline regression function and the 95% Bayesian confidence interval (Wahba, 1983; Nychka, 1988, 1990) superimposed to the measurements and the averages over 100-m (330-ft) sections. The smoothing function gives results that are as "noise-free" as averaging results over 100-m (330-ft) sections. One important difference between the smoothing function and the 100-m (330-ft) average sections is that the smoothing function is an estimate of the deflection slope at 1-m (3.3-ft) intervals (compared to an estimate of the average of a 100-m [330-ft] section) and can therefore be used for project-level applications (compared to network-level applications). Furthermore, a confidence interval can be constructed around the estimate. The operation of smoothing filters the noise from the data at the cost of introducing bias. The GCV criterion finds the compromise between the bias and variance to be a trade-off. In practical terms, if more smoothing is performed, important features that are not spikes due to noise will be smoothed out. This is better illustrated with Section UK_F5.

Figure 3.55 shows the results of smoothing measurements on Section UK_F5. In this case, an appreciable difference between the smoothed regression estimate and the results averaged over 100-m (330-ft) sections can be observed. The figure suggests that results for the 100-m (330-ft) averaged section are smoothing statistically significant features of the deflection slope profile. Therefore, these features are not likely due to random noise and perhaps (depending on whether they are important from an engineering perspective) should not be ignored (or smoothed out).

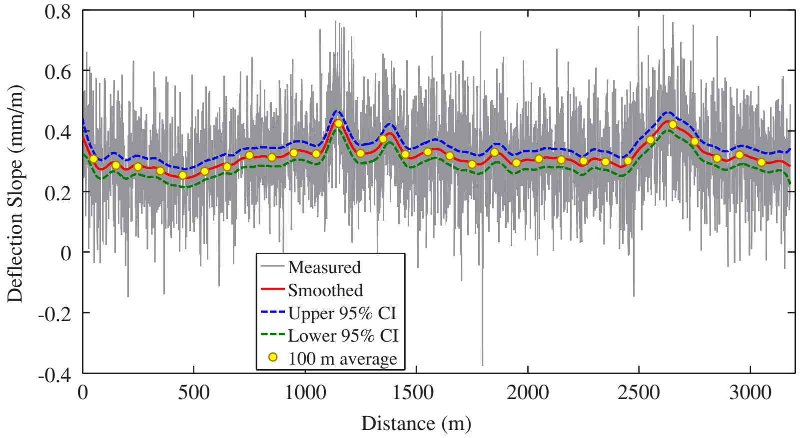


Figure 3.54. Smoothing slope deflection measurements of site UK_F3.

UK_F1 shows an even more extreme example (Figure 3.56). In this case, averaging over 100-m (330-ft) sections is likely to result in smoothing out significant features (both statistically and from an engineering perspective). Figure 3.56 also shows that averaging over 10-m (33-ft) sections results in smoothing out statistically significant features. This was expected, as UK_F1 shows significant variation in the measured deflection slope. In this case, the noise in the signal is relatively small compared to the signal itself. Therefore, smoothing has a much more significant effect on changing the signal than on reducing the level of noise and should be minimal. Again, how much to smooth is controlled by the GCV criterion, which finds a compromise between bias and variance.

Summary

The results presented in this section suggest that the smoothing (or averaging) deflection test results should not be set to a constant value, but rather controlled by the actual deflection profile. Using an "optimal" smoothing may help improve the capabilities of continuous deflection devices to be used for project-level applications. Furthermore, the smoothing spline analysis can be used to identify features that vary with distances as small as 1 m within a certain level of confidence (using the confidence interval as shown in Figure 3.54). Although the limited (in terms of number of sections and section length) data used are only for the TSD, a similar type of analysis should be feasible for the RWD if more closely spaced data are provided. However, closely spaced (raw) RWD measurements were not available for this project and this type of analysis could not be carried out for this device.

Operational Characteristics

Within this study it has not been possible to examine in detail the operational characteristics of the equipment being assessed. Although external factors such as temperature, road geometry, road profile, texture profile, moisture, acceleration, deceleration, and so forth, may have been recorded during the surveys, it is not possible to control these factors and, therefore, not easy to

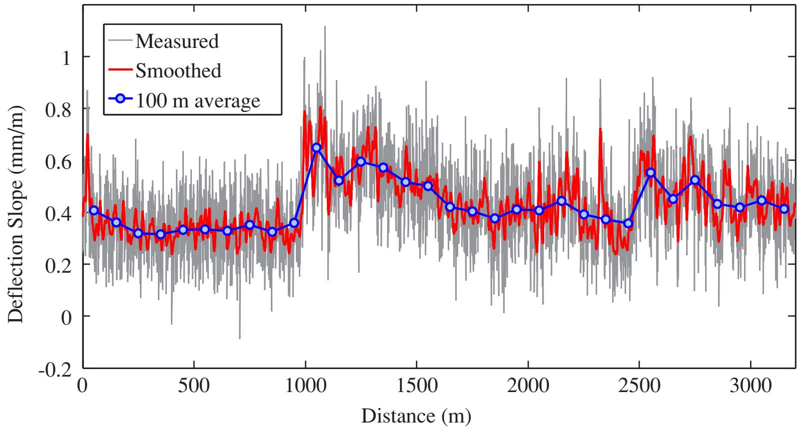


Figure 3.55. Smoothing slope deflection measurements of Site UK_F5.

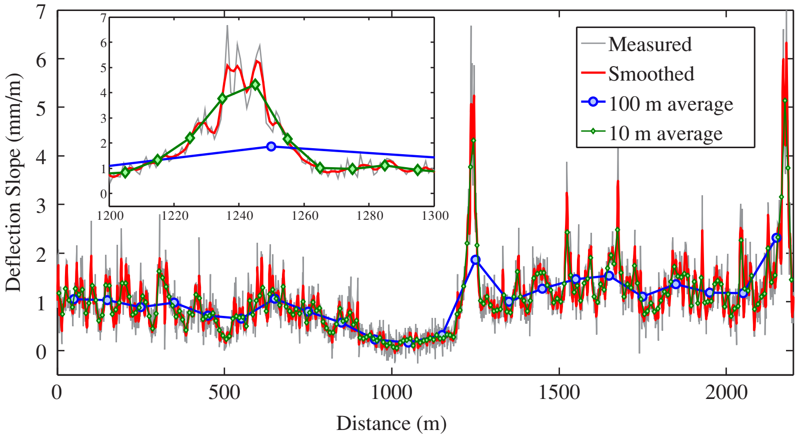


Figure 3.56. Smoothing slope deflection measurements of Site UK_F1.

assess their effect on the measurements. Control of survey speed is possible, but sometimes other uncontrollable effects confound the effort. The following sections discuss these issues together with the measuring capability of current and future devices on the typical range of pavement types encountered on a network.

Operating Conditions

Survey Speed

The RWD is normally operated as close as possible to 80 km/h (50 mph). As yet, no method has been developed for converting surveys at other speeds to the standard operating speed. At present the TSD operates as close as possible to 70 km/h (45 mph) on divided highways, but a range of 60 to 80 km/h (40 to 50 mph) is considered acceptable. For two-lane roadways in the United Kingdom, because of the speed limit, the standard operating speed is 60 km/h (40 mph).

The effect of survey speed has yet to be investigated fully in either device. The deflection response of a pavement will be influenced by a number of factors, which include the speed of the loading wheel and the composition of the pavement. In order to ascertain the extent of the effect, any experiment will need to be very carefully controlled in terms of operating conditions; and the results are likely to vary with the properties, particularly the viscoelastic properties, of the pavement layers. This kind of control was not possible within the scope of the project. However, a limited examination based on available data has been carried out for both devices.

The California RWD demonstration included repeated runs at various speeds on flexible and rigid pavements. Figure 3.57 shows 160-m (0.1-mi) RWD results on two of the tested sections, with flexible and rigid pavements. The figures suggest that RWD deflections are relatively insensitive to truck speed for the speed ranges investigated (50 to 110 km/h [30 to 70 mph]). Since the tests were conducted at different times, some differences for the asphalt pavement could be due to variations in temperature.

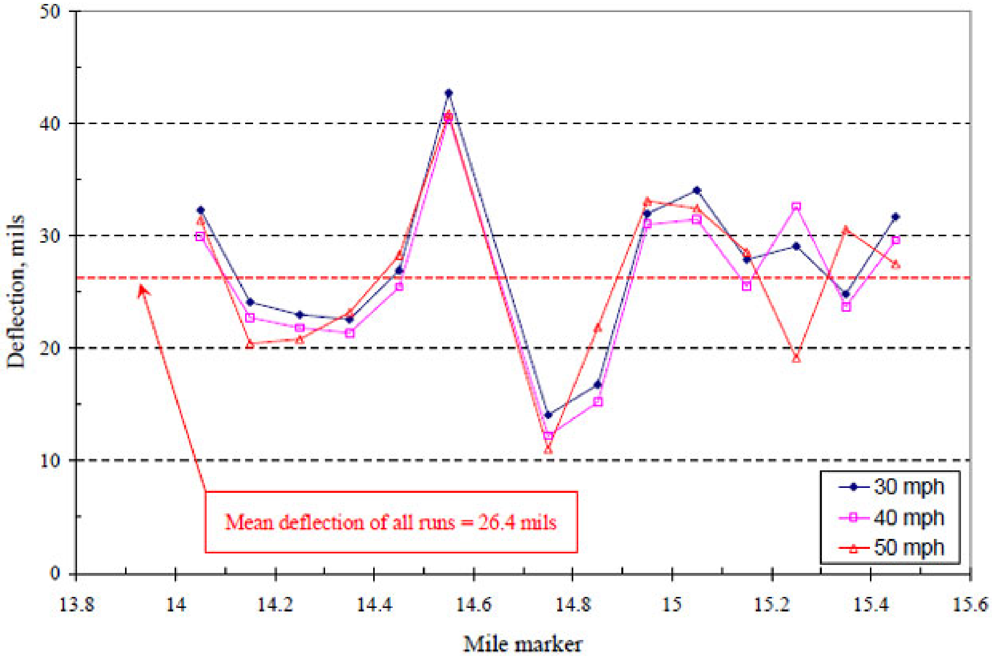
Repeat runs have been carried out with the HA TSD at different speeds. A small change with increasing speed has been shown, but data collected so far have been insufficient to develop a correction procedure to a reference speed. Figure 3.58 illustrates this by presenting the TSD P100 slope profiles as 10-m (33-ft) means for a 1.5-km (1-mi) section with flexible pavement at 60, 70, and 80 km/h (40, 45, and 50 mph).

An analysis of network TSD measurements collected in the United Kingdom during 2010 and the early part of 2011 over a wide range of speeds, some outside the current recommended limits, is shown in Figure 3.59 in the form of a distribution plot. This suggests a reduction in response with increasing speed. However, there are many other confounding effects present in this data, so it can be taken only as an indication of the likely effect of survey speed. The figure shows a two-dimensional version of a three-dimensional plot, in which the lines are contour lines containing given proportions of the total dataset. For example, 20% of the data were collected at speeds of around 61 km/h (38 mph) with slopes from 0.18 to 0.37 mm/m. The other concentration of data is just below 70 km/h (44 mph). These were the two target speeds in the surveys, but other speeds were covered for various practical reasons.

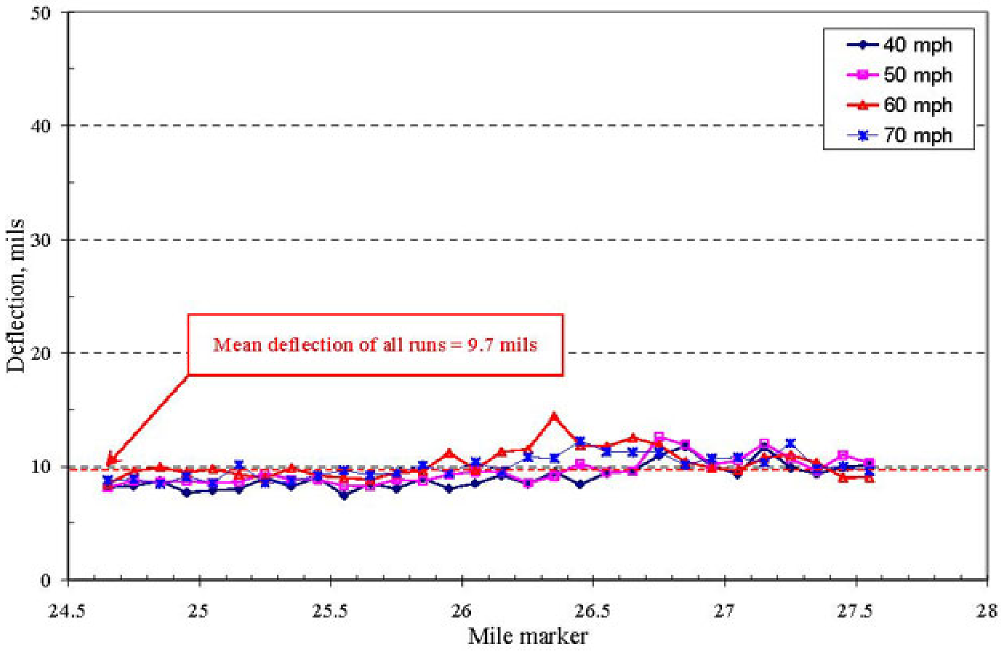
Road Geometry and Profile

The specific effect of road geometry has yet to be investigated for either device. In particular, measurements on curves are a potential issue, especially with the RWD because of the way it compares the same texture profile from the deflected sensors and the undeflected or reference sensor. The two sensors may not follow the same trajectory while measuring on curves.

A superficial examination of the effect of road curvature has been carried out in the United Kingdom by examining the TSD



(a) AC test section on eastbound SR-16, Mileposts 14 to 15.5



(b) JPCP test section on southbound I-505, Exits 24 to 28

Source: ARA, 2007c.

Figure 3.57. Example of repeated RWD runs at different speeds.

network data collected during 2010 and 2011. This examination showed no obvious relationships between longitudinal profiles, gradient, transversal slope, or curvature. The data, with respect to longitudinal profile, are shown in the form of a contour map of the distribution of almost 10,000 lane-km (6,250 lane-mi) of data of deflection slope versus 3-m (10-ft) longitudinal profile variance in Figure 3.60.

Surface Characteristics

Research with the U.K. TSD has shown that surface type can influence the response of the velocity sensors. In particular, new binder-rich surfaces can cause faulty operation of the velocity sensors on the TSD but normal measuring performance returns after a few months of trafficking as the surfacing becomes less

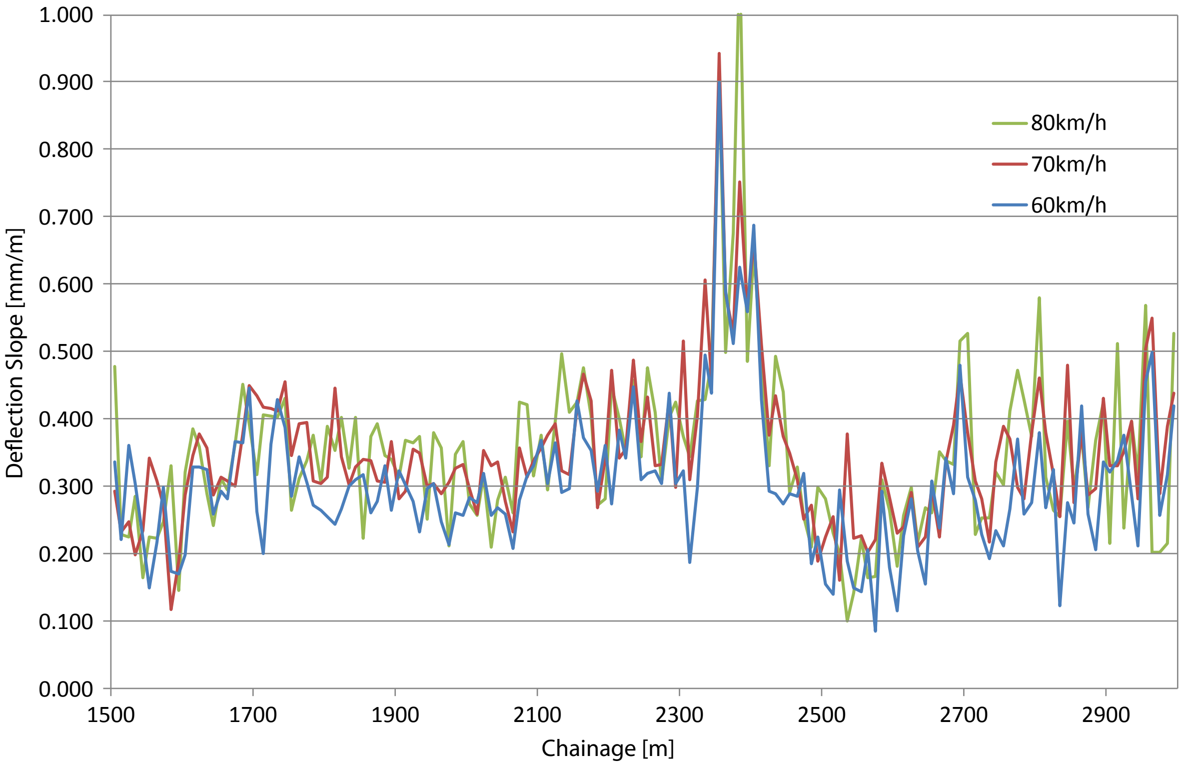
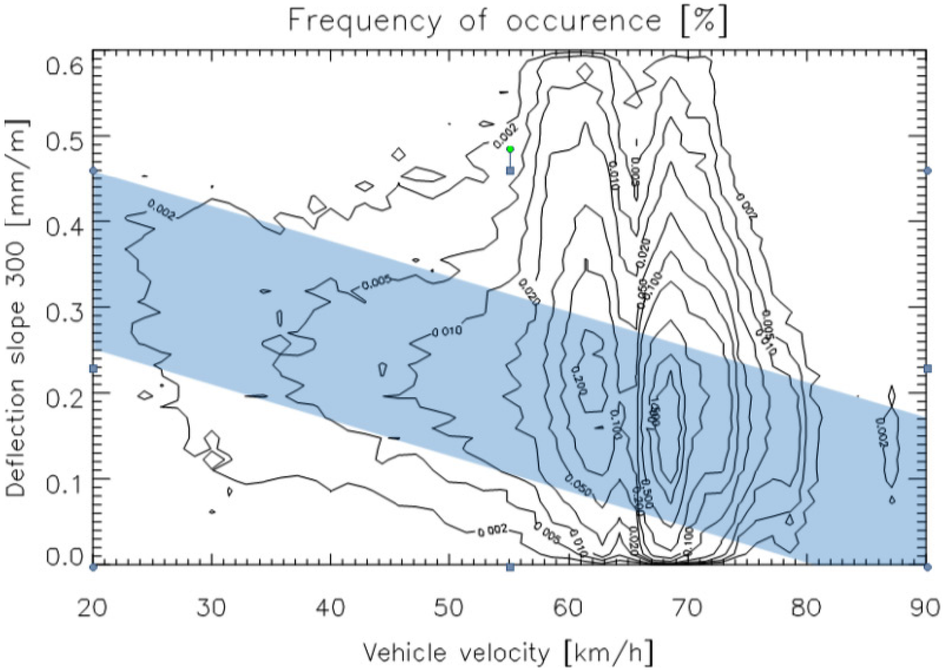


Figure 3.58. TSD slope profiles for 10-m (3.3-ft) means on a U.K. road section at various survey speeds.



Note: The blue area highlights the overall trend of the reduced deflection slope with increased velocity.

Figure 3.59. Effect of survey speed on TSD deflection slope.

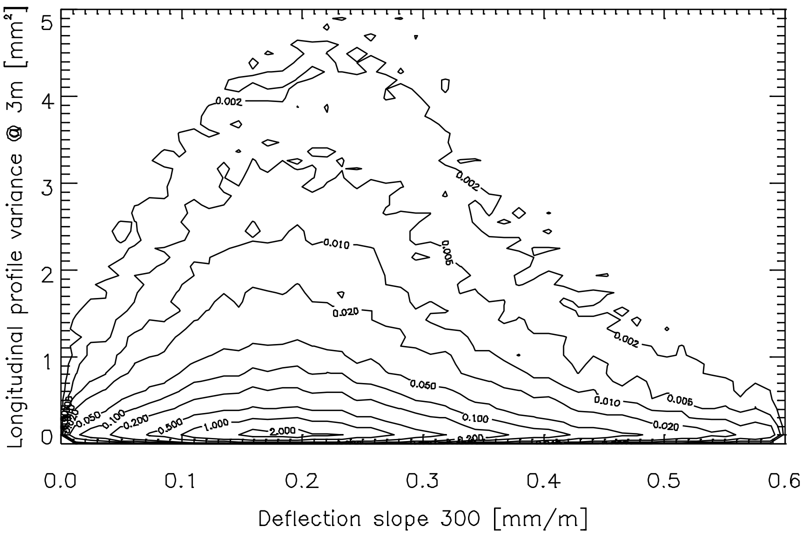


Figure 3.60. Effect of longitudinal profile variance on TSD deflection slope.

reflective. Otherwise, the equipment functions reliably on a wide range of surfaces, including rigid concrete.

This reliability has been illustrated by surveying on a length of road with various types of road surfacing and in various conditions. This work established that the optics perform better on lighter surfaces, such as jointed concrete, and least well on new bituminous surfaces. This conclusion can be seen in Figure 3.61, where the data rate of the four Doppler lasers is shown for one particular survey along a 13-km (8.1-mi) length of a U.K. motorway. The figure shows changes in data rate (the rate at which laser signals are successfully returned from the road surface) over lengths of the jointed concrete and a length of freshly laid thin surfacing in comparison to the rate returned from the old bituminous surface.

This phenomenon is likely due to optical properties of the different surfaces or surface condition. Although it is not fully understood, it is important to identify such features because they help to define the capabilities of the technology, and such information will probably be employed in the quality assurance of TSD data in the future. Information on the effect of such parameters on RWD measurements is not available but is likely to be similar.

Moisture

Both devices use laser-based noncontact sensors that fail to measure correctly when the road is damp or wet. The laser reflection is degraded by the water on the surface.

Dynamic Loading

The specific effect of dynamic loading has yet to be investigated for either device. At present, neither the RWD nor any existing TSDs have the capability to routinely measure dynamic loading on the measuring load. The Danish Road Institute has been exploring this possibility with BASt in Germany using strain gauges mounted on the rear axle of the trailer. The latest TSD, currently being constructed for the South African government, is said to include this technology.

Some have argued that because the equipment has a suspension typical of other trucks, any additional deflection response caused by additional dynamic loads represents what normally occurs at that point on the road and so provides a representative estimate of the structural condition at that location. However, knowledge of the dynamic load would provide a more complete understanding of pavement behavior.

Acceleration and Deceleration

Longitudinal vehicle acceleration and deceleration are likely to affect the accuracy of deflection measurements, so operating limits for these parameters have been developed for the U.K. HA TSD. When operating at normal survey speed, neither device requires traffic management. However, some form of traffic management will be necessary for operation at slower speeds, as well as when operating in nonstandard locations, such as in a U.K. motorway outer lane where trucks are not normally permitted.

Acquisition and Operation Costs

Only the TSD is available commercially, at a cost between $2 million and $2.5 million depending on the number of sensors requested. Although detailed operation and maintenance costs were not obtained for this study, experience in the United Kingdom suggests that the cost of operating

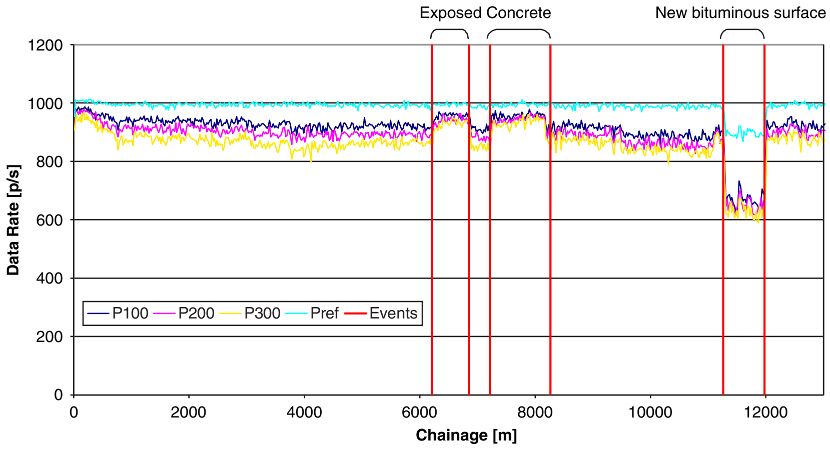


Figure 3.61. Effect of road surfacing type on data rate from each TSD laser (p/s = number of successfully returned laser pulses per second).

the TSD, not including the capital or maintenance costs, is approximately $25 to $40 per mile. Adding the processing cost is estimated to bring this to approximately $75 to $90 per mile.

Measurement Capability

Bowl Shape Detail

The current RWD is designed to measure just the vertical deflection close to the wheels in the outside wheelpath. This should be closely related to the maximum deflection response of the pavement, although the location of this maximum will vary depending on the composition of the pavement and the survey speed, due to any viscoelastic properties of the pavement materials. The RWD as evaluated in this report did not have the capability to measure the full deflection bowl, or a sampled representation of it, as provided by the multiple sensors fitted to most FWDs. However, recent modifications have added an additional sensor to the RWD at a second position farther away from the rear axle to provide such information (see New Development to the Evaluated Equipment section).

At present the two fully operational versions of the TSD measure the vertical velocity of the pavement response to the dual wheel assembly loading at three offsets in front of the rear axle, which is then converted to deflection slope. In the case of the Danish device, these offsets are 100 mm (4 in.), 200 mm (8 in.), and 300 mm (12 in.). In the case of the U.K. device, they are 100 mm (4 in.), 300 mm (12 in.), and 756 mm (30 in.). The deflection sensors respond to velocity (not displacement), which are converted to deflection slope, and therefore cannot directly provide either the full deflection or the maximum value. However as discussed later, the measured slopes closest to the axle, P100 and P300, have shown a strong relationship to the peak deflections measured by other devices. The manufacturer, Greenwood A/S, has developed an approximate relationship that can be fitted to the three offset slope measurements and thus enable estimation of the surface curvature index of the pavement surface under load. At present it is not possible to estimate the full deflection bowl from the current sensor configurations, but a device with more sensors was delivered in 2010.

Both devices currently measure in just one wheelpath in between the two loaded wheels, which are mounted at a slightly wider spacing than are standard truck dual wheels to enable room for the measurement sensors. At present, both measure in the nearside (outside) wheelpath closest to the pavement outer edge in the countries in which they operate. However, measurement in both wheelpaths should be feasible with suitable modifications and at an additional cost. The latest TSD being constructed for the South African government is reported to have the capability of measuring in both wheelpaths.

At present the RWD operates with a 40-kN (9-kip) dual wheel assembly load and the TSD operates with a 50-kN (11-kip) load. Other loads can be employed relatively easily.

Sampling and Reporting Intervals

Both devices sample the raw measurements frequently, the RWD at around 2,000 Hz, equivalent to around 11 mm at 80 km/h (0.4 in. at 50 mph), and the TSD at around 1,000 Hz, equivalent to around 22 mm at 80 km/h (0.8 in. at 50 mph). However, there is much noise in the raw signal, so results are normally reported over much longer lengths. Some examples of different sampling lengths on the results are presented in a later section. Published material on the RWD suggests that the device is suitable for measuring only on flexible and composite pavements, normally presenting results at 160-m (0.1-mi)

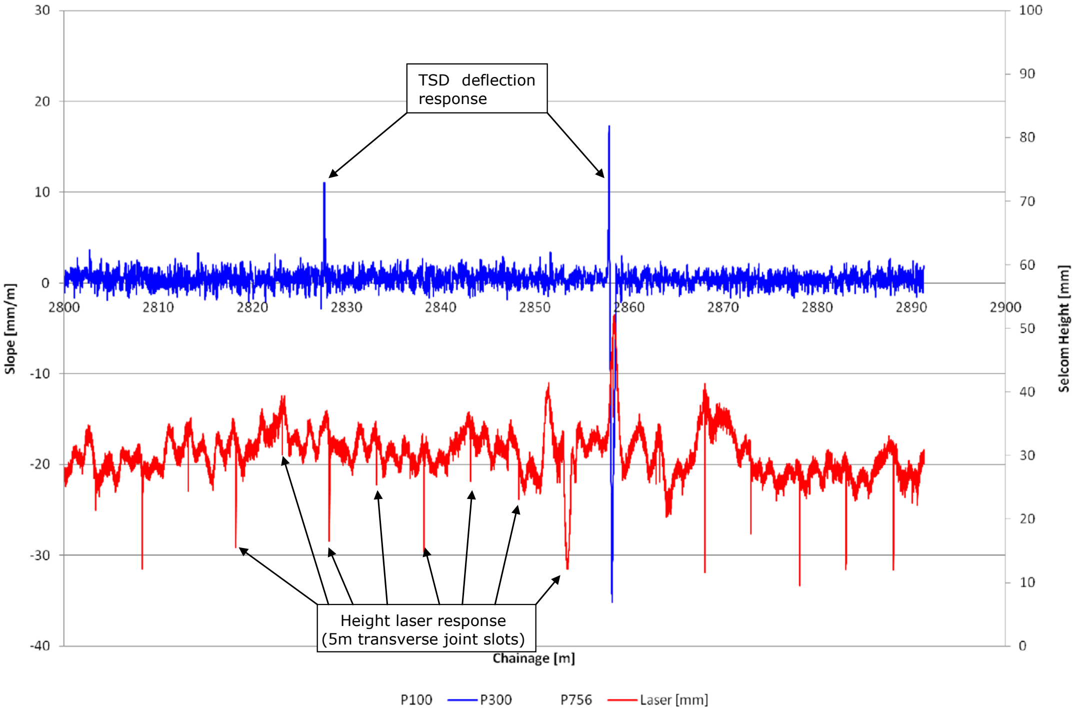


Figure 3.62. Longitudinal profile and deflection slope results from TSD survey on jointed rigid pavement.

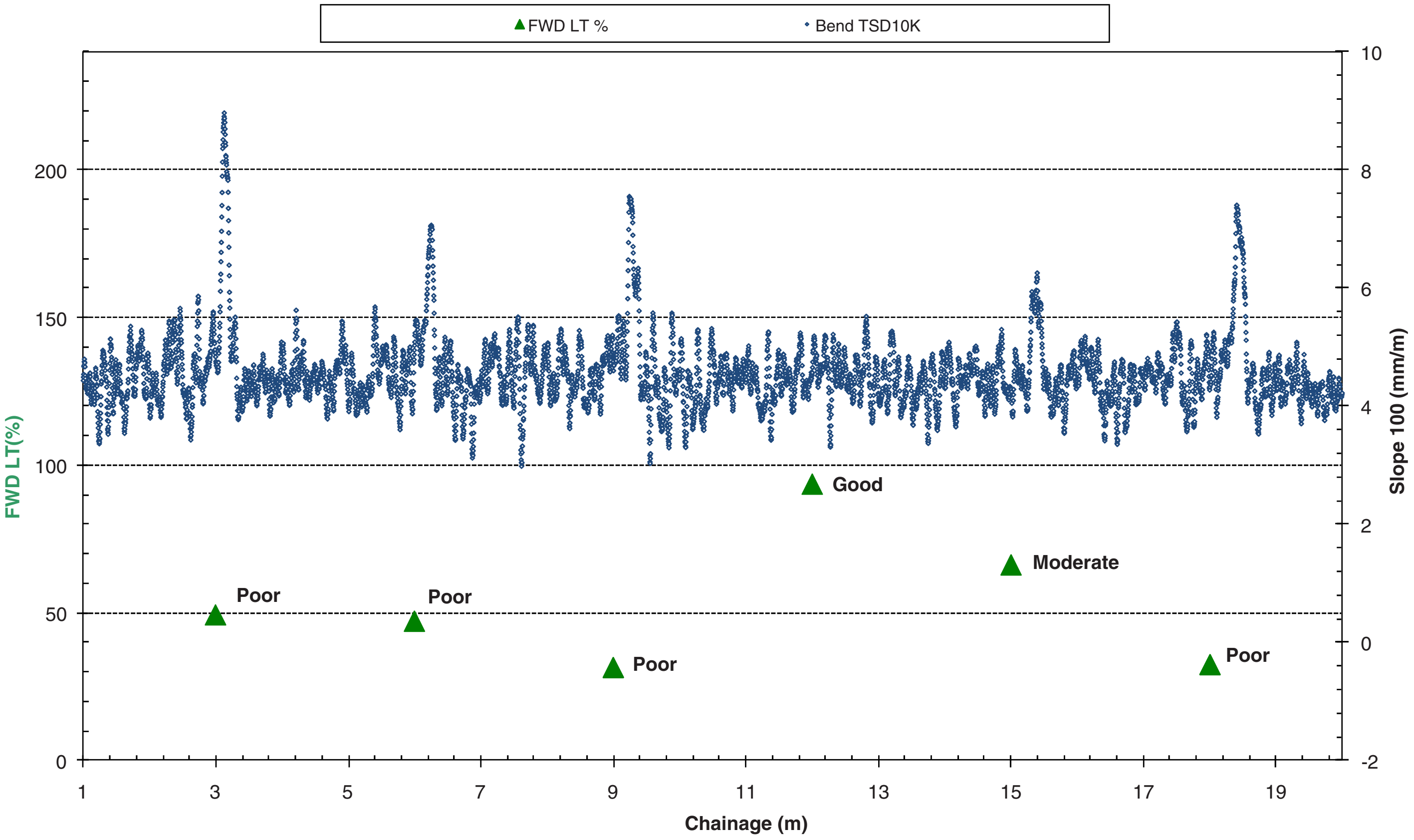


Figure 3.63. Raw TSD slope measured at 10 km/h (6 mph) and FWD joint load transfer efficiencies against location.

intervals. The position with the TSD is similar except that results are normally presented at 10-m (33-ft) intervals. However, some surveys have suggested that shorter length structural variations can be distinguished if the variability is sufficient. This has been discussed further in mathematical terms and examples given earlier in the Denoising and Data Aggregation section.

Joint Load Transfer Efficiency

Limited measurements have been made on an unreinforced jointed rigid pavement on a research track at a survey speed of just 10 km/h (6 mph). Figure 3.62 shows some results over a 90-m (300-ft) length. The red lower profile shows the longitudinal height profile with spikes indicating the 5-m slab joints. The upper blue trace shows the response of one TSD sensor with significant spikes at chainages of 2,827 and 2,859, suggesting poor joint condition. In Figure 3.63, the raw deflection slope profile of another section is shown in comparison to load transfer efficiencies assessed with an FWD. This preliminary investigation suggests that the TSD may have potential to assess the transfer efficiency at joints, but further work is needed to make this a practical routine proposition. No information is yet available on the applicability of either device to unsurfaced granular pavements.

CHAPTER 4

Example Applications and Recent Developments

This chapter presents a series of examples that illustrate potential application of continuous deflection measuring technology. It also identifies some recently developed devices and improvements to the devices evaluated.

Example Applications

Based on the data collected and the analysis performed in previous sections, a number of example applications for the data produced by the continuous deflection measuring devices have been developed. These applications illustrate the use of continuous deflection measurements for network-level pavement management. These applications are not meant to be comprehensive, but rather are intended to show how deflections can be used to address issues applicable to modern pavement management practices.

The applications presented within this section include using measurements obtained from continuous deflection measurement devices to divide pavement sections into homogeneous segments, estimate the strain at the bottom of the asphalt layer, determine the effective structural number (SN) of the pavement, and identify relatively weak pavement sections as well as weak pavement sections defined by absolute thresholds. The segmentation was performed using a statistically based binary segmentation algorithm. The strain at the bottom of the asphalt layer, along with the effective SN, was estimated by using the difference between two deflection slope measurements from the TSD. Identification of relatively weak pavement sections was used to demonstrate the ability of the device to locate anomalies or locally weak sections within a network, whereas identification of weak pavement sections on the basis of thresholds demonstrated the ability of the device to repeatedly identify weak sections.

Using Circular Binary Segmentation to Identify Uniform Sections

For pavement management purposes, pavement deflections (or slope measurements, in the case of the TSD) are often classified into severity categories such as very poor, poor, fair, good, very good, and excellent. In general, different severity levels would trigger different treatments to the pavement. Severity levels can be assigned to individual measurements; however, this can have the following disadvantages:

- Assigning a severity level to each reading can lead to significant variations in the assigned severity levels at adjacent points. This is not practical for pavement management purposes, nor is it practical to apply different treatments at individual points.
- Each deflection (or slope) measurement consists of the actual deflection (or slope) and a random error term. Therefore, a high level of uncertainty is associated with the severity level of each individual measurement. Suppose, for example, a given section is in fair condition. Because of random error in measurements, deflection testing of this section can result in readings that would fall in the poor, fair, or good category.

To address these shortcomings, the deflection (or slope) profile can be segmented into uniform sections identified on the basis of a statistical algorithm. The algorithm chosen to perform the segmentation is the circular binary segmentation (CBS) algorithm that tests for change-points in a given array of data by using a maximal *t*-statistic with a permutation reference distribution to obtain the corresponding *P*-value (Venkatraman and Olshen, 2007). The approach taken by the CBS algorithm is to compare the likelihood ratio of the null hypothesis that there is no change in the data at a specific point to the alternative that there is exactly one change-point at that location. The likelihood ratio is compared against the threshold value of the upper α-quantile of the distribution (Olshen et al., 2004). The CBS algorithm searches for change-points at every point within the array, and then returns each change-point that has likelihood greater than the specified α.

The CBS algorithm, with α equal to 0.01 and the number of permutations equal to 10,000, was used to analyze homogeneous sections for multiple runs of the TSD over the same section. This was completed for each site for 1-m averaging lengths. The values of α and the permutation number were chosen on the basis of recommended values in Olshen et al. (2004).

Two sites are used to illustrate the segmentation: F1, which has the largest variation, and C2, which is one of the sites with the least variation. Figure 4.1 and Figure 4.2 present the segmentation of Sites F1 and C2, respectively. The analysis for F1 yielded as many as 65 change-points.

The segmentation presented in the figures was performed assuming no minimum lengths; thus if the variance changed over very small sections, the algorithm identified the area as the location of a change-point. This can be seen at Site C2 in Figure 4.2; the peak that is identified near 200 m (656 ft) is only 1 m (3.3 ft) long. In practical applications, a 1-m (3.3-ft) section is too short and would be aggregated with the surrounding sections, thus omitting the large peak. To address this, a postprocessor was added to the CBS algorithm that combined sections shorter than a specified length with surrounding sections on the basis of section length and average value.

The minimum length postprocessor was applied to the homogeneous sections for Site F1 and Site C2, 1-m (3.3-ft) averaged data for both 50-m and 100-m (150-ft and 330-ft) minimum lengths. The results for Site F1 can be seen in Figure 4.3. The figures seem to indicate that setting the minimum length to 100 m does not provide adequate detail to clearly identify the peak that occurs between 1,200 m and 1,300 m, or the peak at the end of the section. For Site C2, the minimum length algorithm hides the detail of the peak at approximately 300 m for two of the runs with a 50-m (150-ft) minimum, and for four of the runs with a 100-m (330-ft) minimum length. This is expected because Site C2 is a site with very little structural variability.

The results of the segmentation indicate that the minimum length of a pavement segment should be based on the variability of the deflection profile or, in this case, the deflection slope profile. Practically, it would seem that a structurally variable pavement segment would require more characteristic segments to describe it and, therefore, require smaller specified minimum lengths. However, it is not practical from a pavement management standpoint for an agency to segment its network into pavement sections that are very short. Some minimum length should be specified. In reality, the choice of minimum length should be related to the normal maintenance practice of the highway administration involved.

Computation of Structural Health Indices

Pavement deflection measurements can be inputs into many pavement condition assessment tools, including structural capacity indicators and tools to calculate the remaining service life of pavements. Therefore, it is believed that measurements

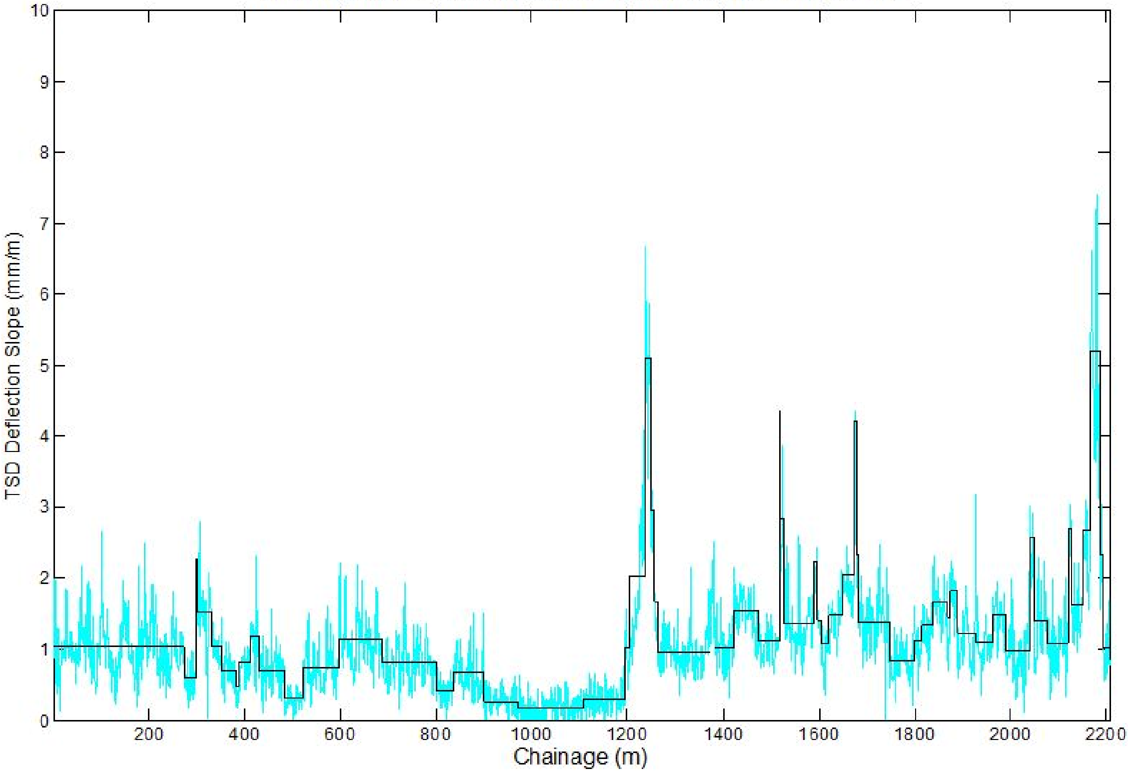


Figure 4.1. Homogeneous sections for Site F1, 1-m averages, Sensor 100.

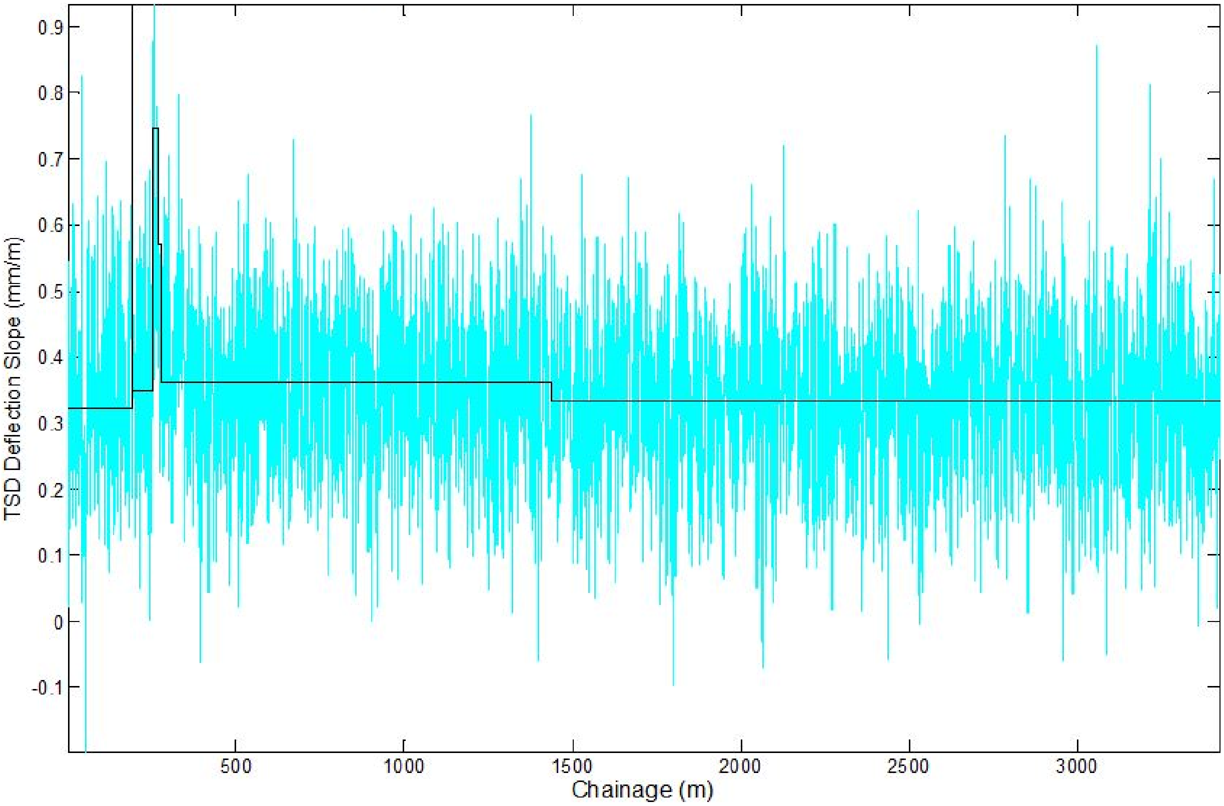


Figure 4.2. Homogeneous sections for Site C2, 1-m averages, Sensor 100.

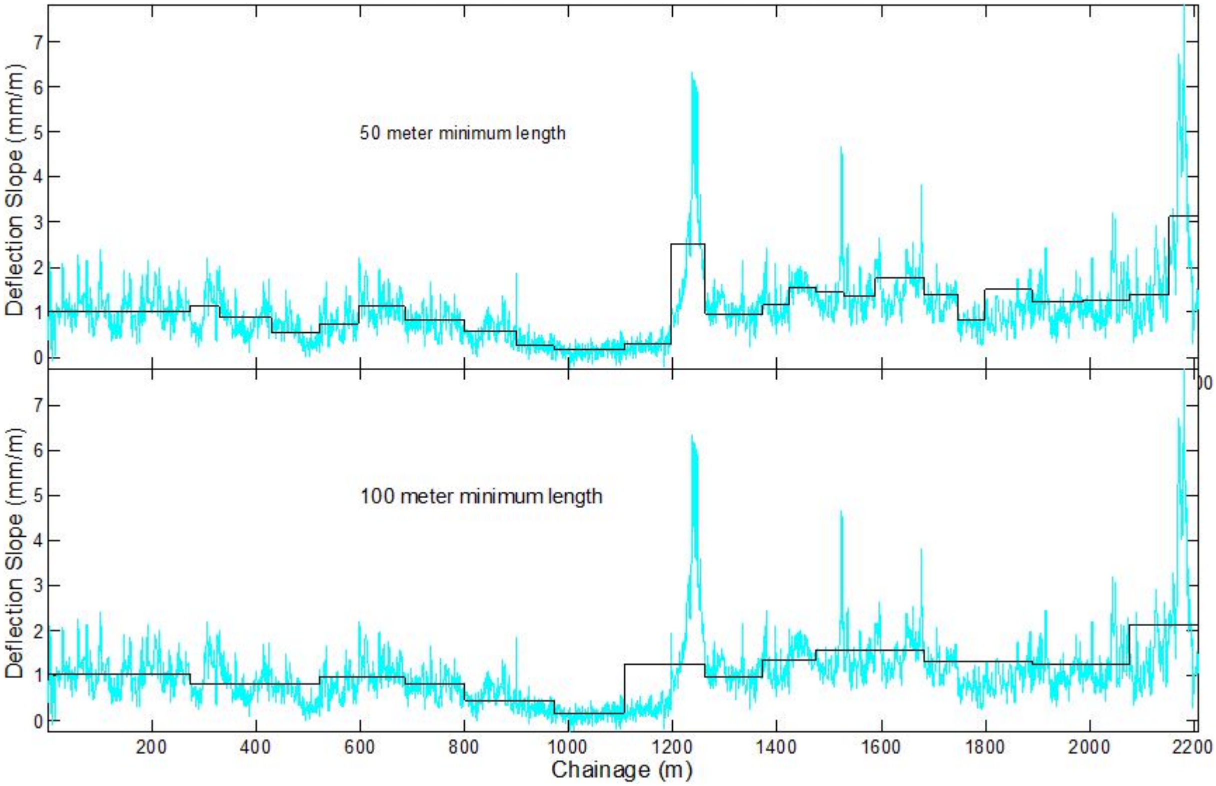


Figure 4.3. Homogeneous sections for Site F1, 1-m averages and specified minimum length.

taken with the continuous deflection measuring devices can be surrogates for the FWD deflection values that are typically input into structural models. ARA reported results from analyzing data gathered from 1,060 km (660 mi) of testing in Colorado and New Mexico and directly implementing the data into a network-level decision process (Hausman and Steele, 2011). Among the benefits cited in the research was at least a 5% cost benefit from incorporating deflection data from the RWD into the network-level decision process.

It may be important to account for the consequences of continuous deflection measurement vehicle dynamics on the pavement response. Yoo and Al-Qadi (2007) discussed the effect of transient dynamic loads on pavement response in terms of dynamic amplifications of strains and concluded that mass inertia and damping forces generated by the transient dynamic loads should be considered for an accurate analysis of pavement responses. Vehicle dynamics could play a significant role in interpreting pavement response, especially when pavement testing is being conducted on very rough roads. However, for network-level analysis, which requires less detail than does project-level analysis, the errors incurred by neglecting the vehicle dynamics are expected to be a small part of the measurement. This is especially true when many measurements are averaged over a pavement section.

Given that the TSD does not measure pavement deflections directly, some corrections may need to be made to the structural models to allow for the deflection slope to be input. However, given the good level of comparability shown between the FWD SCI (or BDI) and TSD SCI (or BDI) earlier in this report, the structural capacity models based on difference between FWD deflections should be applicable to the TSD slope measurements, with some corrections.

Asphalt Layer Strains

The SCI can be directly calculated by using the TSD deflection slope measurements, as previously shown in this report. This is because the SCI is based on taking the differences in measurements. Furthermore, the SCI calculated from FWD deflection measurements has been shown to be an excellent indicator of the strain of the asphalt layer in a flexible pavement (Xu et al., 2002; Thyagarajan et al., 2011). The relationships developed for determining the strain for full depth pavements and aggregate base pavements are presented in Equations 4.1 and 4.2, respectively:

$$\mathrm{Log}(\varepsilon_{AC}) = 0.9977\mathrm{Log}(\mathrm{BDI}) + 3.3057 \qquad \mathrm{R}^2 = 0.987 \tag{4.1}$$

$$\mathrm{Log}(\varepsilon_{AC}) = 0.5492\mathrm{Log}(\mathrm{SCI}) + 0.3850\mathrm{Log}(\mathrm{BDI}) + 0.7812\mathrm{Log}(H_{AC}) - 0.0017H_{AC} + 1.7353 \qquad \mathrm{R}^2 = 0.994 \tag{4.2}$$

where

ε_{AC} = strain at the bottom of the asphalt layer,
H_{AC} = thickness (mm) of the asphalt layer,
SCI = surface curvature index (mm), and
BDI = base distress index (mm).

These equations were developed for use with FWD measurements. They may not be appropriate for deflections measured by using a rolling wheel load moving at traffic speed, as in the case with the TSD.

The equation to calculate the SCI from the TSD measurements was based on the assumption that the slope at the location of the applied load is zero. Because of the viscoelastic nature of pavement, this assumption is not exactly true; but it is expected to be a good assumption. The following equation was used to calculate the SCI from the TSD (trapezoidal integration):

$$\mathrm{SCI(mm)} = 0.5 \times (P100/1{,}000) \times 100\ \mathrm{mm} + 0.5 \times ((P100 + P300)/1{,}000) \times 200\ \mathrm{mm} \tag{4.3}$$

where

$P100$ = TSD measured slope deflection (mm/m) at 100 mm (3.94 in.), and
$P300$ = TSD measured slope deflection (mm/m) at 300 mm (11.8 in.).

The BDI is given by the following equation:

$$\mathrm{BDI} = D300 - D600 \tag{4.4}$$

where

$D300$ = deflection measured by the FWD 300 mm (11.8 in.) from the center of the load plate, and
$D600$ = deflection measured by the FWD 600 mm (23.6 in.) from the center of the load plate.

The equation to calculate the BDI from the TSD deflection slope can be found with an equation similar to the equation used to calculate the SCI. The BDI is defined as the area under the curve defined by the deflection slope values between 300 mm and 600 mm. The equation to calculate this area is the following:

$$\mathrm{BDI(mm)} = 0.5 \times ((P300 + P600)/1{,}000) \times 300\ \mathrm{mm} \tag{4.5}$$

$$P600 = \left(\frac{P300 - P756}{300\ \mathrm{mm} - 756\ \mathrm{mm}}\right) \times 300\ \mathrm{mm} + (P300) \tag{4.6}$$

where

$P300$ = TSD measured slope deflection (mm/m) at 300 mm,
$P600$ = TSD estimated slope deflection (mm/m) at 600 mm, and
$P756$ = TSD measured slope deflection (mm/m) at 756 mm.

Site F1 Evaluation

To demonstrate the applicability of the methods described earlier, the strain at the bottom of the asphalt layer was estimated for Site F1. As mentioned, Site F1 is a structurally variable site with an estimated asphalt layer thickness of 75 mm (3 in.) and a relatively weak underlying cement stabilized layer. The comparison of the SCI calculated from data gathered by the TSD and FWD are presented in Figure 4.4, and the BDI calculated from data from each device are compared in Figure 4.5. The relationship shown in each case was determined using orthogonal regression, since both estimates contain measurement errors. These curves are similar to the ones presented in the comparability between TSD and FWD test results but include only one individual road segment.

By use of the SCI, BDI, and thickness of the pavement, the strain at the bottom of the asphalt layer was estimated along the site for each measuring device. The comparison of the strain at the bottom of the asphalt layer from the two devices is presented in Figure 4.6.

These are very encouraging results considering the various approximations, discussed earlier, that have been used in their derivation.

Effective Structural Number

There are many different ways of estimating the effective SN (SN_{eff}) of a pavement from the results of nondestructive tests. A comprehensive review of this issue is published in Volume 6 of the HDM-4 Manual (Morosiuk and Riley, 2001). For illustrative purposes, the method developed by Rhode (1994) has been selected for the following analysis. This method for estimating the effective SN of a pavement is based on the pavement thickness and the difference between the FWD center deflection and the deflection at 1.5 times the pavement depth. Using the difference in deflections between two points is advantageous for applying this method to the TSD because it is possible to integrate the deflection slope to find the difference in deflection between the two points. The predictive model is based on the assumption that it is possible to estimate the deflection originating solely in the pavement structure knowing that 95% of the deflections measured on the surface of a pavement originate below a line deviating 34 degrees from the horizontal (Irwin, 1983). The steps for determining the effective SN from FWD measurements are as follows:

1. The FWD measurements should be normalized to 9,000-lb load deflections.
2. Determine the deflections at an offset of 1.5 times the pavement depth by using the following interpolation formula:

$$D1.5_{H_p} = \frac{(x-B)(x-C)}{(A-B)(A-C)}DA + \frac{(x-A)(x-C)}{(B-A)(B-C)}DB + \frac{(x-A)(x-B)}{(C-A)(C-B)}DC \qquad (4.7)$$

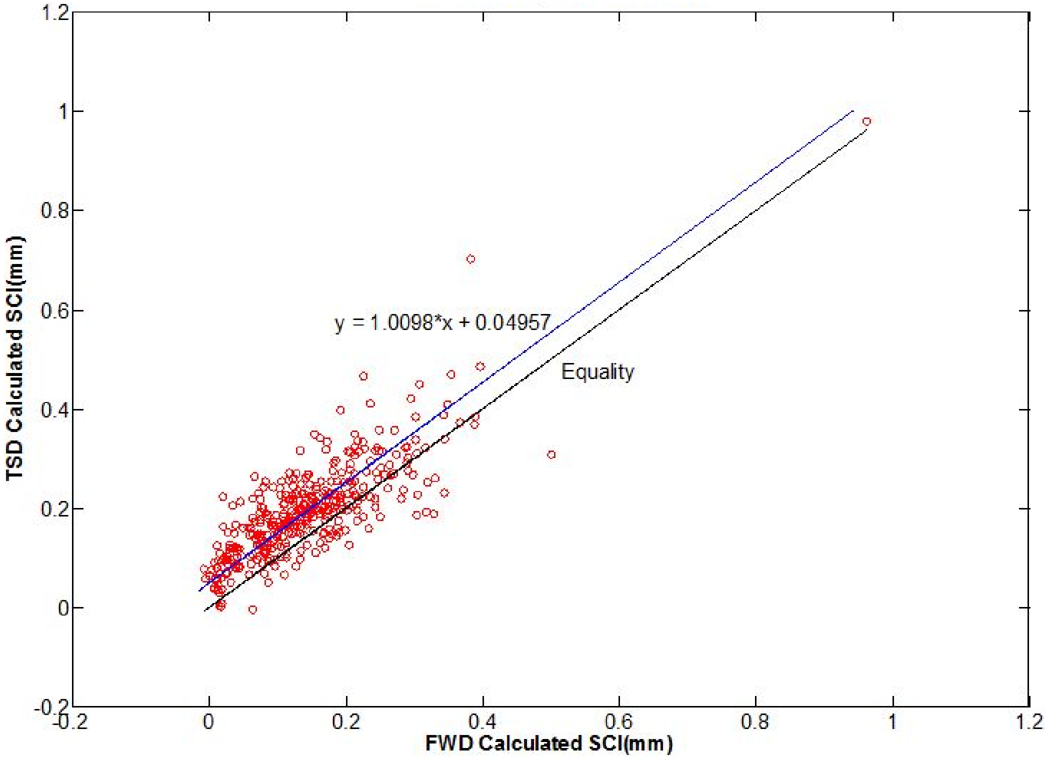


Figure 4.4. Site F1 comparison: TSD-calculated SCI versus FWD-calculated SCI.

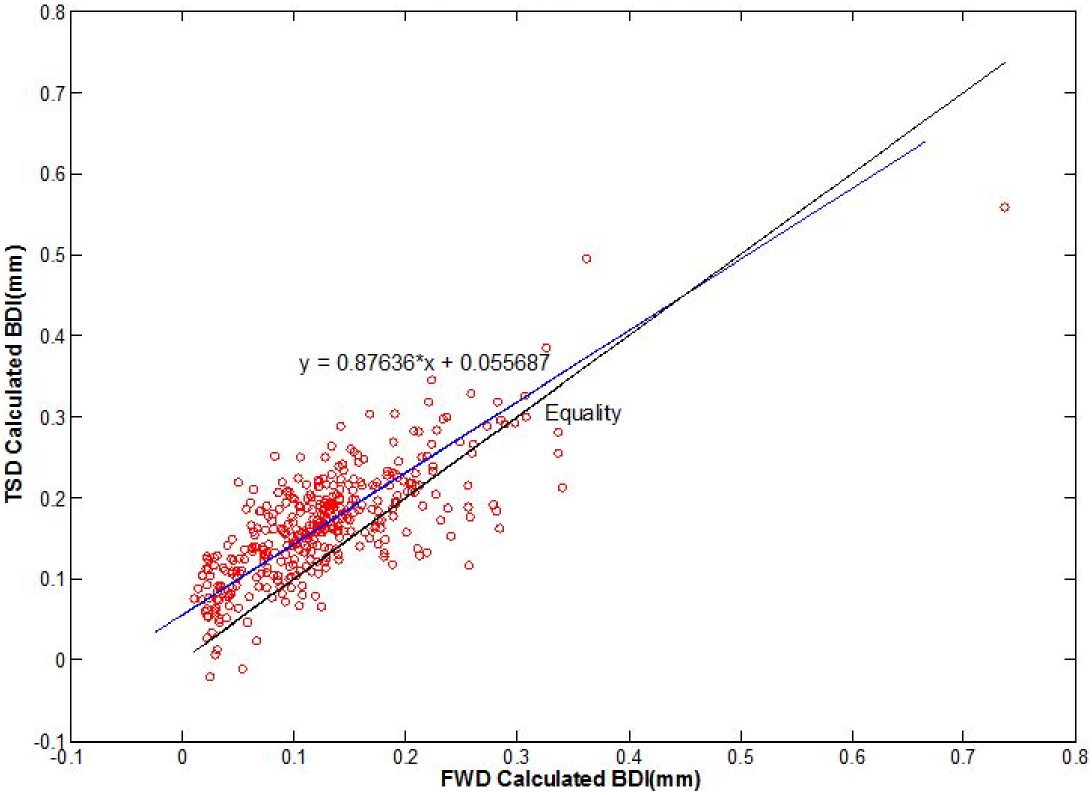


Figure 4.5. Site F1 comparison: TSD-calculated BDI versus FWD-calculated BDI.

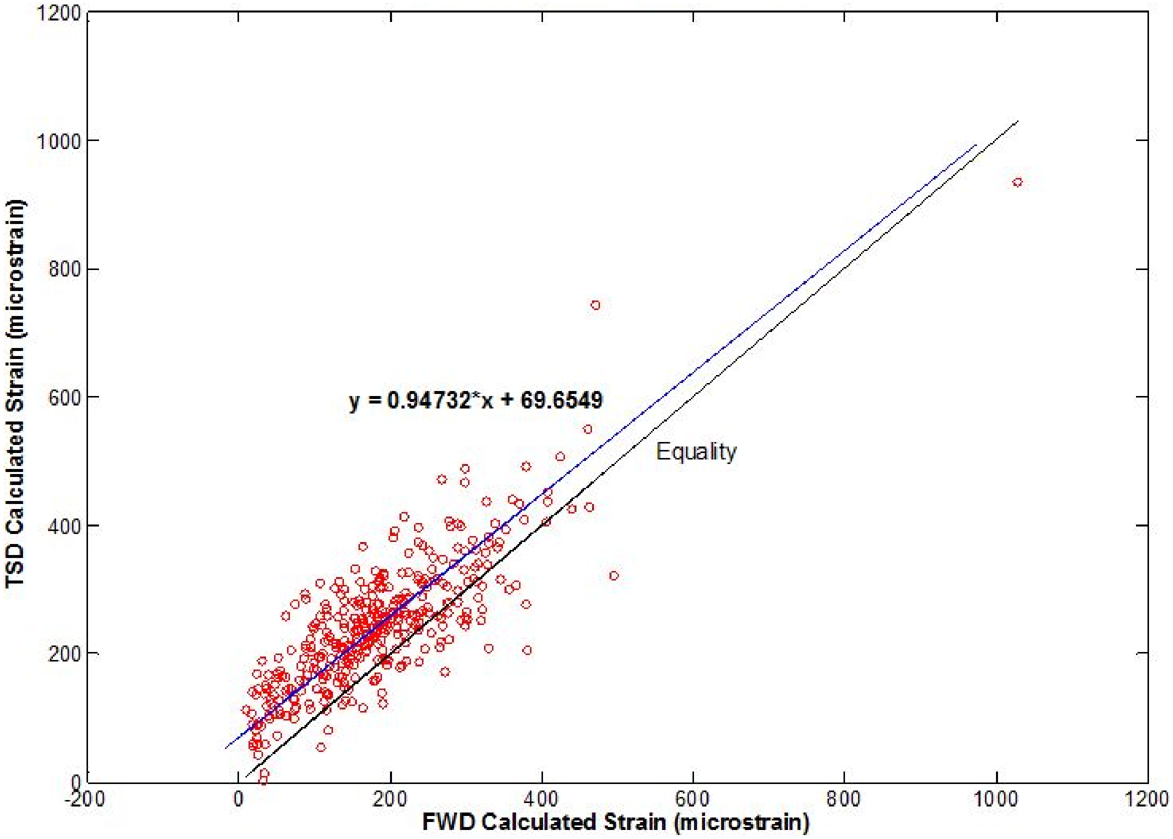


Figure 4.6. Site F1 comparison: Strain at the bottom of the asphalt layer estimated by TSD and FWD.

where

$x = 1.5H_p$,

H_p = depth of the pavement (mm),

A, B, and C = points closest to x where the deflection is known, and

DA, DB, and DC = deflections at points A, B, and C respectively.

3. Determine the structural index SIP of the pavement as follows;

$$\text{SIP} = D0 - D1.5_{H_p} \qquad (4.8)$$

where

$D0$ = peak deflection under the 9,000-lb load (microns), and

$D1.5_{Hp}$ = deflection at 1.5 times the pavement depth (microns).

4. Determine the existing pavement SN_{eff} as

$$\text{SN}_{\text{eff}} = k_1 \text{SIP}^{k_2} H_p^{k_3} \qquad (4.9)$$

where, for asphalt pavement, $k_1 = 0.4728$, $k_2 = -0.4810$, $k_3 = 0.7581$ (Rohde, 1994).

Site F5

Site F5 is a flexible site that was tested using both the TSD and FWD. The structure of Site F5 is shown in Table 4.1. The upper-bound and lower-bound layer coefficients are representative of values typically found in the design of new pavement sections and were used to estimate initial SN values. The high modulus roadbase is treated as an asphalt base layer.

To calculate the SIP from the TSD deflection slope, a similar procedure to that used in estimating the SCI300 and BDI was employed. First, the deflection slope at 1.5 times the pavement depth, or at 690 mm for Site F5, was estimated with the following equation:

$$P690 = \frac{P300 - P756}{300\text{mm} - 756\text{mm}} \times 390\text{mm} + P300 \qquad (4.10)$$

After the deflection slope at 690 mm (27.2 in.) was estimated, the area under the curve defined by the deflection slope was calculated. The area under this curve defines the difference in deflections between the two points between which the area is calculated. The calculation of this area was performed in a way similar to the calculation of the SCI300, by using the assumption that the deflection slope varies linearly throughout the deflection basin, and the deflection slope at the location of the applied load is 0. The result is the SIP defined by Rhode et al. (1994). With use of the SIP, the effective structural number for the section was estimated from the TSD measurements. The results are presented in Figure 4.7.

The results seem to indicate three distinct structural sections within the site. These three sections were visually separated, and the mean section SN_{eff} and upper 95% confidence interval of the data were plotted in the figure. Furthermore, the range of values estimated by the TSD seems to fall largely below the range of expected values for pavement constructed with these layers, as seen in Figure 4.8, as would be expected for deteriorated pavement. The expected values were found by estimating the layer properties for each material defined in Table 4.1 from appropriate literature sources.

Site F3

To further demonstrate the ability of the device to estimate the effective structural number of a section of flexible pavement, the methodology was applied to Site F3, which was in good condition. The structure of Site F3 is shown in Table 4.2. The macadam is treated as an asphalt base layer.

Similar to the procedure for Site F5, the SIP was calculated from the TSD deflection slope. The deflection slope at 1.5 times the pavement depth, or at 630 mm for Site F3, was estimated with the following equation:

$$P630 = \frac{P300 - P756}{300\text{mm} - 756\text{mm}} \times 330\text{mm} + P300 \qquad (4.11)$$

After the deflection slope at 630 mm was estimated, the area under the curve defined by the deflection slope was calculated. The result is the SIP defined by Rhode (1994). With use of the SIP, the effective structural number for the section was estimated using the TSD. The results are presented in Figure 4.9, along with the average and upper 95% confidence interval.

Table 4.1. Structure of Site F5

Layer	Material Name	Date Laid	Thickness (in.)	Upper-Bound Layer Coeff.	SN 1	Lower-Bound Layer Coeff.	SN 2
4	Surfacing	05/28/2007	1.38	0.44	0.61	0.4	0.55
3	High modulus roadbase	05/28/2007	2.36	0.4	0.71	0.3	0.47
2	High modulus roadbase	05/28/2007	8.46	0.4	2.54	0.3	1.69
1	Type 1 granular	05/28/2007	5.91	0.12	0.71	0.1	0.59

Note: SN 1 = 5.65, SN 2 = 4.39.

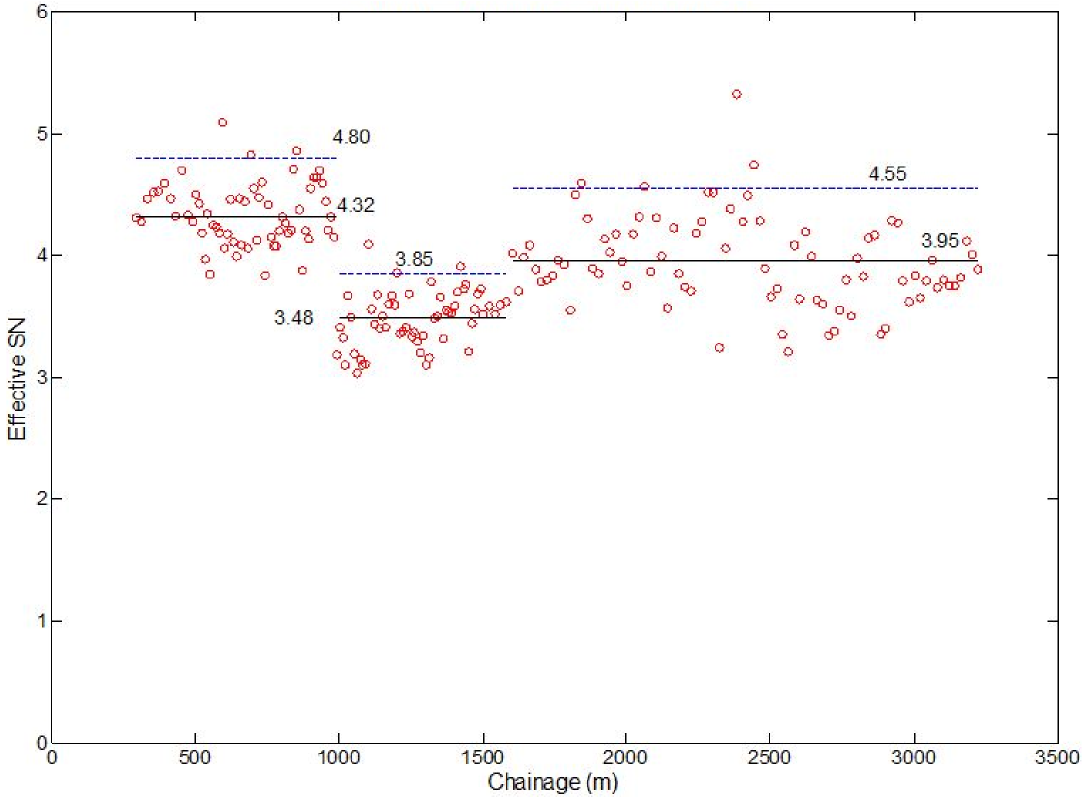


Figure 4.7. SN_{eff} estimated from the TSD for Site F5.

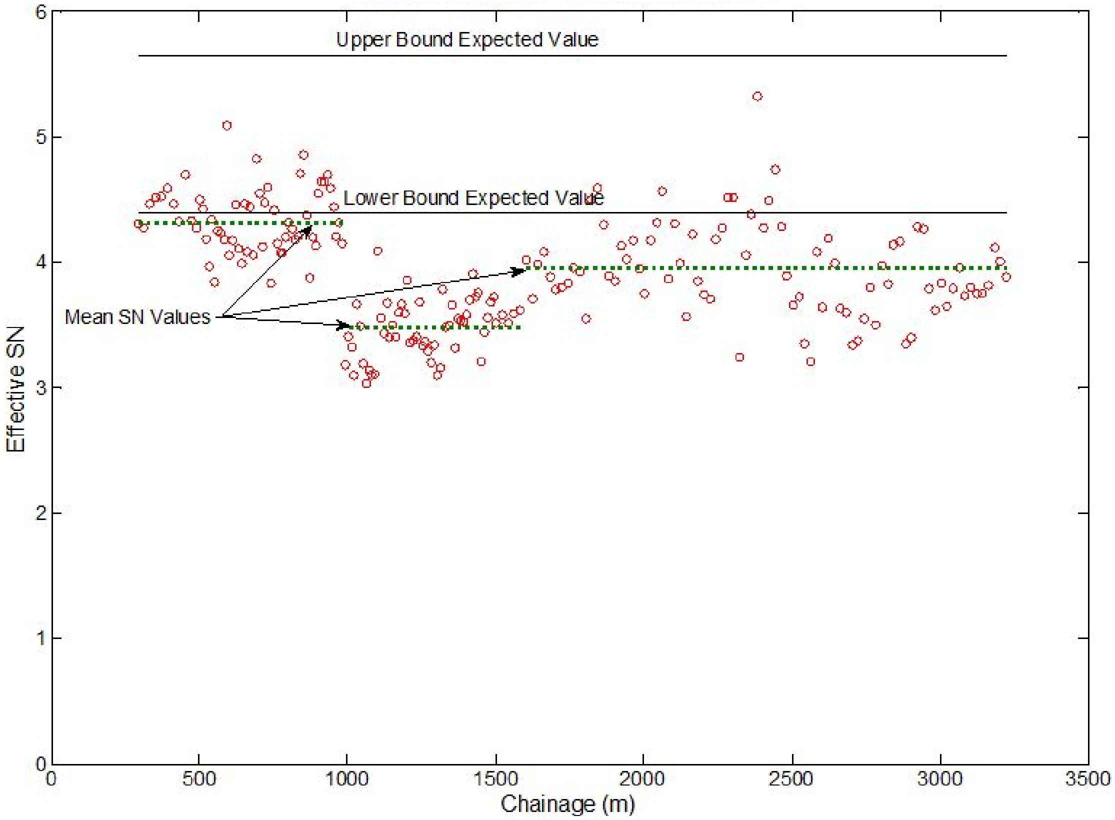


Figure 4.8. Effective SN from TSD for Site F5.

Table 4.2. Structure of Site F3

Layer	Material Name	Date Laid	Thickness (in.)	Upper-Bound Layer Coeff.	SN 1	Lower-Bound Layer Coeff.	SN 2
4	Hot rolled asphalt	7/10/1992	1.57	0.44	0.69	0.4	0.63
3	Heavy duty macadam	7/10/1992	2.36	0.4	0.87	0.3	0.71
2	Heavy duty macadam	7/10/1992	6.69	0.4	2.48	0.3	2.01
1	Type 1 granular	7/10/1992	5.91	0.12	0.71	0.1	0.59

Note: SN 1 = 5.02, SN 2 = 3.94.

The results from Site F3 seem to indicate that, structurally, it is a relatively constant section. This matches what was reported previously in this research. Furthermore, the range of values estimated by the TSD fall generally within the range of expected values, as seen in Figure 4.10.

In general the results from estimating the effective SN at the two sites indicate that the TSD gives a reasonable estimate. It is important to note that the model that was developed by Rhode (1994) used in this approach should be further evaluated to determine if the constants are optimal for use with TSD data. There may be more-appropriate alternative approaches, as mentioned earlier in this section. However, the methodology seems to produce results that reasonably estimate the expected structural number values.

Identification of Weak Sections

A critical need in network-level pavement management is the ability to identify weak pavement sections within the network. In many cases, the managing engineer may desire to identify the weakest portions of the pavement relative to other pavement sections in the network. In a paper describing research on moving pavement deflection testing devices, Rada et al. (2011) described this process as the ability of the device to identify pavement changes or anomalies at the network level. They determined that an important application of the moving deflection testing devices was the ability to determine relative changes of pavement structural condition with a network. In the case of this research, the question becomes whether

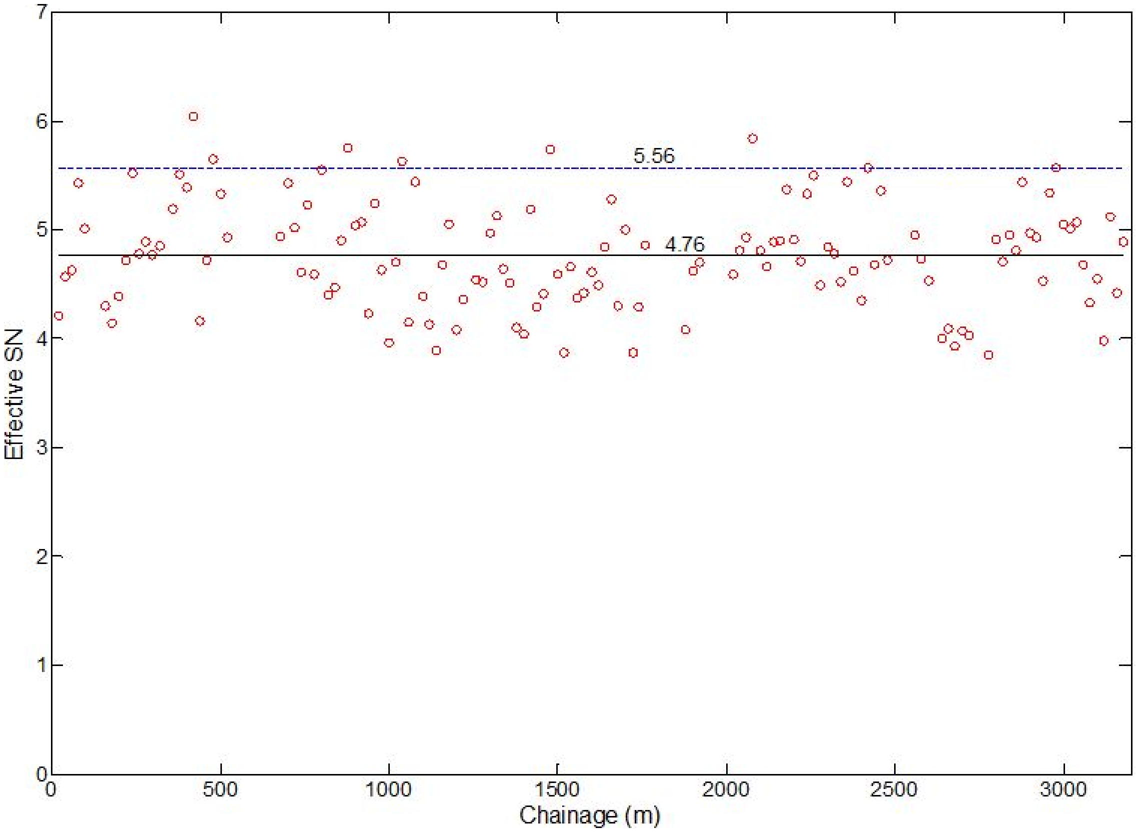


Figure 4.9. SN_{eff} estimated by using the TSD for Site F3.

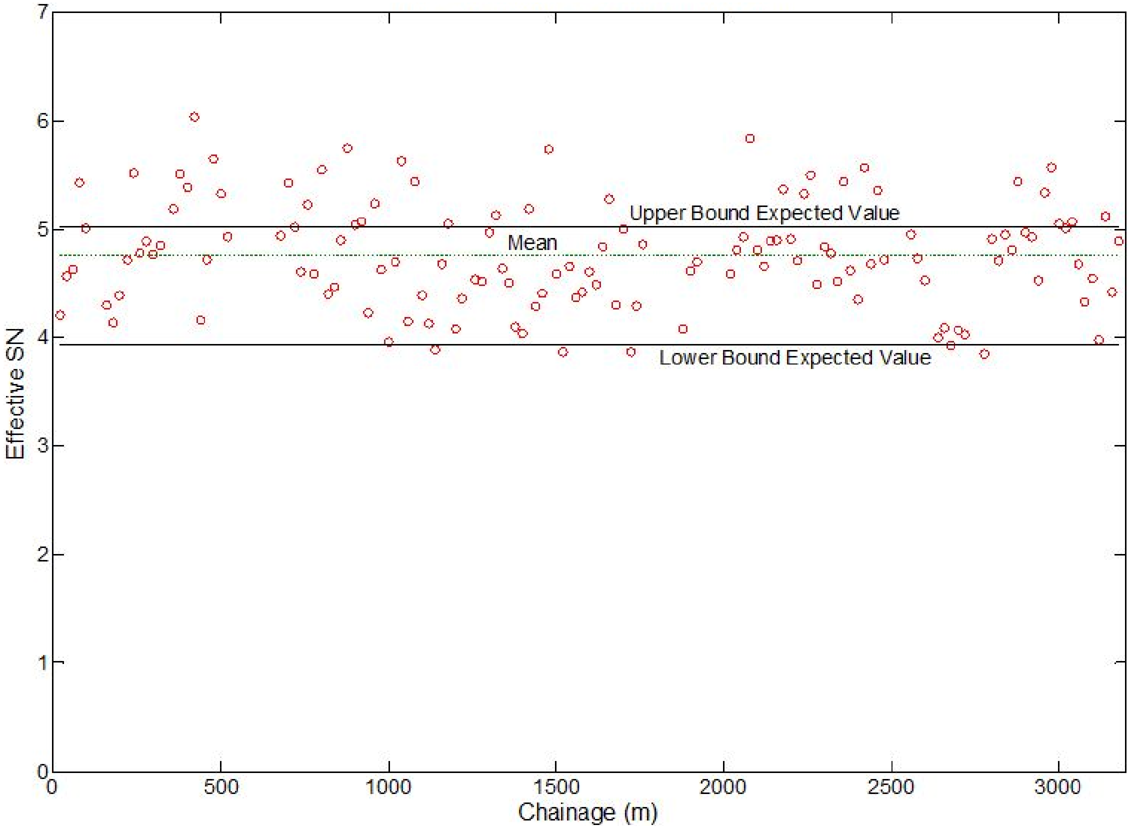


Figure 4.10. SN_{eff} from TSD for Site F3.

the device consistently identified the same sections for each repeated set of measurements, and whether the same sections can be reproduced with a traditional measuring device like the FWD.

U.K. TSD Site F1

Site F1 was a structurally variable site that could clearly be split into several categories (i.e., weak, moderate, and strong) after the site was segmented into homogeneous sections using the CBS algorithm. This is shown in Figure 4.11, where weak sections were identified by a deflection slope value of over 2 mm/m, the strong threshold was set at 1.2, and the very strong sections were identified by deflection values less than 0.5 mm/m. Setting the values for the weak, moderate, strong, and very strong sections resulted in approximately 3% of the data falling in the weak sections, 43% of the data in the moderate category, 42% of the data in the strong category, and 12% of the data in the very strong category. The areas identified as weak may be good candidates for localized patching.

To compare these sections to the data from the FWD, a scatter plot was created comparing the center deflection of the FWD and the TSD P100 averaged over only the sections where FWD data were gathered (Figure 4.12). The FWD center deflections were corrected back to the temperatures that were measured during the TSD testing using the procedure presented in the *LTPP Guide to Asphalt Temperature Prediction and Correction* (FHWA, 1998).

The weak values corresponded to an equivalent FWD center deflection of greater than 995 microns (39 mils), the moderate values corresponded to an equivalent FWD center deflection of between 995 microns (39 mils) and 575 microns (23 mils), the strong values corresponded to an equivalent FWD center deflection of between 575 microns (23 mils) and 205 microns (8 mils), and the very strong values corresponded to values less than 205 microns (8 mils).

Discrimination Between Sections with Good and Poor Structural Capacity

An agency that already uses the FWD center deflection for network-level pavement management may wish to identify the TSD deflection slope value that would correspond to agency thresholds for weak sections. If this is the case, the segments that are identified would no longer be considered different relative to other pavement segments in the section, but weak or strong on the basis of absolute thresholds. A benefit of absolute thresholds is that they would most likely be mechanistically based, leading to a more objective classification of pavement conditions.

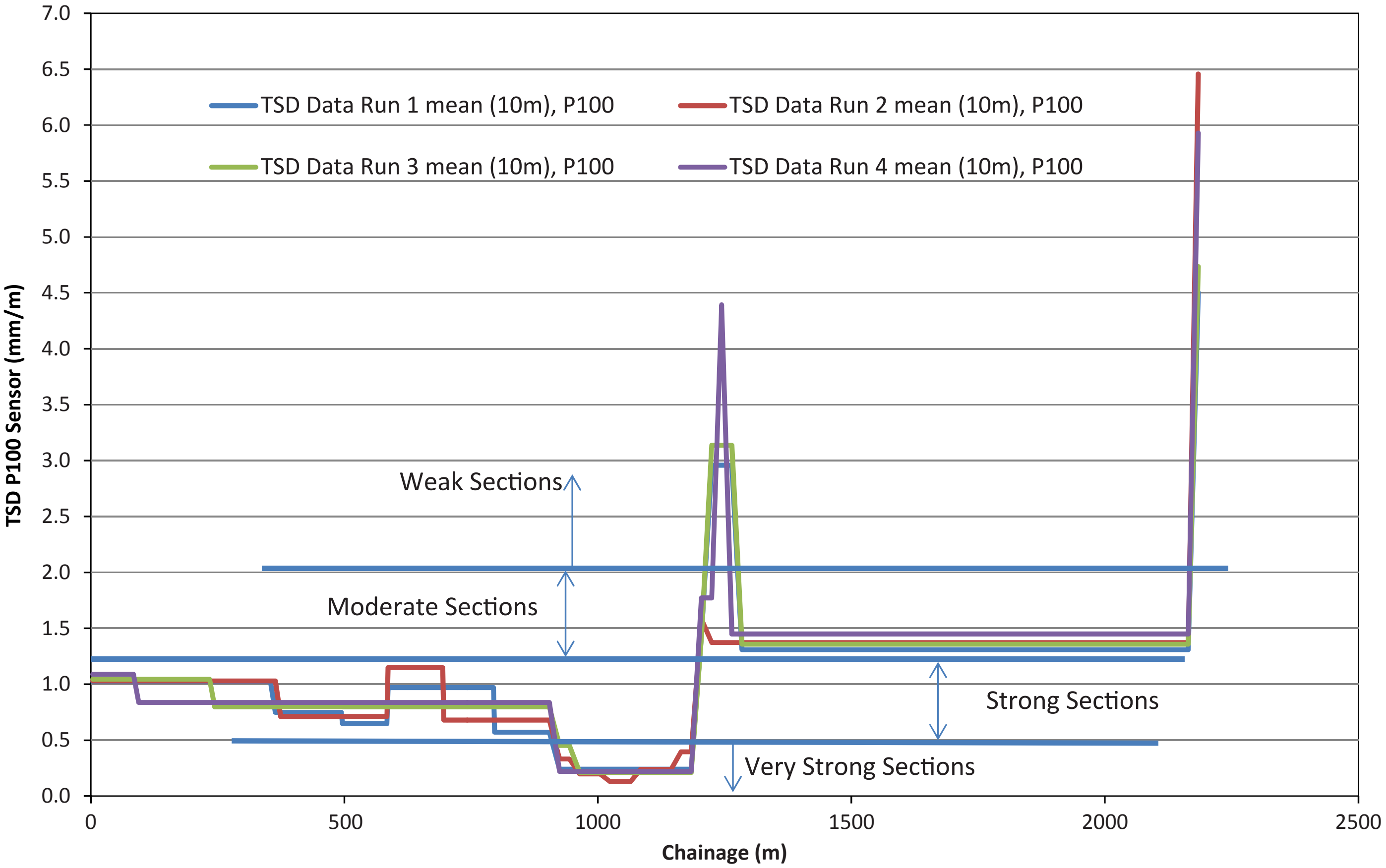


Figure 4.11. Site F1 segmented data.

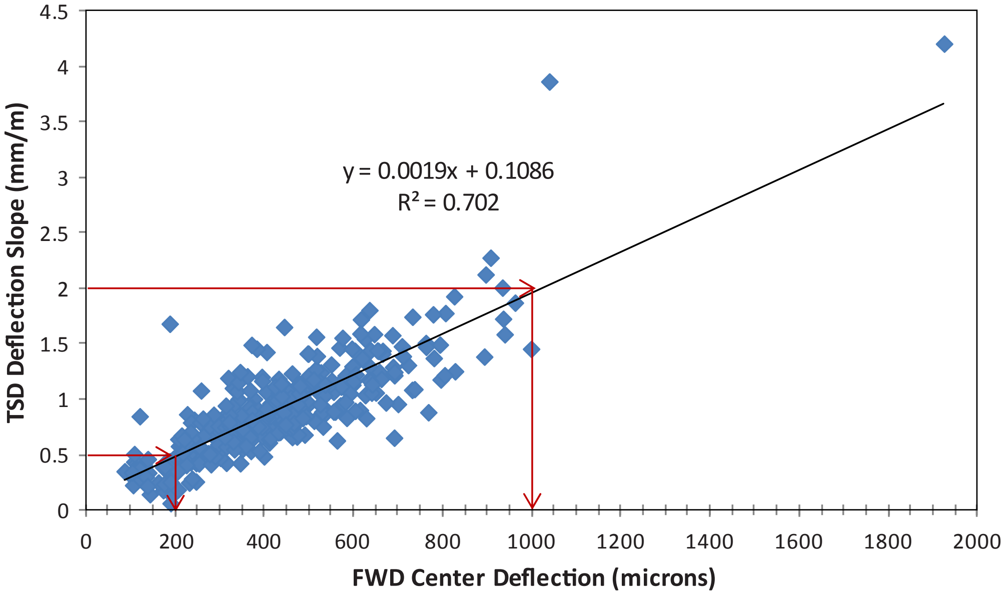


Figure 4.12. Site F1 TSD P100 versus FWD-corrected center deflection.

Identification of Structurally Deficient Sections

To evaluate whether the device can consistently distinguish structurally deficient sections from structurally adequate sections, the segmented data was compared with a set of threshold values. Typical threshold values for the RWD were obtained from a number of RWD demonstration reports available at the FHWA website (FHWA, 2009). These thresholds are based on a subjective rating of structural capacity (ARA, 2007a and b). The threshold values were compared against a set of representative deflection sections, where the representative deflection value was taken as the 95th percentile of readings for one-tailed independent and identically distributed deflection profiles. The following threshold values were obtained from reports summarizing RWD demonstrations in Oregon, California, and Minnesota (note these values were used for interstate and primary roads and might be different for secondary and local roads):

- Very good: <250 microns (10 mils);
- Good: 250–500 microns (10–20 mils);
- Fair: 500–750 microns (20–30 mils); and
- Poor: >750 microns (30 mils).

The threshold values are in terms of equivalent 40 kN (9 kip) FWD center deflections. In order to convert the TSD readings to equivalent FWD center deflection, an average relationship employed in the United Kingdom was used. Furthermore, only the 10-m (33-ft) averaged and segmented measurements were segmented on the basis of the thresholds. The 1-m (3.3-ft) data were deemed too noisy to provide consistent sectioning on this basis, whereas the 10-m (33-ft) data maintained adequate detail while sufficiently reducing the noise level in the measurements.

Using Thresholds for Repeated Identification of Weak Sections

A structurally deficient threshold of 500 microns (20 mils) was used to define structurally weak sections. This threshold value is based on demonstration reports from Connecticut (ARA, 2007b) and Indiana (ARA, 2005a). Table 4.3 summarizes the number of sections with low structural capacity at each test site, as well as the percentage of repeated runs that identified the same structurally weak sections.

Table 4.3. Identification of Weak Sections for Repeated Runs

Site	Average Length of Deficient Sections	Percentage of Weak Sections Identified by All Runs
F1	4,600 ft (1,400 m), 64%	85%
F3	No structurally weak sections identified	
F5	No structurally weak sections identified	
F6	No structurally weak sections identified	
R2	525 ft (160 m), 13%	100%
R3	No structurally weak sections identified	
C1	No structurally weak sections identified	
C2	No structurally weak sections identified	

Identification of Similar Sections

Setting a structurally weak threshold as a standard number may not provide adequate information about the repeated identification of weak sections. For example, for Site F1, the measurements between 584 m (1,916 ft) and 694 m (2,277 ft) for the repeated runs are 484 μm, 594 μm, 419 μm, and 439 μm (19.9 mils, 23.4 mils, 16.5 mils, and 17.3 mils) with an average of 490 μm (19.3 mils). Similarly, the measurements between 95 m and 235 m (312 and 771 ft) are 533 μm, 536 μm, 544 μm, and 439 μm (21.0 mils, 21.1 mils, 21.4 mils, and 17.3 mils). Setting the weak pavement threshold at 508 μm (20 mils) causes these sections to seem not repeatable when identifying weak sections, even though the readings are all relatively close. This is shown in Figure 4.13, which shows repeated runs.

To overcome the shortcoming of applying set threshold values to analyze whether the device could repeatedly identify the same sections, an analysis of the number of locations in which identified uniform sections were within a certain range of each other was performed. The ranges chosen were 125 μm (5 mils), 250 μm (10 mils), and 500 μm (20 mils). Table 4.4 summarizes results from this analysis.

With the exception of Site F1, at least 98% of the representative deflections are within 125 microns (5 mils) of each other and the percentage is 100% for four of the tested sites. Recall that Site F1 is a structurally variable site with large peaks in the deflections at approximately 1,300 m and 2,100 m (0.81 and 1.30 mi). The readings that are not within a 508-μm (20-mil) range of each other occur at the locations of the large peaks and are probably a consequence of the change-points in the segmentation data occurring at slightly different locations for each run.

Summary of Example Applications

In summary, the potential uses for the RWD and TSD mirror the current applications for the FWD network-level measurement. The ability to obtain deflections directly from RWD testing has been shown to provide cost savings in network-level testing schemes. The TSD deflection slopes can be translated into the difference in deflection points, which allows for many useful indices (i.e., the SCI and BDI) to be determined from TSD testing. The difference in deflection points is used

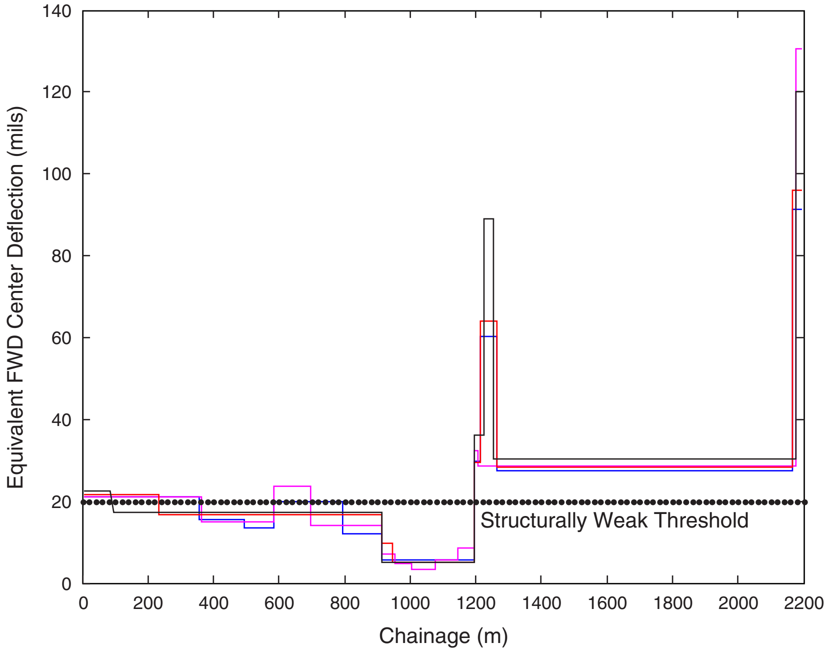


Figure 4.13. Structurally weak threshold applied to representative deflection sections at Site F1 for three different runs.

in many relationships including determining the strains at the bottom of the asphalt layer and determining the effective structural number of a section of pavement. In terms of network-level testing, each device has exhibited the ability to identify relative differences in the pavement structural condition, which is useful for pavement management applications.

Current and Future Developments

Since Phase I of this study was completed, the research team has discovered one additional device that might meet the original requirements of this study. This equipment is briefly described in the following section. However, as this information was discovered after commencement of the study, it was not included in Phase II of the project, data acquisition and comparison. In addition, both the RWD and the TSD have been developed further since Phase I was completed. Therefore, a description of these recent developments is presented.

New Available Equipment

Eyztek Continuous Runway Load Deflection Evaluation Methodology

In 2006, Zybron Inc. (now Eyztek Inc.) was awarded a Phase 1 Department of Defense Small Business Innovative Research

Table 4.4. Identification of Similar Sections

Site	Readings Within 125-micron (5-mil) Range	Readings Within 250-micron (10-mil) Range	Readings Within 500-micron (20-mil) Range	Maximum Range for All Locations microns (mils)	Range of All Readings microns (mils)
F1	77%	95%	95%	1,712 (67.4)	3,226 (127)
F3	100%	100%	100%	74 (2.9)	168 (6.6)
F5	99%	100%	100%	137 (5.4)	201 (7.9)
F6	100%	100%	100%	109 (4.3)	152 (6.0)
R2	100%	100%	100%	112 (1.2)	803 (31.6)
R3	100%	100%	100%	112 (4.4)	112 (4.4)
C1	98%	100%	100%	30.5 (7.1)	269 (10.6)
C2	99%	100%	100%	236 (9.3)	251 (9.9)

(a) (b)

Source: Arora et al., 2006.

Figure 4.14. Eyztek Inc. lighter weight rolling weight deflectometer prototype: (a) frame view and (b) laser mounting beam.

award to develop an air-droppable lighter weight rolling weight deflectometer for the U.S. Army that can rapidly collect continuous data by using noncontact sensor technologies. This was followed by a second award in 2008 to develop the concept further into a more robust prototype incorporating ground-penetrating radar and thermal scanners for additional in-depth information capability, such as estimating layer thicknesses and voids. The manufacturers consider that simultaneous measurement of deflection and pavement thickness is essential for correct interpretation of results. The lighter weight RWD (Figure 4.14) can survey at speeds up to 110 km/h (70 mph) within the normal traffic flow, and traffic control is not normally necessary. As yet, no publications are available on the outcome of these projects. Some further information is available on the company website (Eyztek, 2011).

Developments to Evaluated Equipment

Rolling Wheel Deflectometer

As stated earlier in the report, the deflection measuring system of the RWD consists of a laser-based measuring device mounted on a modified tractor trailer for measuring pavement deflections under the moving load of the truck. The load is set to 80 kN (18 kips) on a single rear axle when measured statically. The device was developed from the late 1990s through 2003, when the first practical testing was conducted.

The design of the device uses a series of industrial laser measuring devices (Selcom) that provide measurements at 2 kHz, and then averages these results over a selected section to eliminate the effects of texture on the readings. The original device provided a single trace of measurements that approximated the values obtained from the center point of an FWD.

Various refinements have been made to the design since 2003; the most significant was in 2009 when the laser devices were moved from a beam below the vehicle into the truck body and mounted in a temperature-controlled enclosure (Figure 4.15). At that time, provisions were made to increase the number of laser devices to provide two simultaneous traces of deflections in the pavement due to the loading, one close to the center of the load and one at a distance of 450 mm (18 in.) from the center. It is thought that these two traces will provide measurements that will approximate two similar simultaneous readings using an FWD.

Traffic Speed Deflectometer

Since the completion of Phase I, two further TSDs have been built to a modified design, the second-generation version, and delivered to their owners. At the time this report was written, a fifth device was under construction for the South African government and was due to be delivered in July 2012. The modified design, which is shown diagrammatically in Figure 4.16, has the following improved features:

- The trailer is now custom built specifically for this device, rather than being based on a container.
- Rather than the three velocity-measuring lasers and one reference laser, the latest devices can be fitted with up to seven lasers.
- The measurement of survey speed, which is a vital part of the measurement process, can now be accomplished with a more robust system. This device uses a motorcycle

(a) (b)

Figure 4.15. 2009 updated FHWA RWD: (a) side picture and (b) enclosed mounting for six laser sensors.

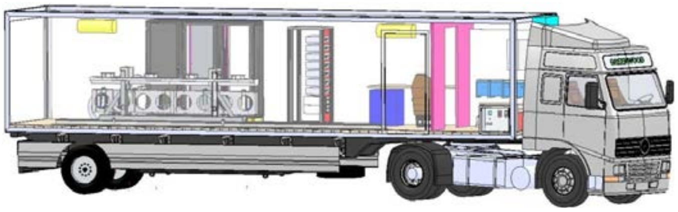


Figure 4.16. Diagram of second-generation version of the TSD.

wheel rather than a bicycle wheel as the main measurement component.

- The mounting beam for the laser sensors is now mounted on longitudinal rails so that its position can be varied. At one extreme, this enables the lasers to be positioned midway between the loaded wheels, providing an improved method of calibration. At the other extreme, the lasers can be positioned so that they are on either side of the loaded wheel. This movable beam also enables multiple test runs with different intermediate positions, rather than single runs with more sensors.

This revised configuration was first fitted to a device that was delivered to the Italian concession agency National Autonomous Roads Corporation (ANAS S.p.A.) in June 2010. This TSD is fitted with seven laser velocity sensors, one for reference and six for measurements. This device and its movable measurement beam are shown in Figure 4.17.

As of December 2011, this device had surveyed around 5,000 km (3,100 mi) for the purposes of research, maintenance identification, and quality control of new construction at survey speeds between 40 and 80 km/h (25 and 50 mph). The operators report a good correlation with FWD measurements

(a) (b)

Figure 4.17. Italian second-generation TSD: (a) side view and (b) movable measurement beam.

Figure 4.18. Polish second-generation TSD.

and a more practical calibration procedure, but no reports have yet been published on their work.

The fourth TSD was constructed for the Pavement Diagnostic Division of the Road and Bridge Research Institute (IBDiM) in Warsaw, Poland. The device is fitted with five laser velocity sensors, one for reference and four for measurements. The device (Figure 4.18) was delivered to Poland in April 2011. As of December 2011, this device had covered only around 20 km (12.5 mi) in comparison tests with the FWD.

Possible Improvements

On the basis of information collected, and especially given the recent enhancement to the devices, it is assumed that the existing systems can record the accurate location of the measurements, measure the survey speed accurately, and measure the surface temperature of the pavement accurately. Thus, the main improvements that may help improve the information obtained from the measurements and widen the range of possible applications, include the following:

- Provide a more complete deflection bowl shape (e.g., by adding additional sensors),
- Provide sufficient quality of measurement signals that local structural deterioration can be reliably identified (i.e., down to 1-m features), thus enabling the potential for use at a project or scheme level,
- Provide pavement-layer thickness measurement capability, such as by adding ground penetrating radar equipment, and
- Measure the dynamic load on the loading wheel assembly.

CHAPTER 5

Conclusions and Suggested Research

The SHRP 2 R06F project described in this report evaluated current technologies implemented in different types of continuous deflection measuring devices, identified the most promising devices for effectively supporting pavement management decisions, evaluated the capabilities of these devices, and identified and illustrated applications that can be useful for supporting pavement management. This section summarizes the main findings and conclusions from the project.

Findings

Equipment Selection

There are a series of continuous deflection devices that can collect data at intervals of approximately 300 mm (1 ft) or smaller by using load levels typical of truck loading (i.e., 40 to 50 kN [9 to 11 kips] per wheel or load assembly). These include three main types of devices:

- Laser-based devices that measure the deflection below an actual moving truck load—including the traffic speed deflectometer (TSD), the rolling wheel deflectometer (RWD), the road deflection tester (RDT), and the airfield rolling weight deflectometer (ARWD);
- Devices that apply a vibratory load—including the Portancemetre, the Measuring Ball, and the rolling dynamic deflectometer (RDD); and
- The image deflection measurement (IDM) device, which uses image analysis methods to determine pavement deflections under loading, which represents a very promising technology but is still in the early stages of development.

Only the devices in the first group are capable of surveying without the need for traffic control. The vibratory devices operate at walking pace, and the IDM device was still being tested in a stationary mode at the time of the evaluation.

From this group and on the basis of information collected in the literature review, the research team identified two devices as the most promising to deliver the information needed by the users under operating conditions compatible with the SHRP 2 objectives. These devices are the RWD and the TSD. The vibratory devices were eliminated from consideration because either they do not apply loads similar to that of a heavy vehicle or they measure at very low speed. The RDT and ARWD were also eliminated from further consideration because the existing prototypes have been decommissioned or reassigned to other uses. The IDM system appears very promising in the detailed evaluation; however, a fully operational prototype is not yet available and at present does not meet the survey speed requirement.

User Needs

The majority of agencies perform at least some deflection testing using the FWD. Most testing is performed to support project-level decisions and only a small number of agencies (five) have incorporated deflection data into their pavement management system. Potential users in general agree that the main advantage of a continuous measuring device would be for supporting network-level decisions. The assessment of user needs suggests the following:

- Important parameters that users indicated should be considered in the evaluation of the equipment include: speed (safety), repeatability, accuracy (and feasibility of establishing correlations with existing technologies, such as the FWD), equipment cost, ease of operation, customer service (availability of service and maintenance), ease of use of the data collected, availability of software for interpretation of the results, reliability, size of the vehicle, relevance of the information (e.g., use in MEPDG/DARWin-ME), and past experience.

- While responses to the initial survey suggested users would like to be able to collect continuous pavement response data to support project-level decisions, follow-up interviews showed that the respondents understand the current limitation of the technologies and agree that network-level applications are more likely in the near future. Furthermore, respondents agreed on the need of pavement structural data to support network-level PMS decisions.
- At the network level, the primary application of the continuous deflection device would be to do the following:
    - Help identify weak (i.e., structurally deficient) areas that can be then investigated further at the project level;
    - Provide network-level data to calculate a structural health index that can be incorporated into a PMS; and
    - Differentiate sections that may be good candidates for preservation (those with good structural capacity) from those that would likely require a heavier treatment (those showing structural deterioration or deficiencies).

Detailed Technology Evaluation

To assess the capability of the continuous deflection technology to support network-level pavement management decisions, the experimental plan evaluated relatively long selected evaluation routes with uniform and variable structural conditions. These network-level sites included flexible, composite, and rigid pavement sections. All attempts were made to include subsections with good, fair, and poor functional conditions within each of these pavement types. These routes included segments that were measured repeatedly, several times in succession, in a single day, and with the FWD. The evaluation included pavement sections on different types of pavement, using various operational conditions, and included reference FWD deflection testing equipment where possible.

The analysis of the collected data resulted in the following observations:

- Repeatability
    - Repeatability of TSD slope for different averaging lengths was a mean of 0.089 mm/m with a range from 0.065 to 0.201 mm/m for 10-m (33-ft) averaging, and a mean of 0.028 mm/m with a range from 0.022 to 0.114 mm/m for 100-m (330-ft) averaging. Except for Site F1, the repeatability of the TSD evaluated with measurements at the different tested sites was found to be similar and relatively independent of deflection slope value. For Site F1, the measurement error (and therefore repeatability) was found to be dependent on the deflection slope value. This could be due to the fact that sites with high deflection slope values are deteriorated pavement sections and have more variability due to distresses (cracking and rutting). Except for a single run for Site C1, TSD repeated runs did not have a statistically significant bias.
    - A method of calculating repeatability using a single TSD run was also evaluated and found to give results that are in agreement with the method using repeated runs for measurements averaged over 1-m (3.3-ft) sections.
    - The correlation of repeated runs varies from 0.05 to 0.89 for 1-m (3.3-ft) averaging, 0.15 to 0.98 for 10-m (33-ft) averaging, and 0.55 to 0.99 for 100-m (330-ft) averaging. The correlation was found to be significantly affected by the range of measurements and is therefore not recommended as a measure of repeatability.
    - The repeatability of the RWD was evaluated with data collected in Virginia and was evaluated to be 51.4 µm (2.0 mils). The RWD repeated runs had a statistically significant bias of 10.9 µm (0.43 mils) on average.
- Comparability
    - The analysis of TSD comparability with the FWD (using TSD measurements averaged over a 10-m interval) showed that there are two distinct relationships between TSD deflection slope and FWD deflection depending on pavement type (one for flexible and composite pavements, another for rigid pavements). This could be expected, as two different quantities (deflection slope and deflection) are measured by each device. These quantities seem to be affected differently by the pavement type.
    - To better evaluate the comparability of the TSD with FWD, measurements from each device were used to calculate the surface curvature index (SCI) and the base distress index (BDI), quantities that can be obtained from each device. In this case, the relationship between the quantities measured using the FWD and those measured using the TSD was the same for all pavement types. Furthermore, the relationship between the indices measured by the TSD and those measured by the FWD was reasonably close to the equality line, which is encouraging (although this might be a subjective opinion). However, there is a significant variation as well as bias in this relationship. For example, for an average SCI or BDI value of 300 µm (11.8 mils), the bias was 30 µm (1.18 mils) (FWD values lower than TSD values) and the comparability was 380 µm (15.0 mils).
    - The analysis of RWD comparability with FWD (using RWD measurements averaged over a 160-m [0.1-mi] interval obtained from New Mexico) was evaluated in terms of the normalized differences. This number was found to be relatively unchanged as a function of deflection. The bias was 23.2% (FWD deflections lower than RWD deflection), and the repeatability was 129.2% (range of [−86.4%; 42.8%]). Note that for both the TSD and the RWD comparison with the FWD, FWD results tended to be lower than TSD and RWD results.

The repeatability of at least one continuous deflection measuring device (i.e., the TSD) can be considered adequate for network-level pavement management applications. The analysis also showed that the device can collect deflection measurements and indices that are comparable to those collected by traditional measurement devices such as the FWD. Additional tests are needed to fully assess the repeatability and comparability of the RWD.

Example Applications

The example applications demonstrated the ability of continuous deflection measurement devices to estimate many parameters important to modern pavement management applications:

- The results of the binary segmentation indicated that the most appropriate minimum length for a pavement section depends on the variability of the deflection profile, or the deflection slope profile. Structurally variable pavement sections required more characteristic segments to describe them; thus, some parameters were required to maintain minimum homogeneous segment lengths.
- The strain at the bottom of the asphalt layer was estimated by using measurements obtained from testing using the FWD and the TSD. The comparison of the results yielded a relationship between the devices' output that approached equality. The effective structural number (SN) was estimated using measurements obtained from TSD testing, and broadly matched the expected SN calculated from the layer composition and surface condition.
- The identification of relatively weak pavement sections was used to demonstrate the ability of the device to locate anomalies or locally weak sections within a network. The results showed that relatively weak pavement sections could be consistently identified using repeated sets of measurements. The identification of weak pavement sections on the basis of thresholds demonstrated the ability of the device to repeatedly identify the same weak sections.

Conclusions

Continuous deflection devices have become a valuable tool in pavement analysis and management. Particularly promising devices include the TSD and the RWD, due to their ability to measure at traffic speed. The study performed in this project has demonstrated that at least one of the continuous deflection measurement devices can do the following:

- Provide repeatability for network-level pavement management applications;
- Collect deflection measurements or indices that are comparable to those collected by traditional measurement devices such as the FWD; and
- Provide measurements that can be used for supporting some of the most critical network-level applications identified by the potential users and possibly assist project-level operations by identifying localized structural deterioration.

However, the technology is only just maturing. Future research should be conducted to further assess the measurement capabilities of these devices, the usefulness of the collected data, and the best way to interpret measurements from such devices. Enhancements to the devices that may help improve the quality of information obtained from measurements and widen the range of possible applications include providing a more complete deflection bowl shape, enhancing the quality of the measurement signal to achieve higher spatial resolution, providing pavement-layer thickness measuring capability, and measuring the dynamic load on the loading wheel assembly.

Recommendations for Implementation

This section summarizes the main products of the project and provides some recommendations on how to move the technology forward. Proposed actions include dissemination efforts, implementation activities, and research needs.

Value Added

Although deflection testing is widely used by state DOTs at the project level, it is much less often used at the network level. FWD testing is the prevalent technology. It allows only stationary measurements, which disrupt traffic flow, limit the number of measurements, and cause safety issues to both the operators and the public using the highway. Although most state DOTs would like to incorporate deflection testing into a pavement management program, only a small number (five, according to our survey) have done so. The main concerns for the adoption of a continuous deflection device, voiced by the respondents, are accuracy, cost, and safety. This project focused on evaluating the accuracy of continuous deflection devices and their application for supporting network-level pavement management. This technology allows collecting data at highway speed, greatly improving the safety of collection personnel. As part of the research process, the research team performed the following:

- Conducted a survey and follow-up interviews with state DOT personnel to request feedback about the need, potential uses, and value of continuous deflection measurements to their agencies; and

- Tested and evaluated continuous deflection devices to evaluate their accuracy and ability to identify homogeneous sections and structurally weak sections. A major aspect, when possible, was to compare these devices with FWD test results (the current industry standard).

Dissemination Efforts

Throughout the course of the project, the research team has developed several journal and conference papers, presentations, and workshops, including the following:

- Use of Continuous Deflection Measurement for Network-Level Pavement Structural Assessment, a poster presented at the Developing a Research Agenda for Transportation Infrastructure Preservation and Renewal Conference held in Washington, D.C., in November 2009.
- SHRP 2 R06F Development of Continuous Deflection Device Project Update, a presentation at the annual meeting of the TRB Committee AFD80 Strength and Deformation Characteristics of Pavement Sections, January 11, 2010.
- Use of Continuous Deflection Measurements for Network-Level Pavement Analysis, a presentation at the Pavement Evaluation 2010 conference, held October 24 through 27 in Roanoke, Virginia.
- Mini-workshop on continuous deflection measurement at the Pavement Evaluation 2010 conference, held October 24 through 27 in Roanoke, Virginia. The workshop helped capture feedback from prospective users.
- SHRP 2 R06F Development of Continuous Deflection Device Project Update, a presentation at the annual meeting of the TRB Committee AFD80 Strength and Deformation Characteristics of Pavement Sections, January 2011.
- Evaluation of Traffic Speed Continuous Deflection Devices, presented at the 91st Meeting of the Transportation Research Board and recommended for publication in the *Transportation Research Record: Journal of the Transportation Research Board.*
- Analyzing Repeatability of Continuous Deflection Device Measurements, presented at the 91st Meeting of the Transportation Research Board.
- Estimation of Pavement TSD Slope Measurements Repeatability from a Single Measurement Series, presented at the 91st Meeting of the Transportation Research Board.
- Two contributions to the Workshop on Continuous Deflection Measurements for Highway Infrastructure Assessments, held during the 91st Meeting of the Transportation Research Board:
    - ○ SHRP 2 Research Update on Continuous Deflection Study; and
    - ○ Deflectograph and Traffic Speed Deflectometer: United Kingdom Experience.

Implementation Plan

Audience and Expertise for this Product Application.

The audience for the research products is made up of the stakeholders who are involved in the design, evaluation, and management of roadways, including the following:

- Public sector (project owners). The main audience includes state DOTs, FHWA, AASHTO, and local governments. Within these agencies, groups of interest include the divisions or sections responsible for pavement assessment, management, maintenance, evaluation, and rehabilitation design.
- Private sector (consultants, road operators, and road constructors). Groups interested in the research products include pavement design and management consultants, road operators (toll road operators, concessionaires, etc.), road construction companies, and manufacturers of asset management data collection equipment.

Recommendations and Future Research

The SHRP 2 R06F project summarized in this report assessed the capability of the continuous deflection measuring technologies for supporting pavement management decisions. However, the conclusions reached were limited by the lack of any side-by-side testing of the two selected technologies on a representative range of pavements and soils. Moreover, adoption of these technologies would be further facilitated by the following recommended research (see Appendix A for more complete descriptions of these projects):

- Side-by-side testing of the RWD and TSD. This study has shown the limitation of comparing equipment on different sites. Therefore, side-by-side field tests with the latest versions of the selected technologies at a variety of locations and with a range of pavement designs are needed to definitively assess the capabilities of the individual devices for network- and project-level applications.
- Developing tools for using the technology to support network-level pavement management business functions. This project would further develop and demonstrate procedures and tools to convert the equipment measurements to engineering parameters that can be used to support network-level pavement management decisions. As illustrated in Chapter 4, these applications can include screening sections that may be candidates for rehabilitation (and thus require project-level investigation) or candidates for pavement preservation. The effort would include using maximum deflection equivalents (already available) to compute a structural indicator, as well as using extra information that should be available from the two lasers on the latest

RWD and the three or more lasers on the TSD to estimate parameters that pavement engineers require for pavement management use (i.e., modified SN or SCI).
- Assessing the potential for using the output from the selected equipment to provide advice on structural assessment requirements (e.g., rehabilitation or surface treatment).
- Verifying the accuracy of the testing equipment by conducting measurements on instrumented sections to measure the absolute deflection. This effort would require designing an experiment and instrumenting pavement sections with accelerometers and strain gauges (or use existing instrumentation, e.g., at a research facility, possibly taking advantage of those where relevant existing instrumentation might be available) to measure the in situ absolute deflection and strain response of the survey equipment to try and verify its accuracy.

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APPENDIX A

Research Problem Statements

This appendix contains more complete descriptions of the four follow-on research projects recommended to facilitate the implementation of this technology. Problem statements, objectives, suggested approach, and urgency and payoff potential are described for each.

Problem 1: Side-by-Side Comparison of Continuous Deflection Measuring Devices

Research Problem Statement

This SHRP 2 R06F project has identified the traffic speed deflectometer (TSD) and the rolling wheel deflectometer (RWD) as continuous deflection measuring devices that have the potential to meet agency needs in terms of deflection testing to support network-level and possibly project-level decisions. The two devices measure different parameters; the RWD directly measures pavement deflection, and the TSD measures pavement deflection slope. Both of these parameters are affected by measurement conditions such as speed and temperature, and these effects are in turn influenced by pavement composition. It is therefore important that the performance of the TSD is evaluated in U.S. conditions, ideally in a side-by-side comparison with the RWD, if the device becomes available, on the same sites and in similar operational conditions (i.e., with the same pavement structures, spatial variability, and pavement temperature). Quality of the information obtained from each device can then be evaluated in terms of signal-to-noise ratio, capability to distinguish weak from strong sections, and capability to identify weak joints in concrete pavement, among other things.

Objective

This proposed research will perform a side-by-side comparison of the TSD and RWD in the United States. Tests will be conducted on the same sections of pavement within the same time period (as close as possible). It is essential for the success of any future comparison that testing of the devices is carried out on the same sites, with exactly the same compositions and spatial variability, and under the same operational conditions. Tests with the latest versions of the selected technologies at a variety of locations and with a range of pavement designs are needed to definitively confirm the capabilities of the individual devices and investigate their potential use for network- and project-level applications.

Suggested Approach

Step 1: Testing of Pavement Sections

The structural condition of pavement sections representing a wide range of designs (flexible, rigid, and composite) and conditions (weak, strong, new, and old) will first be fully characterized in terms of structural condition (e.g., by detailed FWD measurements, ground-penetrating radar [GPR] thickness surveys, and coring). These sections will then be tested with both the TSD and the RWD. Tests will be performed concurrently to minimize the effect of external variables (e.g., temperature) on test results. It is suggested that the raw data from each device be analyzed (i.e., before any averaging is performed). At least three passes for each device are recommended; more are preferred.

Step 2: Data Analysis

Data analysis should involve at least the following: (1) evaluation of measurement noise level; (2) estimation of signal-to-noise ratio; and (3) evaluation of different noise reduction methodologies.

Step 3: Detailed Assessment of Device Capabilities

In this last step, each device will be evaluated for its capabilities to identify weak sections as well as weak joints. Furthermore, each device will be evaluated for its capability to distinguish between sections in poor condition (in need of maintenance) and those in good condition and to produce structural parameters similar to those obtained from FWD testing.

Urgency and Payoff Potential

The proposed research will provide a much clearer indication than is currently available of the relative performance of the two devices and, thus, whether the technologies are ready for adoption by transportation agencies.

Problem 2: Integrating Continuous Deflection Measurements into Pavement Management Business Functions

Research Problem Statement

As of February 2010, only five agencies have incorporated deflection data into their pavement management system (PMS). One of the main reasons for this low number is that FWD equipment, which is currently used to obtain deflection data, is a stationary measuring device that disrupts traffic flow and has a low output rate. This technology provides a low spatial coverage as well as a low production rate (around 20 km/h [12 mph] at 320-m [0.2-mi] intervals). Continuous deflection devices have a dense spatial coverage and a high production rate and are therefore well suited to support network-level pavement management decisions. The devices can be efficiently used to screen sections that may be candidates for rehabilitation (and thus require project-level investigation) or to decide if a section is a good candidate for pavement preservation.

Objective

This proposed research will develop tools for using continuous deflection measurement devices to support pavement management business functions. The effort would use maximum deflection equivalents (already available) to compute a structural indicator, and the extra information that should be available from the two lasers on the latest RWD and the three or more lasers on the TSD to estimate parameters that pavement engineers require for pavement management (i.e., modified SN or SCI).

Suggested Approach

Step 1: Data Processing and Interpretation of Continuous Deflection Measurements

The effort will first determine the best methods to process and use the data for PMS applications by using data from the SHRP 2 R06F project. This involves estimating the true deflection from noisy measurements by using available signal processing and statistical methods and segmenting deflection measurements to reflect different pavement conditions.

Step 2: Application to PMS

The second step will develop methods for identification of structurally weak sections, screening sections needing different treatments (rehabilitation or preservation), and calculating remaining service life. These methods can then be used to develop and recommend the following: (1) a structural pavement condition index that can be used for network-level pavement management, (2) an algorithm to scope pavement M&R projects at the network level, and (3) a framework for specifying structural capacity thresholds.

Urgency and Payoff Potential

The proposed research will help establish a link between network-level and project-level resource allocation. This will improve the overall efficiency of pavement management business decisions.

Problem 3: Pavement Structural Assessment Methods Using Continuous Deflection Measurements

Research Problem Statement

Continuous deflection measurement devices have high spatial coverage and production rates and are therefore well suited to support network-level pavement management decisions. Measurements collected by these devices are contaminated with noise, however, as illustrated in this report. The effect of noise can be reduced using statistical signal processing methods. These methods are essential for the potential use of the output of continuous deflection measurement devices in providing advice on structural assessment requirements. This will possibly allow output of continuous deflection devices to be used for structural assessment requirements such as rehabilitation or surface treatments.

Objective

This proposed research will evaluate the possibility (or at least determine how much improvement is needed) of using data from selected devices to compute structural condition indicators relevant for supporting structural assessment and rehabilitation. Current methods of averaging measurements over specific distances are far from optimal. Much better methods based on statistical analysis that trades off between the variance and bias are available to better estimate the pavement deflection from noisy measurements. Furthermore, these methods can provide estimates of confidence intervals for denoised measurements. With these confidence intervals, engineers can suggest structural treatments based on acceptable risk levels.

Suggested Approach

Step 1: Review of Potential Data Analysis Methodologies

There are a number of statistical signal processing tools for denoising of data, such as spline and kernel smoothing, frequency domain filtering, and wavelet denoising through nonlinear thresholding or shrinkage of wavelet coefficients. Each method has advantages and disadvantages. For example, spline smoothing is a linear operation and, therefore, is not well adapted to large spatial variability; however, it is very robust to the distributional properties of measurement errors. On the other hand, wavelet denoising is adaptive to spatial variability; however, much of the theory has been developed for the case of normally distributed errors, and handling different types of distributional errors can be challenging.

Step 2: Structural Assessment

This step will concentrate on developing (empirical, semi-empirical, and theoretical) methodologies to calculate relevant structural parameters from continuous deflection measurements. A certain level of confidence (based on the statistical analysis in Step 1) can be associated with those structural parameters, so that a risk level can be associated with the different treatment and rehabilitation options.

Urgency and Payoff Potential

The proposed research will facilitate the incorporation of pavement structural condition considerations into the pavement management process, which can help improve the efficiency of pavement management business decisions.

Problem 4: Evaluation of the Absolute Accuracy of Continuous Deflection Measuring Devices on Instrumented Road Sections

Research Problem Statement

The SHRP 2 R06F study has evaluated the performance of two continuous deflection measuring devices, the traffic speed deflectometer (TSD) and the rolling wheel deflectometer (RWD). The results show that their measurements are broadly comparable to the deflection measuring device currently widely used in the United States, the falling weight deflectometer (FWD). However, there are differences between the measurements, because the type and rate of loading are very different between traffic-speed rolling wheel devices (the TSD and the RWD) and a static impulse loading device (the FWD). Therefore, to confirm that the devices are measuring what is claimed, it is necessary to compare the measurements of the devices with the response of a pavement under that load. To achieve this, a number of pavement sections with a range of different structural designs should be comprehensively instrumented and the response under the loading wheels of each device should be compared with the measurements of the built-in instruments.

Objective

This proposed research will evaluate the accuracy of continuous deflection devices by using measured absolute deflection, acceleration, and strains from instrumented pavement sections. This effort may include testing on existing facilities or specifically instrumented pavement sections.

Suggested Approach

Step 1: Design of Experiment

In the first step, candidate pavement sections will be selected for instrumentation with state-of-the-art accelerometers and strain gauges. These sections will reflect a wide range of pavement types and conditions. If possible, preliminary testing of the continuous deflection device on existing instrumented facilities should be performed. Results from this testing should be used to better design the instrumentation of the selected pavement sections.

Step 2: Testing and Evaluation

Testing will be conducted on the instrumented test sections under various conditions, in accordance with the designed experiment. These tests will allow the accuracy of the measurements and the impact of various operational parameters to be determined. Two of the most important operational parameters that will be investigated are testing speed and pavement temperature.

Urgency and Payoff Potential

The proposed research will allow a detailed evaluation of the accuracy of continuous deflection devices, which is critical for assessing long-term prospects of the technology and for developing required standards.

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Related SHRP 2 Research

Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform (R02)
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