Technical Report Documentation Page

1. Report No. FHWA/TX-98/1422-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EVALUATION OF THE ROLLING DYNAMIC DEFLECTOMETER AS A TOOL FOR PAVEMENT MANAGEMENT		5. Report Date October 1996 Revised November 1997 6. Performing Organization Code
7. Author(s) Michael Garrow and W. Ronald Hudson		8. Performing Organization Report No. 1422-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-1422
12. Sponsoring Agency Name and Address Texas Department of Transportation Construction/Research Section P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Research Report (9/96 — 8/97) 14. Sponsoring Agency Code

15. Supplementary Notes

Project conducted in cooperation with the Federal Highway Administration.

16. Abstract

This project was undertaken to assess the current condition and capabilities of the Rolling Dynamic Deflectometer (RDD). In doing so, we first conducted a literature review that compared the RDD with similar pavement deflection measuring devices. We also reviewed literature on noncontacting probes and instruments that the RDD currently uses, as well as others that could potentially be incorporated into the RDD's design in the future.

Next, we developed a methodology for measuring the pressure distribution existing beneath the RDD's loading wheels. These measurements are important because the accuracy of the RDD's pavement evaluation depends, in part, on the RDD's ability to apply loading pressures that mimic normal vehicle loading pressures as closely as possible. This methodology uses pressure-sensitive film to identify the pressure footprint beneath the RDD's loading wheels. A factorial experiment design involving the pressure-sensitive film that considers the magnitude of the load and the temperature of the RDD's loading wheels was developed.

Finally, we identified a number of potential uses of the RDD for the structural evaluation of pavements in the field. These potential uses were grouped into the following categories: (1) assessment of pavement variability, (2) forensic studies, (3) load-zoning studies, (4) examination of joint behavior, and (5) miscellaneous. For each potential use, we identified the advantages and disadvantages of using the RDD.

17. Key Words Rolling dynamic deflectometer, pavement management system (PMS), pavement variability, joint behavior, deflection data	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 46	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EVALUATION OF THE ROLLING DYNAMIC DEFLECTOMETER AS A TOOL FOR PAVEMENT MANAGEMENT

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Research Report 1422-1

Research Project 0-1422
Stationary and Continuous Measurements with the Rolling Dynamic Deflectometer

Conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

October 1996
Revised: November 1997

PREFACE

The recommendations of this report will be useful in guiding any future research efforts with the Rolling Dynamic Deflectometer (RDD). Potential field uses for the RDD that might be explored with future research are also identified in this report. Finally, suggestions have been made that could enable the Rolling Dynamic Deflectometer to more efficiently yield information regarding a pavement's structural capacity.

Prepared in cooperation with the Texas Department of Transportation (TxDOT) and the U.S. Department of Transportation, Federal Highway Administration

ACKNOWLEDGMENTS

The authors acknowledge the expert assistance provided by Mark McDaniel (DES), who served as the TxDOT project director for this study. Also appreciated is the guidance provided by the other members of the TxDOT Project Monitoring Committee, which included K. Alkier (CMD), Carl Bertrand (DES), and D. Chen (DES).

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SUMMARY

This project was undertaken to assess the current condition and capabilities of the Rolling Dynamic Deflectometer (RDD). In doing so, we first conducted a literature review that compared the RDD with similar pavement deflection measuring devices. We also reviewed literature on noncontacting probes and instruments that the RDD currently uses, as well as others that could potentially be incorporated into the RDD's design in the future.

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Finally, we identified a number of potential uses of the RDD for the structural evaluation of pavements in the field. These potential uses were grouped into the following categories: (1) assessment of pavement variability, (2) forensic studies, (3) load-zoning studies, (4) examination of joint behavior, and (5) miscellaneous. For each potential use, we identified the advantages and disadvantages of using the RDD.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

A pavement management system (PMS) is a set of tools or methods that assist decision makers in identifying optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time. In order for a PMS to operate as efficiently as possible, several kinds of information are needed as inputs. These include: (1) section description, (2) performance-related data, (3) historic data, (4) policy-related data, (5) geometry-related data, (6) environmental-related data, and (7) cost-related data [Ref. 1].

Serviceability data identify how well a pavement serves the traveling public at the present time. Also, through deterioration curves, performance-related data can be used to predict how well the current pavement network will serve the public in the future. Performance-related data can be further broken down into the following four subcategories: (1) roughness data, (2) surface distress data, (3) surface friction data, and (4) deflection data [Ref. 1].

Data from these four subcategories function at both the network and project levels within a PMS. At the network level, a PMS identifies priority programs and work schedules that agree with budget constraints. At the project level, the decisions made at the network level are physically implemented on a project-to-project basis according to the schedule identified at the network level. Deflection data can be used at the network level to describe the network's present structural adequacy, predict the network's future structural adequacy, identify structural deficiencies within the network, prioritize the rehabilitation work to be performed on the network, and determine seasonal load restrictions. At the project level, deflection data can be used to aid in overlay designs, to determine the as-built structural adequacy of a pavement, and to estimate remaining service life and load restrictions for a pavement [Ref. 1].

Clearly, deflection data are required within a PMS in order to assess the pavement's current condition and to predict the needs of the network in the future; therefore, the importance of a deflection monitoring device to obtain the deflection data cannot be overstated. Some of the common deflection monitoring devices used in the past include the falling weight deflectometer (FWD), the Dynaflect, and the Benkelman Beam. Although these devices have been used successfully in the past, they are not without their deficiencies. One of the most substantial drawbacks associated with these instruments stems from their inability to continuously monitor a pavement's deflections resulting from a given load. As a result, the variability that is inherent in pavement structures cannot easily be accounted for with a few discrete deflection tests. In order to deal with variability, some pavement managers need to take additional deflection tests. Without careful attention this can become very costly [Ref 1]. Discrete point deflection tests also require traffic rerouting and control. It would be desirable to develop a moving deflection device, and this need has prompted a project to address this issue.

An additional concern for safety arises when using stopped measuring devices to obtain deflection data. With stationary equipment, lane closures must often be used for extended periods of time to acquire the deflection data. This requirement puts the highway users and the data acquisition field crew at a higher-than-normal risk. The less time that is required to obtain deflection data, the lower the risk to highway users and field crews. A rolling deflectometer might reduce this problem. Trials with the rolling deflectometer have shown that under low or medium traffic levels, the device may be used without lane closure.

Thus, there is a defined need for a rolling deflection monitoring device. Such equipment will not only aid pavement managers in assessing the pavement's inherent variability; it will also reduce agency and users costs and improve safety by limiting the time required to perform deflection data acquisition. A prototype piece of equipment known as the Rolling Dynamic Deflectometer (RDD) has been developed to provide continuous deflection readings for a given dynamic load. It is important to evaluate this equipment for Texas Department of Transportation (TxDOT) use.

The RDD was developed by equipping a large truck with a servo-hydraulic vibrator, a data acquisition system, accelerometers, and loading wheels. Currently the RDD uses two loading wheels spaced approximately 1.2 m (4 ft) apart from one another to load the pavement. The design of the loading wheels has undergone recent modifications. The current loading wheel design is comprised of a 152-mm (6-in.) diameter aluminum hub coated with 114 mm (4.5 in.) of hard urethane. The aluminum hub has ridges at its interface with the urethane that prevent the urethane from debonding from the aluminum hub during use. In addition, steel plates have been attached to both sides of the loading wheels in order to further ensure that the aluminum hub and urethane coating remain attached during use.

The vibrator applies peak-to-peak vertical dynamic forces as large as 310 kN (70 kip) to the RDD's loading wheels. In addition, a hydraulic system uses a system of air springs to superimpose a constant static force ranging from 67 to 180 kN (15 to 40 kip) on the dynamic force. The dynamic deflections generated from the dynamic load are monitored continuously with receiver wheels through the use of accelerometers. During the RDD's initial development, only one receiver wheel positioned midway between the dual loading wheels monitored the pavement's dynamic deflections [Ref. 2]. Currently, the RDD uses four receiver wheels, or sensors, to monitor the pavement's response to the dynamic loading. The peak-to-peak dynamic deflection measured with the receiver wheels is divided by the peak-to-peak dynamic load applied to the pavement to obtain a continuous measure of the pavement's flexibility at the receiver wheel locations. The configuration of the loading and receiver wheels is described in Chapter 2.

1.2 OBJECTIVE OF PROJECT

The purpose of Project 0-1422 is to evaluate the effectiveness of the RDD as a deflection data acquisition tool and to upgrade the equipment for routine use. This report focuses on identifying and evaluating the RDD's potential effectiveness. A separate report will identify and evaluate the equipment upgrades that have occurred over the last year; it will also present results of several field tests using the RDD.

The RDD's potential effectiveness will be addressed while considering the RDD's current capabilities. These current capabilities have been compared to the capabilities of similar systems that have been identified through a literature search. This literature search will also serve to identify the latest views within the research community on the various noncontact probes in use. In addition, a listing of potential future uses will be accompanied by a summary of the RDD's advantages and limitations as compared with discrete deflection monitoring devices.

The RDD's possible effectiveness will be evaluated through a side-by-side comparison with the FWD in a routine field test. A separate report for this project will address the results of this field test.

1.3 SCOPE OF THIS REPORT

This report summarizes the work that has been performed over the last year to assess the RDD's potential for use as a deflection data acquisition tool. The organization of this report is as follows:

Chapter 1 identifies the problem and describes the objectives of Project 0-1422. Chapter 2 presents the methodology and findings from the literature review. These findings are broken down into three categories: (1) the development of other rolling devices similar to the RDD, (2) the current use of noncontacting probes and instruments to monitor pavements, and (3) other topics relevant to the RDD.

Chapter 3 presents the methodology that was developed to measure the pressure distribution existing under the RDD's loading wheels. These measurements are meant to ensure that the RDD's loading wheels don't apply to the pavement pressures such as might damage the pavement or affect the RDD's measurement results.

Chapter 4 identifies various potential uses for the RDD. As the current project is at its conclusion, Chapter 4 holds particular importance because it identifies the areas of research that may be especially fruitful to pursue in the future. Finally, Chapter 5 presents the conclusions and recommendations of this report.

CHAPTER 2. LITERATURE REVIEW

2.1 METHODOLOGY

A literature search was conducted in order to fulfill the requirements of Task 1 for Project 0-1422. Since the RDD is a prototype piece of equipment developed at The University of Texas at Austin, much of the literature relevant to the RDD was expected to be found within the Center for Transportation Research (CTR). However, the goal of this literature search was to not only document the work that CTR has performed, but to also identify any other devices similar to the RDD that are also currently under development. Finally, this literature search attempted to report on the latest techniques for using noncontacting sensors to measure the deflection of a pavement subjected to a load, and to report on background technology relevant to the RDD.

The initial portion of the literature search was based on RDD-related research conducted at The University of Texas at Austin through CTR. Several relevant research reports were identified, including thesis reports on rolling systems by both Brent Rosenblad and Blake Cotton. While these reports effectively introduced the RDD concepts, additional references were needed to determine what others within the research community had developed and encountered while trying to measure pavement deflections continuously.

Accordingly, a Transportation Research Information Service (TRIS) literature search was conducted at CTR in order to identify articles relevant to the RDD. The TRIS system is a national database that provides an abstract of articles found through key-word searches. (This abstract enables users to determine whether the article is relevant to their needs.) The literature search yielded a number of efforts that have been carried out by other research teams. None of these have yet produced an acceptable working system. The details of the search are discussed below.

2.2 FINDINGS

The findings from the literature review are summarized in the following pages, along with the appropriate reference information. The findings of the literature review are categorized according to the following: (1) the development of rolling devices similar to the RDD, (2) the current use of such noncontacting probes as lasers and sensors to monitor pavements, and (3) background topics relevant to the RDD.

2.2.1 Development of Other Rolling Devices Similar to the RDD

In their 1994 report [Ref. 3] Cotton et al. describe the development of a trailer-mounted system for use in detecting irregularities in rigid pavements. One of the more applicable aspects of this article falls under a section that describes different ways of detecting delaminations in rigid pavements. Within this section, Cotton describes a piece of equipment called the Collograph.

The Collograph was developed in France in 1983 by Le Laboratoire Central des Ponts et Chaussees. It appears to share many characteristics with the RDD. First, the Collograph performs continuous measurements of a pavement's dynamic deflection generated by a moving vibratory load (in this case, a roller that contains a vibrating mass). The weight of the mass itself is 3,000 N (675 lb) and an additional sinusoidal force with an amplitude of 2,000 N (450 lb) is generated at a rate of 60 Hz. As a result, a sinusoidal force that varies from 5,000 N (1,125 lb) to 1,000 N (225 lb) at 60 Hz loads the pavement, creating dynamic deflections.

These dynamic deflections are monitored by a receiver that consists of a soft rubber wheel filled with liquid and containing four vertically oriented hydrophones. The hydrophones produce voltages proportional to the vertical dynamic displacements. This voltage output can be immediately evaluated on site. Thus, the Collograph applies a sinusoidal load to the pavement and measures the resulting displacement continuously, much like the RDD. However, the loads that the Collograph applies to the pavement are smaller than those applied by the RDD. The Collograph applies load from 1,000 N (225 lb) to 5,000 N (1,125 lb). As stated in the article, the limited literature available on the Collograph means that its reliability and accuracy have yet to be proven.

Along with the Collograph, Cotton describes his trailer-mounted system that was designed to detect irregularities in rigid pavements. Contained within Cotton's trailer is a source wheel and a receiver wheel, which have been designed such that signals can be transmitted into and out of the pavement in an optimum manner. Cotton's trailer is also equipped with acoustical boxes at both the source wheel and the receiver wheel, a design meant to minimize outside noises created by the vehicle or by other sources. Cotton's trailer-mounted system uses source testing frequencies in the range of 1.5 kHz to 2.0 kHz. His system is also equipped with a high-sensitivity Wilcoxon Model 728T accelerometer. Cotton states that for pavement analysis, high-frequency measurements are most common and, therefore, the monitoring of particle acceleration is of most importance. To accomplish this, Cotton recommends piezoelectric accelerometers. In addition, Cotton recommends that high-amplitude signals be analyzed with low-sensitivity accelerometers and that low-amplitude signals be analyzed with high-sensitivity accelerometers [Ref. 3].

Paquet [Ref. 4] describes a piece of equipment designed to measure pavement deflections in his 1978 report. In this article, Paquet describes the basic operation and features of the CEBTP Curviameter and subsequently gives recommendations for its future use.

The CEBTP Curviameter works like a moving Benkelman Beam. The Curviameter consists of a large truck fitted with a 12.45-m (40.85 ft) track assembly (see Ref. 4 for illustration). A 4-m (13-ft) section of this track assembly lies on the ground at any given point in time and passes between the dual tires of the right rear-wheel system, while the remaining 8.45-m (27.7-ft) section of the track assembly is looped over the right rear-wheel system.

During testing, the truck travels at a constant speed of 18 km/hr (11.2 mph) while a sensor (or a "pick up" as Paquet calls it) mounted on the track remains stationary on the ground and monitors the pavement's curvature and deflection from the time the right rear-wheel system is 2.5 m (8 .2 ft) in back of the sensor to the time the right rear-wheel system is 1.5 m (4.9 ft) in front of the sensor. The pavement deflection that the sensor monitors results from the load applied from the CEBTP Curviameter's weight. The sensor is a geophone similar to those used in the RDD and the FWD. As a result, the CEBTP Curviameter measures the pavement deflection at the location of the sensor during the time the 4-m (13-ft) length is traversed. The next 8.45 m (27.7 ft) involves no measurement by the sensor as it travels around the loop. Another cycle resumes when the sensor is placed on the pavement again.

Paquet evaluated accelerometers and geophones to use in monitoring the pavement deflection. Initially, he chose the geophone but experienced problems in its use with the Curviameter. This problem seemed to be associated with the fact that the geophone itself was rotated with the Curviameter belt and did not have time to settle down. Currently, the Curviameter uses accelerometers, though they are not as applicable for our use with the RDD.

This Curviameter moves at a slightly higher speed than the initial version of the RDD. However, it does not allow for continuous measurements of pavement response. Although the Curviameter has been available for some time, it is not at present widely used.

Rish et al. [Ref. 5] have taken another approach to continuously profiling pavement deflection. Their research and findings are presented in their 1995 article that describes the development and capabilities of a continuous deflection monitoring device dubbed the "Rolling Weight Deflectometer" (RWD). This device is used to evaluate airfield pavements. The RWD continuously monitors the pavement's deflections generated by the load it applies to the pavement.

The RWD is comprised of a trailer equipped with four optical triangulation pavement sensors used to determine the deflection of the pavement under load. In addition, the RWD contains a high-speed data acquisition system and a high-pressure tire assembly that is used to load the pavement. Finally, a fifth wheel is used as an odometer to enable the user to identify exact pavement locations for various deflection readings. In preliminary experiments, the RWD compared well with FWD tests run at the same locations.

To monitor pavement deflection, the RWD makes geometric calculations from four optical triangular measurements. As shown in Figure 2.1, sensors A, B, C, and D monitor the distance to the pavement as a load is placed at the rolling wheel at sensor D's location. First, sensors at locations A, B, and C are used to calculate an unloaded height, h, at location C. As the RWD traverses the pavement, sensors at locations B, C, and D use a similar algorithm to calculate the loaded height, h', at the same point on the pavement (which now falls under sensor D). Because the sensors are 2.8 m (9 ft) apart, the readings from sensors A, B, and C fall outside of the deflection basin created at sensor D's location; therefore, the deflection generated by the load is h - h'.

The RWD uses this algorithm to calculate deflection measurements at 0.30-m (1-ft) intervals, to an accuracy of 40 microns (0.0015 in.). Presently, the RWD operates at a speed of 10 km/hr (6 mph).

The RWD is used primarily by airfield pavement engineers. However, Rish et al. have also begun preliminary design on a highway RWD. They hope the highway RWD will include the following capabilities: (1) a minimum 50 km/hr (30 mph) deflection measurement speed, (2) pavement temperature measuring capability with each deflection reading, (3) load measuring capability with each deflection reading, and (4) an accuracy of 20 microns (0.0008 in.) [Ref. 5].

2.2.2 Review of Sensors Used to Monitor Pavements

Bodocsi et al. [Ref. 6] performed a series of tests involving four different deflection measuring set-up combinations: (1) the linear voltage displacement transducer (LVDT), (2) the geophone, (3) the Dynaflect, and the (4) falling weight deflectometer (FWD). The testing compared vertical deflection readings from six joints at the Ohio Department of Transportation's pavement testing site. In this program, the pavement deflections measured by the LVDTs and the geophones were produced by a fully loaded, two-axle truck traveling at various speeds (0, 16, 56, and 80 km/hr [0, 10, 35, and 50 mph]).

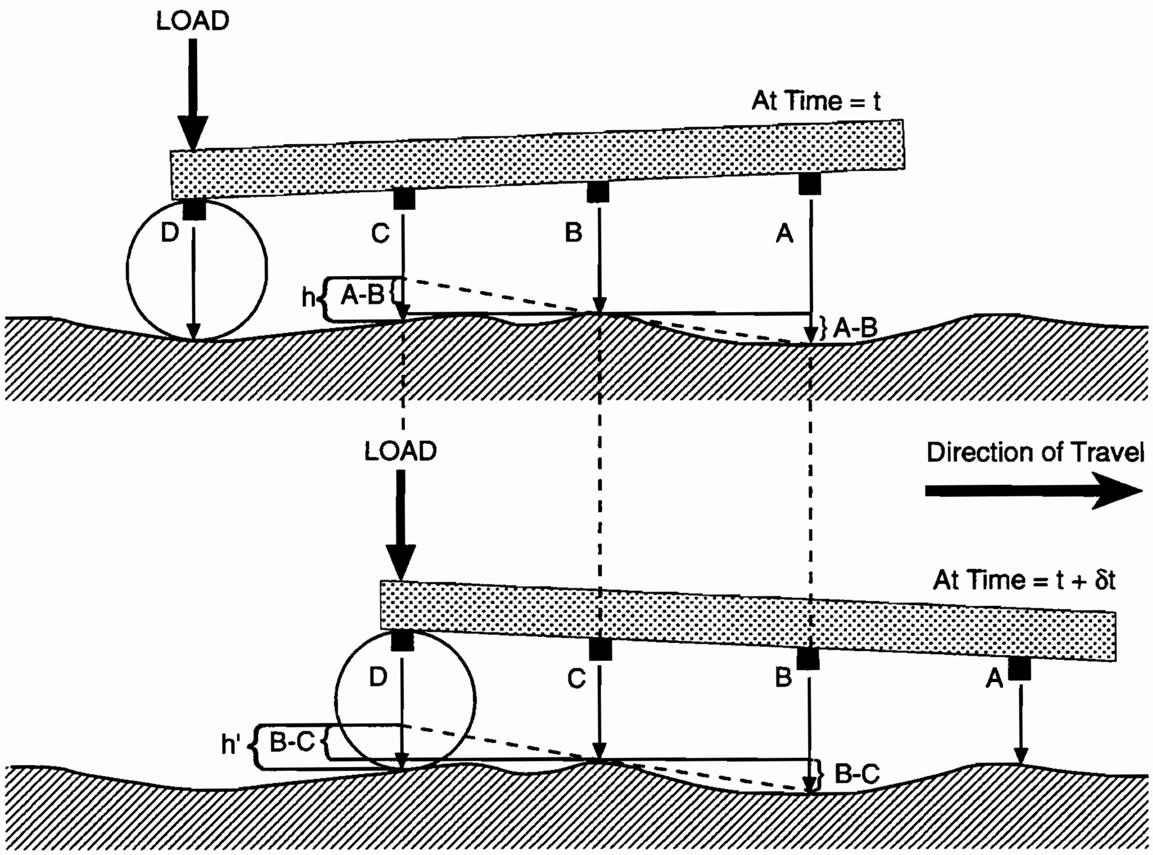

Figure 2.1 Surface deflection algorithm of the RWD [Ref. 5]

The article describes some of the advantages and disadvantages of the various instruments. For instance, the LVDT requires a fixed reference point in order to measure relative displacements. This limits its potential usage. The geophone, on the other hand, doesn't require a fixed reference point for its measurements. However, a geophone cannot measure static deflections, and the deflection measured by a geophone must occur at speeds that create motions within the frequency range of the geophone. For this particular study, that frequency range was 4.5 Hz to 10 Hz [Ref. 6].

Larsen et al. [Ref. 7] have conducted research using noncontacting instruments to measure pavement deflection. They presented the results of their research in a 1994 article that describes the features and working mechanisms behind the Profilograph, a piece of equipment that has been used to improve the data collection of the Danish pavement management system.

The Profilograph uses lasers to measure a pavement's surface characteristics over a wide range of wavelengths. The Profilograph is capable of measuring the micro structure of a pavement at wavelengths of 10^{-3} mm; it is also capable of measuring pavement profiles, such as vertical curves, using wavelengths on the order of 10^6 mm. In addition to gyroscopes and accelerometers, the Profilograph contains seventeen lasers mounted to a beam placed near the front bumper of the vehicle. The majority of these lasers are concentrated in the wheelpaths of the vehicle. As the vehicle travels along the pavement, the lasers take readings of the pavement's profile at every 5 mm (0.2 in.). These readings are then used to find an average reading over an 8-cm (3.15-in.) distance. The Profilograph has been used to evaluate the surface characteristics of a pavement, such as roughness, cross fall, rutting, and curvature. Finally, and perhaps most importantly, the Profilograph performs these measurements while the vehicle is operating at speeds of up to 100 km/hr (62.1 mph), which is near normal traffic speed. Thus, the Profilograph can operate without disturbing the flow of traffic [Ref. 7].

The technology used in the Profilograph, however, may not be applicable to the RDD. As stated in the article, the lasers measure the distance between the beam on which they are mounted and the pavement surface to an accuracy of 0.5 mm. The extensive list of all the components needed to operate the Profilograph properly includes laser sensors, laser box, gyros, accelerometers, thermometer, control desk for measuring beam, computer screen, computer keyboard, computer, computer storage, and a power source. The total cost of the system was not mentioned in the article.

Masliwec [Ref. 8] studied the use of lasers in civil engineering applications. His observations are presented in a 1990 article that describes the use of lasers to monitor, over an extended period of time (more than a few minutes), the displacement and velocity of bridge bearings in steel and concrete bridges.

These lasers monitored the displacement and velocity over tetraflouoroethylene (Teflon)-bearing surfaces in bridges. The laser was comprised of a computer-controlled position transducer, which had the ability to make precise measurements over a large range of motion. To begin taking measurements, a laser head, interferometer, and a receiver were attached to an optical bench. In addition, a retroreflector was placed perpendicular to the optical bench on the bridge bearing. Then the optics of the system were aligned and the laser was fixed to a set position, allowing the monitoring to begin.

The results of the tests seem promising. The lasers have detected movements caused by high-frequency oscillations. In addition, the lasers have indicated motion proportional to the amount of traffic and the size of the vehicles in a number of locations [Ref. 8].

Nazarian and Bush [Ref. 9] discuss the use of geophones for measuring deflections. Their article on the operating principle of a geophone describes several uses of geophones, specifically the impulse method and the frequency response method.

In general, the choice between the two methods involves a tradeoff between accuracy and time. The impulse method is easier to use than the frequency response method; however, the impulse method generates less accurate data than the frequency response method. In addition, the frequency response method generates more complete data than the impulse method, since the entire displacement-time history is determined with the frequency response method, whereas only the maximum deflection of a pavement is found with the impulse method. The use of the impulse method is limited to short-duration loadings, while the frequency response method's results are independent of the duration and shape of the impulse [Ref. 9]. Generally, the frequency response method appears to be better suited for use with geophones.

In addition, deflection surveys have been conducted through the use of a Pavement Deflection Data Logging Machine (PDDLM), which is the British version of a Deflectograph. The PDDLM monitors the maximum pavement deflection in both wheelpaths generated by the application of a given vehicle load. The PDDLM is equipped with a beam assembly that is positioned beneath the vehicle supplying the load, between the vehicle's two axles. A sensitive angular measurement is made of the beam rotation that is converted into the vertical movement of the end of the sensing probe using trigonometry. This beam assembly rotates as the vehicle's rear-wheel load passes the beam assembly. Currently, the PDDLM typically gives deflection readings at 3.8-m (12.47-ft) intervals at a speed of 8 km/hr (5 mph).

In their 1992 article, Tandon and Nazarian [Ref. 11] evaluated various sensors that measure pavement deflection. The article compares five mechanisms used to monitor a pavement's deflection under load. The five mechanisms are as follows: accelerometers, linear variable differential transducers (LVDTs), proximeter probes, laser optocators, and velocity transducers (geophones). The comparison is made with respect to the accuracy and precision the instruments provide, with consideration given to such other factors as ease of use in the field and cost. Their comparisons are summarized in Table 2.1.

According to the authors, proximeter probes are hard to use in the field because one must place them only 2 mm (0.08 in.) from the load at a true perpendicular angle in order to obtain reliable deflection measurements.

Table 2.1 Comparison table of deflection measuring devices [Ref. 11]

Sensor	Accelerometer	LVDT	Geophone	Proximeter	Laser
Cost	$350	$350	$40	$400	>$10,000
Supporting Device(s)	Power Amplifier ($300)	Power Supply ($400)	–	Power Supply ($400)	–
Precision, Steady-state	Moderate	Good	Good	Very Good	Excellent
Precision, Impulse	Poor	Good	Good	Very Good	Good
Accuracy, Steady-state	Moderate	Good	Good	Excellent	Excellent
Accuracy, Impulse	Poor	Good	Good	Good	Good
Field Worthiness	Good	Moderate	Very Good	Moderate	Poor
Mounting	Very easy	Difficult	Very Easy	Difficult	Difficult

For this particular study, the authors ultimately recommend the use of geophones over accelerometers to monitor pavement deflection. Tandon and Nazarian point out that geophones are less expensive than accelerometers. In addition, Tandon and Nazarian show that geophones demonstrated good accuracy and precision in the tests they conducted on the instruments during both steady-state and impulse motion. The accelerometer, however, demonstrated only moderate precision and accuracy for steady-state motion, and demonstrated poor precision and accuracy while monitoring impulse motion [Ref. 11]. Yet it should be noted that these comparisons are based on frequencies in the range of pavement loadings, and that the comparisons would reverse at frequencies above something on the order of 500 Hz.

Walker and Harris [Ref. 12] have performed research on noncontact pavement crack detection. Their article describes the development and use of lasers in noncontact pavement crack detection for the Texas State Department of Highways and Public Transportation (now TxDOT). The development of the crack detection system involved using laser probes on the department's surface dynamics profilometer in order to measure the crack detection capabilities of these laser probes. In addition, hardware and software were obtained and developed in order to complete the development of the system. The hardware included the Selcom laser probes, Motorola open-ended VME architecture, and a Compaq portable personal computer. The software that was developed incorporates two crack detection algorithms written in C code. These algorithms include the autocorrelation difference (Codiff) method and the running-mean downup method (Downup). The Codiff method checks for a high variance from the data collected on the pavement from the lasers, a condition that indicates sharp cracks. The Downup method works on the notion that a crack consists of a downward slope followed by an upward slope. The algorithm searches for a downward slope it considers to be acceptable insofar as crack detection is concerned, followed by an acceptable upward slope. Walker and Harris recommend the use of the Downup method over the Codiff method.

They developed a system that can provide crack detection measurements in real time at speeds of up to 96.5 km/hr (60 mph) while making use of only two or three narrow beams of laser light. Specifically, the system can detect alligator and block cracking when the Selcom lasers are mounted in the wheelpaths. In addition, with the introduction of more lasers, traverse cracking and rutting can be detected [Ref. 12].

Oliver [Ref. 10] examines how the British have used deflection measurements to manage their structural maintenance requirements at the network level. Specifically, this article elaborates on the equipment and methods the British have used to make a case for the need of funds to rehabilitate their network (which is not presently in an optimal condition).

First, the British have utilized the High Speed Road Monitor (HSRM) in assessing the condition of the network. The HSRM uses lasers to perform condition surveys covering large portions of the network with a marginal level of detail. The British have also used the HSRM as a tool to perform a broad initial inspection of the condition of their network. Information from the HSRM is then used to target specific areas where slower, more detailed, condition and deflection surveys will take place.

Another article found in the *Engineering News Record* [Ref. 13] expands on a subject reported on previously by Oliver [Ref. 10]. This article elaborates in detail on the HSRM, which has been developed by the Transport and Road Research Laboratory (TRRL) for the U.K. Department of Transport (DOT). The instrument was manufactured by WDM Ltd. in Bristol, England.

The HSRM can perform condition surveys of a pavement while traveling at speeds of up to 97 km/hr (60 mph). The HSRM provides information on longitudinal profile, wheelpath rutting, surface texture, road alignment, gradients, crossfalls, and curvature radii. The HSRM, comprised of a long trailer that is towed by a vehicle, performs these tasks through the use of lasers. The trailer is equipped with six laser sensors that measure the road profile, rutting, surface texture, and road alignment. In addition, the trailer is equipped with inclinometers and distance transducers that measure the gradients, crossfalls, and curvature radii. The data are logged automatically on a magnetic cartridge that rests in the towing vehicle. The HSRM's lasers can measure profiles to an accuracy of 1.5 mm (0.06 in.), pavement texture to an accuracy of 0.2 mm (0.008 in.), and rutting to an accuracy of 2 mm (0.08 in.).

Finally, the HSRM's lasers also read 0.6 m-by-0.3 m (2 ft-by-1 ft) bar code plates placed along the road network in order to allow for rapid location identification. Four thousand of these plates are installed along the road network to be surveyed [Ref. 13].

Once again, this laser technology appears to be useful because it makes collection of pavement condition data at high speeds possible. However, the high cost and estimated accuracy of the lasers were considered to be deterrents to their use with the RDD.

2.2.3 Other Topics Relevant to the RDD

Roque et al. [Ref. 14] have identified a possible benefit of using a dual-load testing system in pavement deflection tests, as opposed to a single-load system. Their conclusions are presented in their 1992 article.

The authors of that article feel that the present single-load FWD inadequately differentiates between the different layer moduli of the asphalt concrete, the base, and the subbase in a flexible pavement, because changing the asphalt concrete modulus by 20 percent may have the same effect on the FWD's deflection basin as, for example, changing the base course modulus by 40 percent. Therefore, a particular FWD deflection basin is not unique to one combination of layer moduli.

The authors feel that, through the use of two loading wheels, they can examine the transverse and longitudinal deflection profiles from the dual-load system and uniquely find the correct near-surface layer moduli of the pavement. The authors have used the loading and sensor configuration shown in Figure 2.2 in their analysis [Ref. 14]:

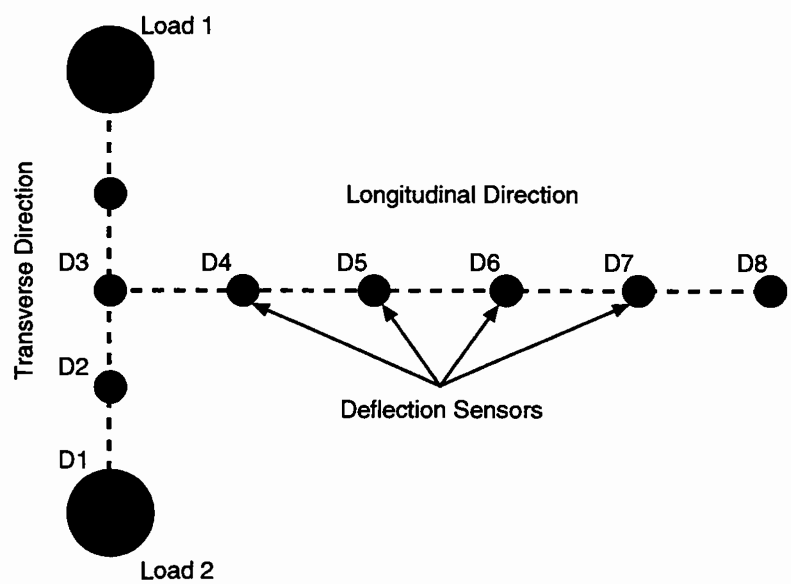

Figure 2.2 Plan view of dual load and sensors for analysis [Ref. 14]

As shown in Figure 2.2, the authors arranged five geophone deflection sensors in the longitudinal direction and three deflection sensors in the transverse direction to monitor the displacement profiles in both of these directions. This view of the loading wheels and deflection sensor locations shows similarities to a possible RDD loading wheel and sensor location scheme shown in Figure 2.3.

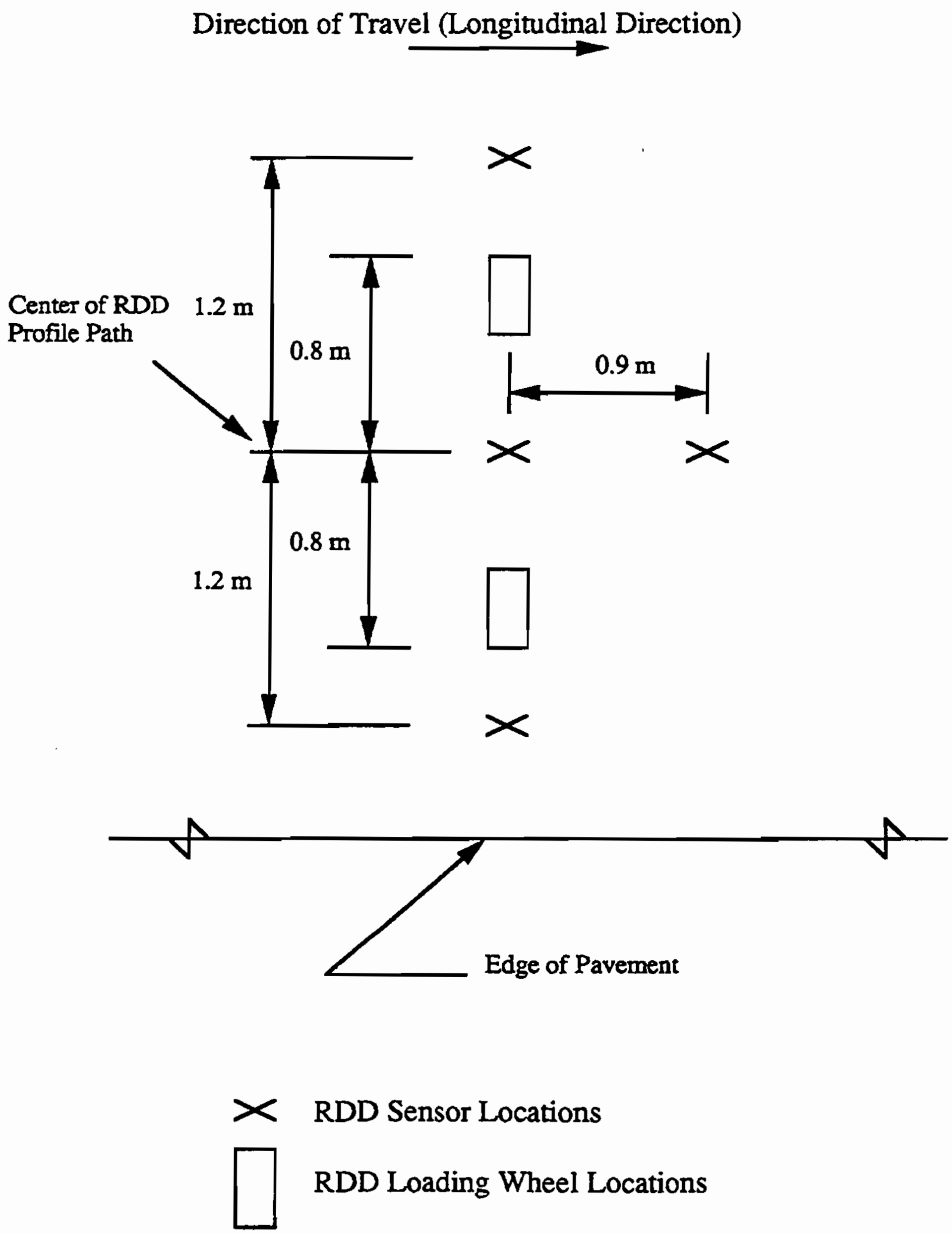

Figure 2.3 Possible RDD dual load and sensor scheme

The authors of this article seem to demonstrate, through experimentation with a dual-load testing system, that the asphalt concrete modulus has a significant impact on the shape of the transverse deflection basin and little impact on the shape of the longitudinal deflection basin. Similarly, the base course modulus seems to greatly affect the longitudinal deflection basin, yet has little impact on the transverse deflection basin.

In theory, the RDD should be able to be used in a similar manner to better discriminate between the modulus of the asphalt concrete layer and the base layer within a flexible pavement. With a dual-load system and multiple sensors, every single pair of transverse and longitudinal deflection basins should be able to uniquely estimate the asphalt and base moduli, respectively, through modulus backcalculation.

The authors point out that efforts have been made in the past to use the Dynaflect's dual-loading system to discriminate between a pavement's near-surface layer moduli. The disadvantages of using the Dynaflect for that study was the Dynaflect's small, fixed loading levels and the Dynaflect's semirigid, noncircular loads. Small, fixed loading levels limit one's ability to estimate effective layer moduli because these estimates may change with the loading levels. The RDD doesn't share this problem with the Dynaflect, as the RDD is able to apply a range of loads to a pavement. Semirigid, noncircular loads are difficult to model with today's analysis programs; they also prevent measurements from being taken beneath the load. The RDD does share this problem with the Dynaflect, as the RDD's loading wheels are coated with a hard urethane and don't apply circular loads to the pavement. However, this concept introduces interesting possibilities for future work with the RDD.

Rosenblad et al. [Ref. 15] have conducted research that also has applicability to the RDD. The results of their research are presented in a 1995 report that evaluated and compared two stress-wave methodologies used within a rolling system to detect pavement irregularities. These two methodologies are the impact-echo method and the impulse-response method. Within the background section of the report, Rosenblad draws a comparison between the Collograph (see section 2.2.1.1) and the RDD. Rosenblad points out the similarities between the RDD and the Collograph, but notes that the Collograph operates at a scale smaller than that associated with the RDD. In other words, the dynamic loads the Collograph applies to the pavement are smaller than those applied by the RDD; the pavement defects detected by the Collograph are also smaller than those detected by the RDD.

From Rosenblad's description of the impulse-response method, the methodology grounded in the impulse-response method appears very similar to the methodology by which the RDD operates. The impulse-response method uses low-frequency impacts to apply a load to the pavement. The resulting response of the pavement is measured using velocity transducers attached to the pavement surface.

In addition, another stress-wave method used in flaw detection that has similarities to the RDD is the automated sounding device. Unlike the RDD, this method uses high-frequency compression waves as its principle mechanism for evaluating pavements. However, like the RDD, the system contains a rolling source and receiver system. The rolling source consists of a pair of rigid steel wheels acted upon by a solenoid-driven plunger oscillating at 60 Hz. The receivers consist of two wheels filled with oil and equipped with vertical hydrophones spaced 0.3 m (1 ft) apart. The system accepts output in the range of 300 to 1,200 Hz; through the use of a

DC rectifier, a voltage output is plotted by pen. This method has been tested for its flaw-detection capabilities, a task that the RDD is not specifically suited to perform. The tests show that this device is less effective in detecting flaws than the more established chain-drag method [Ref. 15].

2.2.4 Summary

It is important to review the literature in any new research project to insure that you are not treading old ground and to obtain information relative to the subject being reviewed. In this case, the literature review showed that no one is currently carrying out rolling deflection measurements using a process similar to that used for the RDD. Additional details were also obtained with respect to various transducers and other types of deflection measuring devices.

In summary, the literature review strongly suggests that the effort to develop and evaluate the RDD should continue, and that there is high potential for use of such technology if it is successfully developed.

CHAPTER 3. PRESSURE DISTRIBUTION UNDER THE RDD'S LOADING WHEELS

3.1 INTRODUCTION

This chapter presents the methodology that was developed to measure the pressure distribution existing beneath the RDD's loading wheels while the RDD is in use. The determination of these pressure distributions is required for several reasons. First, the RDD is capable of applying very heavy loads to a pavement, on the order of about 150 kN (33 kip) when the static and dynamic loads are combined. Given that the RDD cannot currently apply static loads less than approximately 67 kN (15 kip) during routine use [Ref. 2], the device indeed exerts extremely high forces on a pavement.

Second, the RDD uses solid wheels to load the pavement, as opposed to standard pneumatic (fluid-filled) wheels. These wheels consist of a solid 150-mm (6-in.) diameter aluminum hub enclosed in 110 mm (4.5 in.) of hard (50D durometer) urethane. The current loading wheels are about 200 mm (8 in.) wide. Consequently, the heavy forces that the RDD applies to the pavement aren't spread over a substantial area. This suggests that the pressures existing beneath the RDD's loading wheels could potentially be very high.

For these reasons, the pressures existing under the RDD's loading wheels during routine use should be identified and compared with the pressures imposed on highway and airfield pavements by typical traffic and aircraft loads. Yoder states that typical aircraft loads apply pressures ranging from approximately 860 kPa (125 psi) to 1,380 kPa (200 psi) [Ref. 16]. Therefore, should the RDD's loading wheels create loading pressures far in excess (2,800 kPa or greater) of typical loading pressures, then the resulting impacts on the RDD's flexibility determinations should be considered.

3.2 METHODOLOGY

Several possible methodologies are available for determining "pressure footprints" under static-loaded wheels. These methodologies include the use of pressure-sensitive film and the use of pressure transducers, which were used by the Center for Transportation Research in previous studies [Refs. 17, 18]. Dr. Kurt Marshek has evaluated current, updated pressure-sensitive film and recommended its use in this application.

The pressure-sensitive film consists of two layers: a color-forming layer and a color-developing layer. When placed between a load and a smooth, hard surface, the color-forming layer reacts to the load by releasing a color-forming substance onto its color-developing layer. This color-forming substance is housed within microcapsules that rupture at different pressures. The density of the resulting film color indicates the pressures imposed by the load. The more dense (or dark) the color of the film, the higher the pressure. The film's manufacturers supply a color-reference chart that allows one to approximate the pressures existing under a loading wheel for the particular temperature and humidity conditions at the time of testing.

It should be noted that a pavement's surface texture isn't identical to the "smooth" surface proposed for testing here. However, a smooth surface is proposed for this test to allow for clearer visual identification of the pressure footprint created from the RDD's loading wheels.

Several different types of film exist for monitoring different pressure magnitudes. The three types of film that we were most interested in record pressures ranging from 480 kPa – 2,410 kPa (70 psi – 350 psi), 2,410 kPa – 9,650 kPa (350 psi – 1,400 psi), and 9,650 kPa – 48,920 kPa (1400 psi – 7100 psi), respectively, given that these ranges covered the expected loads of the RDD. Once a microcapsule ruptures and releases its color-forming substance onto the film's color-developing layer, the resulting color impression does not change. In this way, the pressure-sensitive film displays the maximum pressure existing at any point under the load at the time it reaches its maximum. The resulting color contours define the load distribution under the wheel.

It should be pointed out that the use of such film is limited to static load. However, the distribution and load under the particular type of tire being used is illustrative of the distribution of any load applied to the tire.

The project team, which included Dr. Virgil Anderson, identified an experiment that varies the magnitude of the static load with the temperature of the RDD loading wheels to evaluate load distribution. This factorial experiment design includes a low, medium, and high static load and cool, average, and warm temperatures. Three experiments are proposed for each of the possible combinations of the above temperatures and static loads in an effort to ensure repeatability in the experiments. To obtain these replicates, each successive trial should use a load level that differs from the previous trial. This means that twenty-seven total experiments are proposed where a loading wheel of the RDD is loaded onto the pressure-sensitive film. The factorial design is shown graphically in Figure 3.1.

The RDD's minimum current static load is roughly 67 kN (15 kip). This minimum would constitute the "low" load, while static loads of roughly 89 kN (20 kip) and 111 kN (25 kip) will constitute the "medium" and "high" loads, respectively. Likewise, we propose that the RDD's loading wheels be tested at temperatures of roughly 4.5°C (40°F), 21°C (70°F), and 38°C (100°F) to mimic the range of temperatures that will typically occur during routine field testing.

Before undertaking the fully designed experiment, we conducted a pilot study in order to identify any field difficulties that might be associated with using the pressure-sensitive film. As with any initial evaluation, we did find some problems. The windy conditions on the day of the pilot test made the film difficult to handle; therefore, future tests need to be run in an enclosed building if possible. Cutting the film to size in the field was difficult, but this problem can be eliminated by knowing the exact sizes of films to be used and precutting them for future studies.

The field pilot study indicates that the film pressures shown are adequate for evaluating the load distribution under the wheel, and, at some future time, the full experiment should be carried out.

Because the final wheel configuration and materials were being selected as the project was ending, the full experiment could not be conducted. The full experiment is available for future use should it be needed at any later date.

STATIC LOAD

Temperature of loading wheels	Low	Medium	High
Cool	3 Replicates	3 Replicates	3 Replicates
Average	3 Replicates	3 Replicates	3 Replicates
Warm	3 Replicates	3 Replicates	3 Replicates

Figure 3.1 Factorial experiment design for pressure distribution testing with the RDD

CHAPTER 4. USES FOR THE ROLLING DYNAMIC DEFLECTOMETER

4.1 INTRODUCTION

This chapter discusses potential uses for the RDD and outlines how the RDD has the potential for improving pavement evaluation. The most widely used device for pavement structural evaluation in TxDOT today is the falling weight deflectometer (FWD). This device is currently used and certainly does a good job. The Dynaflect is also used, although it is generally being phased out. Owing to the moving nature of the RDD, it has the potential for increasing the quantity of data as well as the coverage that can be applied to a pavement network, as compared with existing equipment. Five potential uses for the RDD are grouped into the following categories: (1) assessment of pavement variability, (2) forensic studies, (3) load-zoning studies, (4) examination of joint behavior, and (5) miscellaneous studies.

4.2 ASSESSMENT OF PAVEMENT VARIABILITY

4.2.1 Identification of Weak Spots along a Pavement Section

Since the RDD is a rolling deflection device, it has the ability to provide an approximate, continuous pavement deflection profile. Such a continuous profile can provide a great deal more information about the variability of the structural response of the pavement than can be accounted for by discreet deflection measuring devices. That is not to say that the detail of the information at each location will be as great as the detail obtained from the FWD, for example. Nevertheless, there are certain applications within the highway community for which a continuous profile would be very beneficial. This is particularly important, for example, in network evaluation of pavement structural response.

The RDD to date does not provide the detailed deflection information needed to estimate layer coefficients or layer moduli. Instead, the RDD calculates a composite pavement response or stiffness. In some dynamic circles, this is termed the *composite flexibility* of the pavement, which is, of course, the inverse of stiffness. To date, a simple data acquisition system has been used for the RDD because the main purpose was to interpret the ability of the RDD idea itself to work effectively. Since early tests have shown that the idea of a moving, vibrating load has potential, it should be possible in the future to improve and to increase the number of sensor locations and the data acquisition speed. As new computer technology becomes available, the quantity and type of data acquisition is virtually unlimited. These are, of course, future concerns, since multiple sensors have not yet been used at the time of the writing of this report.

The RDD is a promising tool for identifying weak spots in a pavement section — that is, those spots that have excessive deflection or, for example, deflection more than 20 percent greater than the average deflection. In rigid pavements, weak spots may result at joints and cracks or from the presence of a void beneath the concrete layer. In flexible pavements, areas of high deflection may be related to inherent variability in the base material, water in the subgrade, fatigue in the surface layer, or to many other pavement deterioration characteristics. If continuous deflection profiles or near continuous deflection profiles are taken with the RDD, those spots that are identified as weak spots or trouble spots could later be studied in more detail with the more precise FWD (if desired by the engineer). This will be discussed under the topic of overlay design.

4.2.2 Aid in the Determination of an Overlay Design of Existing Pavement Sections

The RDD's ability to account for the variability in pavements leads to another potential use, namely, aiding in the determination of a proper overlay design of a pavement section. Upon traversing a pavement section, the RDD generates a continuous profile of the section's overall flexibility. Engineers can use this information to generate an appropriate overlay design for the pavement section. This overlay design may be a "worst case" design, where the overlay for the entire section is based on the additional structural capacity needed at the weakest point in the pavement section. Alternatively, the overlay design may take the pavement's variability into account, with a thicker overlay placed at weaker points along the pavement section and a thin overlay placed at stronger points along the pavement section.

The choice of a desired speed at which to profile is important, given that there is a tradeoff between precision and time. While traveling at higher speeds, the RDD will average the pavement's flexibility over greater distances, yielding less precise measurements of pavement flexibility. Yet at higher speeds one can potentially evaluate a greater amount of pavement. Conversely, at lower speeds one obtains a more precise evaluation of the pavement's flexibility, though less pavement is evaluated per unit of time.

4.2.3 Identification of Uniform Pavement Locations for MLS and Other Research

One of the major problems that has occurred over the years in conducting research is associated with how to deal with inherent variability in constructed field pavements. When the mobile load simulator (MLS) goes to a field section, its ability to predict accelerated pavement life depends on how well the test location represents the balance of the test section. The same is true when a few deflection tests are used to represent a relatively long pavement section. The availability of an RDD would make it possible to pretest a section to determine its general uniformity. Subsections within the test section could then be identified for further observation. In the case of the MLS program, a section would be accepted for MLS testing only if it exhibited a reasonable level of uniformity over a required length, such as 1.61 km (1 mile) or more.

Similar problems arise for any field evaluation of pavement layers or other materials. For example, when microsurfacing is to be compared with other surface repair techniques, it is necessary that the characteristics of the control section and the various test section treatments be relatively uniform. Otherwise, the variable strength in the underlying pavement will be misinterpreted as an effect of the material being tested on the surface. The RDD would make it possible to set up such field evaluations in a uniform way and could greatly enhance TxDOT's ability to evaluate field materials trials effectively.

4.2.4 Quality Assurance

An important component in the construction of pavements is the ability to construct a pavement that has attributes (strength, thickness, etc.) that fall within the specified range value. These specifications are intended to ensure that an "as-built" pavement actually possesses the intended design strength. The RDD is well suited to ensure that as-built pavements possess strengths that fall within the specification. The RDD's ability to continuously profile a pavement's strength and stiffness makes it useful in identifying those portions of an as-built pavement that don't measure up to the criteria required for the project. This should encourage the building of pavements having more uniform attributes throughout, reducing the overall variability of the as-built pavements.

The most important concern for this potential use pertains to the RDD's inability to currently apply static forces less than approximately 67 kN (15 kip). As such, when testing quality control on rigid pavements, a 30-day grace period between construction and quality control testing should be observed to allow the concrete to gain most of its strength. With flexible pavements, engineers should note the pavement's design strength before testing with the RDD. Engineers obviously shouldn't use the RDD to test quality control on pavements designed for loads less than the minimum RDD load. In addition, the pressures that exist under the loading wheels of the RDD should be considered to ensure that the surface of the pavement doesn't break up as a result of pressure peaks. This topic, which was to be examined in detail as part of Project 0-1422, is recommended for future study. The contact pressures between the RDD and the pavement shouldn't exceed approximately 2760 kPa (400 psi). Otherwise, these contact pressures may affect the flexibility readings that the RDD obtains because of permanent deformation in the asphalt surface. With these guidelines in mind, engineers should have little or no trouble using the RDD as a tool in pavement quality control.

4.2.5 Facilitate Data Collection at the Network Level in a PMS

Most of the other uses that have been mentioned relate to applications within the project level of a pavement management system (PMS). However, because the RDD gives quick, overall determinations of a pavement's structural capacity, it is also suited for use at the network level in a PMS. The RDD can be used in conjunction with the FWD at the network (and project) level in a two-stage sampling plan. Since the RDD is meant to assess the pavement's variability much more quickly and accurately than the FWD, but lacks the detail of the FWD, the two instruments could be used in conjunction in a sampling plan that could be part of the Texas Pavement Management Information System (PMIS).

In the first stage, the RDD would traverse the pavement section and identify the fields (a region where a relatively constant structural capacity exists for some length) that exist within the section. In addition, the RDD would locate areas where the pavement is severely deficient structurally. Then, in the second stage, the FWD could sample within each of these fields. The FWD's more detailed data could aid engineers in pinpointing the cause of structural problems, should any problems exist.

Several issues should be addressed in conjunction with this potential use for the RDD. First, the mobility of the RDD should be considered keeping time limitations in mind. Because of the vast size of the state of Texas, the locations of the sites for this two-stage sampling plan could span many miles. Therefore, pavement engineers would have to plan the logistics of this sampling to minimize the time spent traveling between pavement testing locations. In addition, as previously stated, the RDD can currently profile about 915 m (3,000 ft) at a time, as longer distances generate an excessively cumbersome amount of data. This limitation affects the time required to perform this two-stage sampling plan. However, future improvements made to the RDD's data collection system could substantially address this limitation.

4.2.6 Identification of Voids Under Rigid Pavements

Voids under a rigid pavement greatly increase the stresses that exist within loaded rigid pavements. Among other reasons, voids can occur as fine material in suspension is pumped out from under the concrete by the action of loads passing over the pavement. This leaves the concrete partially unsupported, thus increasing the stresses within the concrete that can lead to deterioration and to a premature loss of serviceability.

Because the RDD can effectively monitor a pavement's overall structural adequacy by continuous monitoring, it is well suited to identify the location, severity, and extent of voids under rigid pavements. With the RDD, engineers can simply profile a rigid pavement and observe increases in overall pavement flexibility (decreasing stiffness) at locations where the RDD passes over a void. Of course, other imperfections in the pavement (e.g., joints, cracking, low layer moduli) will cause changes in the RDD response. Therefore, it is important that engineers have the ability to relate changes in a pavement's flexibility with the actual location on the pavement where these changes in response occur. This will aid engineers in determining the cause of the increase in the pavement's flexibility. With a distance measuring mechanism, engineers can relate the RDD's output to actual positions on the pavement with greater accuracy. Recent modifications to the RDD have included the addition of a distance measuring mechanism.

It is important also to note that the RDD alone cannot determine the cause of a pavement's increased flexibility. The RDD provides information only on location, severity, and extent of changes in structural response. The determination of the cause of structural deficiencies is a separate investigation.

In addition, when trying to detect voids, engineers using the RDD must consider the tradeoff that exists between speed and precision. When operating at high speeds, a pavement's flexibility is averaged over greater distances than when operating at low speeds, in order to obtain the continuous profile of pavement flexibility. As such, with higher speeds, the precision of the flexibility measurements decreases and voids that only encompass small areas may not show up as large increases in flexibility (as they should). Therefore, prior to conducting a field survey to monitor the location, severity, and extent of voids within a rigid pavement, engineers should select an RDD speed appropriate to their particular needs within the project. Currently, the RDD operates at maximum speeds of about 3–5 km/hr (2–3 mph).

4.3 FORENSIC STUDIES

4.3.1 Forensic Investigations

Since the RDD produces a continuous reading of pavement flexibility, it can lend itself to forensic investigations by helping to determine whether a pavement's loss of serviceability results from a loss of structural adequacy. Many factors can cause a pavement to lose serviceability. Unfortunately, most of these factors also result in an increase in pavement flexibility. As such, detecting a high flexibility with the RDD will not determine the exact cause of the pavement's loss of serviceability.

However, several situations exist where a reduction in a pavement's serviceability isn't necessarily caused by a reduction in the pavement's overall structural capacity. For instance, severe cracking of a thin asphalt surface layer increases the distress of a pavement and, subsequently, causes the pavement's serviceability to drop. However, since the thin asphalt layer does not carry much of the load, the pavement's overall structural capacity isn't affected to a great extent by the distress at the surface. In this type of situation, pavement engineers can use the RDD to observe whether or not the location of the surface distress correlates with a loss of flexibility. In this manner, within a forensic study engineers can determine whether the cause of the surface distress is independent of the pavement's structural adequacy.

Once again, engineers should use proper judgment before deploying the RDD in this situation. The use of the RDD in performing a forensic investigation on a cracked pavement should be limited to those cracked pavements that can withstand the RDD's minimum load and the contact pressures existing beneath the RDD's loading wheels without excessive damage occurring to the pavement. Reducing the RDD's current minimum static load from its present value of approximately 67 kN (15 kip) is a modification worthy of future research. This modification would allow engineers to perform forensic studies of this nature on a larger number of pavements.

4.3.2 Potential for Early Detection of Cracks in Bases (or other Subsurface Layers)

At pavement locations where cracking in bases is suspected, the RDD can be used as a tool to assess the overall structural adequacy of the pavement in question. Since the RDD gives a continuous reading of a pavement's overall flexibility, it is capable of detecting changes in a pavement's structural capacity owing to factors that aren't readily observable by simply looking at the pavement surface. Obviously, detecting an increase in flexibility in a pavement having no visible defects at the surface doesn't necessarily mean that cracking within the base caused this increased flexibility. However, if one suspects that cracking within the base of a pavement has occurred at a certain location, one can use the RDD to confirm that a reduction in structural adequacy has occurred at this location. This will aid in identifying pavement locations where more detailed investigations are warranted to determine the exact cause of the pavement's reduced structural adequacy. In addition, the RDD can aid in determining the severity and extent of this reduced structural adequacy.

Again, since the cracking that occurs in the base of a pavement will reduce a pavement's ability to resist loads, prior to using the RDD engineers should take steps to ensure that the minimum loading of the RDD will not cause excessive damage to the pavement. Factors that should be considered include the pressure that exists under the RDD's loading wheels, the estimated thicknesses of the pavement's respective layers, and the estimated moduli of the pavement's respective layers.

4.3.3 Location of Areas of Stripped Asphalt Pavement

Stripping of asphalt concrete within a pavement is a serious problem that, if not accounted for, leads to a serious reduction in a pavement's structural capacity. Stripping occurs in an asphalt concrete layer as moisture seeps into the layer, causing the asphalt and aggregate within the asphalt concrete to separate from one another. As a result, an asphalt concrete layer that is assumed to have a modulus of elasticity of about 6,890,000 kPa (1,000 ksi) may actually have a modulus of only about 344,500 kPa (50 ksi) as a result of stripping [Ref. 16]. Stripping occurs often in overlaid rigid pavements, as water from the subbase seeps through the joints and cracks in the concrete slab and reacts with the asphalt concrete.

The RDD's ability to continuously profile a pavement's flexibility can be used by pavement engineers to profile pavements where stripping is suspected. The areas of the overlaid pavement that have been stripped will yield higher flexibilities than pavement locations not affected by stripping. This information will be helpful to pavement managers who need to know a pavement's existing structural capacity in order to decide whether to overlay a pavement or perform more serious rehabilitation. If a stripped pavement is thought to have a relatively high asphalt concrete modulus, an overlay may be used to maintain the pavement. However, this overlay will not last as long as anticipated because the overlay will lie over a weak unbound layer, not over a bound asphalt concrete layer that provides substantial support.

Owing to the fact that the RDD is currently used only to monitor a pavement's overall flexibility, engineers cannot use the RDD to identify the layer or layers within a pavement structure that cause the pavement to be structurally deficient. Therefore, if the RDD's flexibility reading increases while profiling a pavement where stripping is suspected, engineers will not know whether stripping or some other defect caused the increased flexibility. However, recent modifications to the RDD have provided the RDD with multiple sensors and, thus, greater potential to identify deficient layer(s) within a pavement structure through future research. In addition, even with only one reading of the pavement's overall flexibility, the RDD can give engineers the specific locations of pavement sections that require further investigation to identify areas of stripping. Then, other techniques may be used to determine the exact cause of the pavement's increased flexibility.

4.4 LOAD-ZONING STUDIES

4.4.1 Evaluation of Existing Routes for Possible Load-Zoning

One of the advantages of the RDD is its ability to apply a range of loads to a pavement. By applying heavy loads to pavements, the RDD is capable of loading pavements into their nonlinear stress-strain regions. This was demonstrated at the Texas Transportation Institute (TTI) testing facility. At a given pavement location at the TTI testing facility, the RDD calculated a higher pavement flexibility when larger loads were applied to the pavement [Ref. 2]. This indicates that the pavement was stressed into its nonlinear region by the larger loads and, thus, produced more strain per unit stress.

With multiple runs of the RDD using different loads, the RDD should be able to determine where a pavement begins to act in a nonlinear fashion. Thus, the RDD can theoretically be used to evaluate existing pavements for possible load-zoning. The RDD can test pavements that are candidates for load-zoning by determining the stress levels at which they behave nonlinearly. If these stress levels are sufficiently small, such that they are often encountered at existing traffic levels, then serious consideration should be given to load-zoning the pavement.

Currently, the RDD is not equipped for automated load-zoning studies, though this has been considered for the future. Consequently, the RDD is currently capable only of providing information regarding the location of pavement sections where nonlinear behavior occurs owing to existing loading levels. Through future research, the possibility exists for analyzing this information to determine the reliability with which the pavement can handle typical traffic loads and extra-heavy loads. This might be accomplished by creating an algorithm that will determine the maximum number of loading repetitions per year that the pavement can safely withstand at a certain reliability for a number of different, commonly occurring axle loads. With these modifications, the RDD could evaluate existing routes for possible load-zoning even more effectively than it can at present.

4.4.2 Assess Damage after Extra-Heavy Loads Are Applied to Pavements

Related to the concept of load-zoning is the assessment of how much damage extra-heavy loads impart to a pavement. Since the RDD is capable of applying extra-heavy loads to a pavement and of subsequently measuring the resulting pavement flexibility, it is capable of determining the extent of a pavement's nonlinear response to a load. At light loads a pavement's flexibility is expected to remain relatively constant as it behaves in a linear elastic fashion. However, with extra-heavy loads, the pavement's flexibility increases because its displacement per unit of force is larger in the nonlinear region. As such, extra-heavy loads "yield" a pavement, causing an increase in the pavement's RDD flexibility reading.

With the RDD, one can apply a known extra-heavy load to a pavement and monitor how much the pavement's flexibility reading increases compared with its original flexibility reading (in the linear elastic region). Specifically, this may be accomplished by profiling a load-zoned road candidate with the RDD in two different areas, such as the wheelpath of the lane that carries the extra-heavy loads (the right or "slow" lane) and the center of the lane that carries the lighter loads (the left or "fast" lane). The more the pavement's flexibility reading has increased as a result of the extra-heavy loads that have been applied by the existing traffic, the more the pavement has yielded and the greater the damage to the pavement. By making a comparison of the flexibility readings from these two areas, one can assess whether or not the damage resulting from the extra-heavy loads is great enough to warrant load-zoning the pavement. This methodology can be used to assess potential and/or existing routes for extra-heavy vehicles within Texas.

Obviously, the FWD can be used in a similar analysis by monitoring the deflection bowls that result from FWD drops in the two areas of pavement mentioned previously. However, unlike the RDD, the FWD cannot thoroughly capture the variability in the pavement's flexibility readings that may exist over the length of the road section in question. In addition, the RDD is better equipped to apply heavy loads to a pavement.

Unlike the FWD, however, the RDD cannot currently give a deflection (or flexibility) reading directly under the load. This information is more useful than deflection readings away from the loads, because this direct measurement is less prone to error than measurements taken away from the load. Engineers should consider the pros and cons of the various devices when deciding which is most appropriate for this type of load-zoning study.

4.4.3 Assess Predetermined Routes for Extra-Heavy Loads

The use of predetermined routes that carry extra-heavy loads relies on the assumption that these routes can withstand extra-heavy loads without an excessive loss of structural adequacy. The pavements along these routes should be able to carry extra-heavy loads without being stressed into the nonlinear elastic region of their stress-strain curves.

The RDD is capable of testing the existing routes that carry extra-heavy loads to determine the loading levels that stress the pavements into their nonlinear elastic region. By comparing this loading level with the existing loading level from the extra-heavy loads, the RDD tells engineers whether the pavement actually has adequate structural capacity to withstand these extra-heavy loads.

Alternatively, engineers could load the pavements with loads lighter than the existing extra-heavy loads and then subsequently load the pavements at levels equal to the existing extra-heavy loads. If a substantial increase in pavement flexibility is noted as the extra-heavy load is applied, then the existing extra-heavy loads force the pavement into its nonlinear elastic range, precipitating a substantial loss in the pavement's serviceability.

In addition, the overall structural adequacy of these pavements can be monitored over time with the RDD. In this way, the RDD gives engineers an idea of how soon maintenance or rehabilitation must be performed on these pavements, and whether the design of these pavements must be changed in the future to better withstand the extra-heavy loads. As stated previously, the FWD could be used to perform similar analyses. In deciding between the two devices, one must weigh the information gained through the RDD's ability to quickly account for the pavement's variability against the FWD's ability to monitor the deflection occurring directly under the load.

4.5 EXAMINATION OF JOINT BEHAVIOR

4.5.1 Identify Joints of Overlaid Rigid Pavements

Over the past year, the RDD has been used to evaluate the rigid pavements at Dallas-Ft. Worth (DFW) International Airport. The results of these tests show that the RDD gives very clear indications of the locations of joints within a rigid pavement. At joint locations, the RDD's reading of flexibility increases. Although the RDD hasn't been tested in this capacity yet, one would imagine that the RDD could very easily be used to identify the location of overlaid joints existing in an overlaid rigid pavement. With the knowledge of the location of overlaid rigid joints, pavement engineers can then determine whether cracking that subsequently occurs in overlaid pavements is a result of these joints (reflection cracking), or whether the cracking is due to other factors, such as inadequate asphalt overlay design, thermal cracking, or moisture. This type of analysis may also prove useful within forensic studies.

As mentioned previously, the tradeoff between the RDD's speed and the precision with which it generates its continuous profile of flexibility is an issue that engineers must tackle before conducting field studies with the RDD. When monitoring a pavement for overlaid joints, the RDD will probably have to travel at relatively low speeds (3–5 km/hr or 2–3 mph) in order to safely avoid "missing" the joint by averaging the pavement's flexibility over too large a distance. However, the RDD still has a clear advantage over other field testing devices in detecting overlaid joints in terms of speed because of its ability to continuously profile a pavement. With the FWD, for instance, engineers have no way of determining where to perform their various FWD drops on the overlaid pavement and can only hope to uncover the location of the overlaid joint(s) without spending too much time and money. Again, the RDD sidesteps this problem through its ability to continuously profile pavements.

4.5.2 Assess Load Transfer at Joints in Existing Pavements

The concept of load transfer at joints within a rigid pavement is important from the standpoint of maintaining the pavement's serviceability. Load transfer is needed to effectively distribute shear stresses from loads across joints. As such, good load transfer is needed to ensure that high stress concentrations do not build up on one side of a joint when a load is applied near a joint. High stresses within a rigid pavement cause premature cracking, which in turn leads to a loss of serviceability.

The RDD can be used to assess the ability of a joint to transfer loads in a number of ways. First, the RDD may be operated using a single sensor to compare the relative efficiencies among joints. This may be accomplished by comparing the flexibility readings at various joints traversed by the RDD. In a limiting case, with perfect load transfer, the RDD would not detect a substantial change in a pavement's flexibility as it traversed a joint. However, because joints are discontinuities in a pavement and cannot transfer moments, there must be an increase in the pavement's flexibility at joint locations. Given the previous two statements, one can use the RDD to compare the effectiveness of the load transferring capabilities among joints by profiling the joints with the RDD and monitoring the resulting increases in pavement flexibility at the joints. Joints yielding higher values of flexibility demonstrate lower load transfer capabilities than joints yielding lower values of flexibility. Of course, the attributes of the pavement structure must also be considered when comparing the flexibility values, as joints within thicker pavements will inherently yield lower flexibilities than joints within thinner pavements.

This type of a study was performed at DFW Airport by profiling with the RDD in a longitudinal direction and monitoring the relative performance of the transverse joints along the RDD's path. This testing produced good results (high signal-to-noise ratios with the measurements) as the RDD traveled at a speed of only about 0.4 m/s (0.8 mph).

Once again, the RDD's precision is controlled in part by the speed at which the RDD traverses the pavement. With faster speeds, less precise measurements of pavement flexibility are possible. Therefore, in order to ensure fair comparisons between the load transferring capabilities of various joints, the RDD's speed should remain relatively slow while profiling joints for comparative studies. In addition, the RDD should travel at a fixed speed when traversing all the joints that will be included in the comparison, to ensure that the comparisons aren't biased. Although the RDD must travel at a relatively slow fixed speed in order to make meaningful comparisons between the performance of various joints, it again has the ability to continuously profile a pavement. Thus, the RDD saves time because it requires less set-up time than other evaluation tools that are placed down, used to test the pavement, picked up and moved to the next location, and placed down once again.

Load transferring capabilities can also be assessed with the RDD through the use of multiple sensors. As shown in Figure 4.1, the RDD's current sensor configuration allows for four sensor locations. The exact location of these sensors can be adjusted to cater to the specific situation at hand.

By profiling along a joint in the manner shown in Figure 4.1, the RDD can continuously evaluate joint performance. Sensor A should always detect a smaller deflection created by the loading wheels than sensor C, because it is located at the same distance from the loads as sensor C, but it is across a discontinuity from the loads. Thus, even with perfect shear transfer performed by the joint, no moment will be transferred across the joint, resulting in smaller deflections. With smaller deflection readings, sensor A should indicate lower pavement flexibilities than sensor C. By dividing sensor A's flexibility reading by sensor C's flexibility reading, an assessment of how well the joint transfers the load is created. This quotient will always be a number between 0 and 1. The closer the quotient is to 1, the more effectively the joint transfers shear. This quotient can be continuously monitored along the length of the joint to assess the joint's performance.

4.5.3 Evaluate Joints for Repair or Replacement

Since the RDD is capable of assessing the load transferring capabilities of joints within a pavement, it may also prove useful as a tool for prioritizing the repair or replacement of joints. As previously mentioned, the overall flexibility of a pavement increases at joint locations. By profiling the joints within a pavement, the RDD can quickly determine how much the pavement's overall flexibility increases as it passes over each joint. By making comparisons between the relative flexibilities that the RDD calculates at each joint for a given pavement structure, one can establish criteria to evaluate the joint's performance in terms of the overall flexibility reading given by the RDD. From there, criteria can be established by which joints having a flexibility higher than a particular flexibility will be targeted for repair or replacement.

Once again, in determining the criteria to evaluate a joint's performance in terms of its increase in flexibility relative to other joints, a fixed speed probably no faster than 3–5 km/hr (2–3 mph) should be used. This ensures that the comparisons are all based on measurements of the same precision, which ensures that the comparisons aren't biased. Also, direct comparisons should be limited to joints within pavements of similar thicknesses, as thicker pavements will inherently have lower flexibilities than thinner pavements.

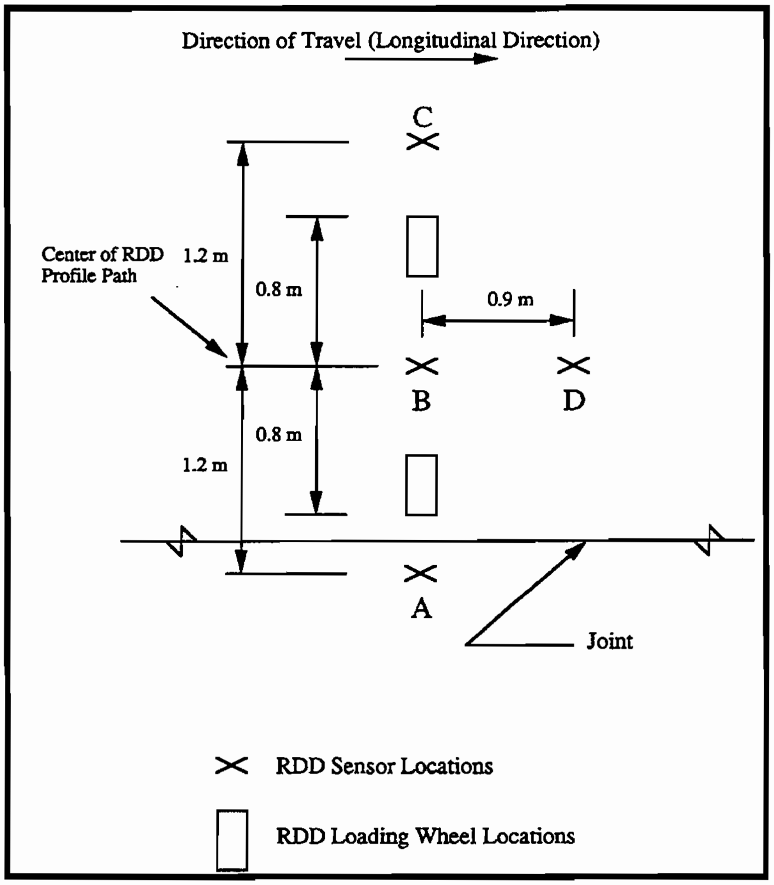

Figure 4.1 RDD dual load and sensor scheme to continuously monitor joint performance

4.6 MISCELLANEOUS

4.6.1 Determination of Depth to Bedrock

With its ability to determine the resonant frequency within a pavement structure, the RDD has the capability of estimating the depth to bedrock for a pavement structure. This information is helpful because linear elastic theory can be used with the depth-to-bedrock estimate to backcalculate estimates for the layer moduli. With more accurate estimates of depth to bedrock, more accurate estimates of layer moduli can be backcalculated using linear elastic theory. Currently, engineers can also use the FWD to obtain estimates of the depth to bedrock. The RDD performs in a manner similar to the FWD in that it obtains estimates for depth to bedrock at discrete points along a pavement, not continuously. Therefore, although the FWD is a more established tool for estimating the depth to bedrock, the RDD provides engineers with an alternative to the FWD, should a need arise.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The initial phase of this project, which included an extensive literature review and much discussion of pavement structural evaluation with other researchers, uncovered no device that is fully capable of providing a continuous deflection profile. Evaluation of the RDD to date suggests that it has much potential and that its continued development is worth pursuing. The RDD can be a useful new tool for assessing the structural capacity of pavements. Its greatest asset is its ability to continuously monitor pavement deflection and, thus, to provide extensive information about the variability of structural capacity. The traveling speed of the prototype device (3-5 km/hr [2-3 mph]) is not as high as can hopefully be developed in subsequent production models. However, it does make it possible to collect up to 32 km (20 miles) of continuous pavement profile in a working day, and this represents productivity greater than available with fixed, stopped deflection measuring devices.

In summary, the authors conclude that while much work remains to be done to refine the various aspects of the RDD, it has strong potential for becoming an effective tool for pavement structural evaluation and could provide capabilities not available with existing measurement devices. We further conclude that additional work to speed up the process, to add additional sensors, and to continue its development is warranted.

5.2 RECOMMENDATIONS

1. It is recommended that work continue on the testing and development of the RDD. Some of this work is currently underway and, while outside the scope of this report, will be described in subsequent project reports.
2. It is recommended that efforts continue to improve the onboard data processing to reduce the quantity of data processing necessary in the office.
3. It is recommended that work continue to speed up the operation of the RDD, which is also associated with the speed at which data can be processed.
4. It is recommended that the RDD be tested in the field on various pavement types and that side-by-side comparisons be made between the RDD and the FWD for various pavement types and locations. It would be useful to compare variability and cost associated with the two types of deflection measuring devices. It would also be useful to get better estimates of the quantity of pavement that can be covered in a given working day in terms of equipment productivity.
5. It is recommended that an effort be made to reduce the minimum static load that the RDD applies to the pavement. Initial tests on flexible pavement showed some minor marking of the pavement surface owing to high static loads on the small load wheel. Reduced minimum loads and associated contact pressures would reduce the possibility of damaging weak pavements during the testing process.
6. Finally, based on the literature review and on preliminary field tests, it is recommended that work continue on improving and testing the RDD for its application to pavement management.

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