NCHRP SYNTHESIS 381

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Falling Weight Deflectometer Usage

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Falling Weight Deflectometer Usage

A Synthesis of Highway Practice

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SUBJECT AREAS

Pavement Design, Management and Performance, and Materials and Construction

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Donna Vlasak
Senior Program Officer
Transportation
Research Board

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

This synthesis reports on the state of the practice of falling weight deflectometer (FWD) usage as it involves state departments of transportation (DOTs) using these devices to measure pavement deflections in response to a stationary dynamic load, similar to a passing wheel load. The data obtained are used to evaluate the structural capacity of pavements for research, design, rehabilitation, and pavement management practices. It is anticipated that this synthesis will provide useful information to support guidelines, advancing the state of the practice for state DOTs and other FWD users, as well as equipment manufacturers and other involved in pavement research, design, rehabilitation, and management. Based on a survey conducted for this report, 45 state highway agencies (SHAs) reported using 82 FWDs, produced by 3 different manufacturers. The importance of FWDs among SHAs appears to be reflected in the survey results, as it was noted that SHAs conduct FWD tests on up to 24 100 lane-km (15,000 lane-miles) annually.

Survey information presented in this report is supplemented by an extensive literature search, as well as communication with FWD calibration centers and FWD manufacturers. Individual SHA websites were also searched. Although current practice was limited to the United States, research published internationally was considered for historical context and for potential future research topics. A series of case studies share lessons learned from utilizing FWDs.

Sirous Alavi, Sierra Transportation Engineers, Reno, Nevada, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

FALLING WEIGHT DEFLECTOMETER USAGE

SUMMARY

Falling weight deflectometers (FWDs) have been in use since the 1980s. These devices are used to measure pavement deflections in response to a stationary dynamic load, similar to a passing wheel load. The data obtained are used to evaluate the structural capacity of pavements for research, design, rehabilitation, and pavement management purposes. The number of FWDs in use and the importance of their role in pavement engineering practice are expected to rise as agencies move toward mechanistically based pavement design. The interpretation of FWD data is a key method for estimating the in situ moduli of pavement layer materials.

This synthesis of highway practice for FWD use will provide information needed to support guidelines for advancing the state of the practice. Information for this synthesis was gathered in the following four phases:

- Literature search and review
- Survey of state highway agency (SHA) representatives
- Communication with calibration center operators
- Communication with FWD manufacturers

The literature review was conducted from several sources. TRB maintains the Transportation Research Information Services (TRIS) database, which contains bibliographical information from transportation-related research in the United States. Further information was found through the International Transport Research Documentation (ITRD) database. Individual SHA websites were searched for FWD usage information. The proceedings of the FWD User's Group meetings provided supplementary information to the synthesis. Published research articles, such as a pooled-fund study related to FWD calibration, were used as resources. Established guidebooks for FWD usage, such as the *Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements* and the Florida Department of Transportation's (DOT's) *Falling Weight Deflectometer Handbook* provided sensor spacings, load levels, and other useful data. In addition, the standards published in the *Annual Book of ASTM Standards*, procedures published by AASHTO, and articles in the *Transportation Research Record* provided valuable procedural descriptions.

The bulk of synthesis information was gathered by means of a survey. Survey invitations were sent to FWD administrators in each of the 50 SHAs in the United States. Forty-five of those 50 invitees responded, for a response rate of 90%.

The following observations were made based on survey data and literature research:

- SHAs are currently using 82 FWDs.
- Most SHAs are currently following FWD guidelines of their own creation rather than the Long-Term Pavement Performance guidelines.
- Although most SHAs do not have written FWD maintenance plans, maintenance activities are being performed.

- The 1994 Strategic Highway Research Program (SHRP)/LTPP FWD reference calibration procedure has been replaced by a newly developed 2007 FHWA calibration procedure that has been adopted by calibration centers.
- Of SHAs surveyed, 55% review a written equipment inspection checklist before departing for testing and the same percentage follows a written warm-up procedure.
- Despite accident prevention measures such as traffic controls, 29% of survey respondents reported accidents occurring within the past 5 years.
- The survey indicated that 89% of survey respondents keep raw FWD field data for more than 5 years and 84% keep these data indefinitely.
- Among SHAs with an FWD program, an average of 2,194 lane-km (1,363 lane-mi)—with a median of 644 lane-km (400 lane-mi)—are tested annually. Additionally, 187 full-time employees work for these programs.
- From the survey results, the responding SHAs' expenditures varied widely (from no program to $850,000 annually) for their FWD programs.

CHAPTER ONE

INTRODUCTION

PURPOSE

Falling weight deflectometers (FWDs) have been in use since the 1980s. These devices are used to measure pavement deflections in response to a stationary dynamic load, similar to a passing wheel load. The data obtained are used to evaluate the structural capacity of pavements for research, design, rehabilitation, and pavement management purposes. Based on a survey conducted for this synthesis, 45 state highway agencies (SHAs) reported using 82 FWDs produced by three different manufacturers (Appendix B, Questions 2–6). Ninety percent of all SHAs responded to this synthesis survey. Responding agencies are listed in Table 1. The number of FWDs in use and the importance of their role in pavement engineering practice are expected to increase as agencies move toward mechanistically based pavement design. The interpretation of FWD data is a key method for estimating the in situ moduli of pavement layer materials.

The importance of FWDs among SHAs was reflected in survey results. SHAs conduct FWD tests on up to 24,100 lane-km (15,000 lane-mi) annually (Appendix B, Question

TABLE 1
RESPONDING STATE HIGHWAY AGENCIES

State	Responding Agency
Alabama	Alabama Department of Transportation
Alaska	Alaska Department of Transportation and Public Facilities
Arizona	Arizona Department of Transportation
Arkansas	Arkansas Highway and Transportation Department
California	California Department of Transportation
Colorado	Colorado Department of Transportation
Connecticut*	Connecticut Department of Transportation
Florida	Florida Department of Transportation
Hawaii	Hawaii Department of Transportation
Idaho	Idaho Transportation Department
Illinois	Illinois Department of Transportation
Indiana	Indiana Department of Transportation
Iowa	Iowa Department of Transportation
Kansas	Kansas Department of Transportation
Kentucky*	Kentucky Transportation Cabinet
Louisiana	Louisiana Department of Transportation
Maine	Maine Department of Transportation
Maryland	Maryland State Highway Administration
Michigan	Michigan Department of Transportation
Minnesota	Minnesota Department of Transportation
Mississippi	Mississippi Department of Transportation
Missouri	Missouri Department of Transportation
Montana	Montana Department of Transportation
Nebraska	Nebraska Department of Roads
New Hampshire*	New Hampshire Department of Transportation
New Jersey	New Jersey Department of Transportation
New Mexico	New Mexico Department Of Transportation
New York	New York State Department of Transportation
North Carolina	North Carolina Department of Transportation
North Dakota	North Dakota Department of Transportation
Ohio	Ohio Department of Transportation
Oregon	Oregon Department of Transportation
Pennsylvania	Pennsylvania Department of Transportation
Rhode Island	Rhode Island Department of Transportation
South Carolina	South Carolina Department of Transportation
South Dakota	South Dakota Department of Transportation
Tennessee	Tennessee Department of Transportation
Texas	Texas Department of Transportation
Utah	Utah Department of Transportation
Vermont	Vermont Department of Transportation
Virginia	Virginia Department of Transportation
Washington	Washington State Department of Transportation
West Virginia	West Virginia Department of Transportation
Wisconsin	Wisconsin Department of Transportation

*Responded by stating that the agency does not have an FWD program.

87). Similarly, survey respondents noted its usefulness as a structural section design aid; FWD data was cited as a pavement rehabilitation strategy decision criterion in five states (Indiana, Louisiana, Montana, Nevada, and Oregon) (Appendix B, Question 88).

Calibration protocols suitable for all FWDs currently sold in the United States (other than lightweight FWDs) were developed as part of the Long-Term Pavement Performance (LTPP) program and adopted by AASHTO. FWD calibration centers were established to provide service across the continental United States. These centers are currently located in Colorado, Minnesota, Pennsylvania, and Texas. Calibration center records suggest that many of the FWDs currently being used are not calibrated on a regular basis. Absent calibration, agencies have no way to be sure that their substantial investments are yielding meaningful results. Similarly, the knowledge and information exchange that takes place at annual meetings of the FWD User's Group (FWDUG) suggests that many aspects of FWD use and data application are inconsistent among owners and operators.

The purposes for collecting FWD data have a major influence on the highway agency practices. This synthesis of highway practice for FWD use provides information needed to support guidelines for advancing the state of the practice.

RESEARCH METHODOLOGY

Information for this synthesis was acquired by the following means:

- Literature search and review
- Survey of SHA representatives
- Communication with calibration center operators
- Communication with FWD manufacturers

Several sources were explored for the literature review including the Transportation Research Information Services (TRIS) database, which contains bibliographical information from transportation-related research in the United States; the International Transport Research Documentation (ITRD) database; And individual SHA websites that were searched for FWD usage information. The proceedings of the FWDUG meetings provided supplementary information to the synthesis. Published research articles, such as a pooled-fund study related to FWD calibration (Orr et al. 2007), were used as resources. Established guidebooks for FWD usage, such as the *Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements* (Schmalzer 2006) and the Florida DOT's *Falling Weight Deflectometer Handbook* (Holzschuher and Lee 2006) provided sensor spacings, load levels, and other useful data. In addition, the standards published in the *Annual Book of ASTM Standards*, procedures published by AASHTO, and articles in the *Transportation Research Record* provided valuable procedural descriptions.

The bulk of synthesis information was gathered by means of a survey. Invitations to take the survey were sent to FWD administrators in each of the 50 SHAs in the United States. Continuous communication with SHA representatives resulted in 45 of those 50 invitees responding; a response rate of 90%.

Administrators of the four LTPP FWD calibration centers (see Table 2) were asked about their FWD practices. Each calibration center provided logs of FWDs calibrated at their respective centers. Additionally, the calibration centers described their pricing, durations of calibration sessions, and training protocols.

Four manufacturers of FWDs, Carl Bro, Dynatest, JILS, and KUAB, were also contacted. All four provided detailed maintenance recommendations, product descriptions, descriptions of training services, and data collection and processing software information. The manufacturers described their sales in the United States, broken down by agency use.

SCOPE

This synthesis study was limited to FWD usage by SHAs within the United States. Although current practice was limited to the United States, research published internationally was considered for its historical context and potential

TABLE 2

SURVEYED LTPP FWD CALIBRATION CENTERS

Calibration Center Location	Administering State Highway Agency
Denver, Colorado	Colorado Department of Transportation
Maplewood, Minnesota	Minnesota Department of Transportation
Harrisburg, Pennsylvania	Pennsylvania Department of Transportation
College Station, Texas	Texas Department of Transportation

Note: Additional calibration centers are operated by the Indiana Department of Transportation (West Lafayette), Dynatest, Inc. (Starke, Florida), and Foundation Mechanics, Inc. (El Segundo, California).

future research topics. Because synthesis studies summarize current practices, most information reviewed was published after 1999; exceptions were made if more current information was not available. While searching for case studies among the research articles, the focus was on projects that used the FWD for a specific application.

ORGANIZATION OF REPORT

This synthesis report is organized into ten chapters. The balance of chapter one reviews the report's structure and defines key terms and phrases. The report structure is summarized with brief explanations of chapter content. Key terms are provided within the Definitions section. This chapter concludes by describing the survey that was completed by SHA representatives.

Chapter two describes FWD equipment. Although not intended to be a comprehensive, technical description, the general mechanism is explained. Additionally, this chapter briefly lists FWD manufacturers, models, and maintenance practices. The physical setup, including sensor spacings and nominal loads practiced by SHAs, is discussed.

Chapter three reviews calibration practices. Manufacturers' recommended calibration schedules, as well as other calibration schedules, are provided. Locations of calibration centers, calibration frequency, and related costs of calibration center operation are provided. This chapter relates costs incurred by SHAs related to FWD calibration.

Chapter four examines the collection, management, and storage of FWD data. Titles and vendors of FWD software are listed, along with the file formats they support. Field data quality control and quality assurance measures are described, along with each method's popularity. Test site protocols are also reviewed, including SHA operator safety and traffic control methods.

Chapter five describes analysis of FWD data by SHAs. The principles of back-calculation and forward calculation are briefly reviewed as are software packages for FWD data analysis.

Chapter six focuses on personnel training methods. Qualifications and certifications for new FWD operators and data analysts, as described by SHA survey respondents, are included. Additionally, training opportunities outside one's SHA, are described, such as the FWDUG and the National Highway Institute, are examined.

Chapter seven discusses FWD program administration, including the topics of budgeting, allocation, and staffing. This chapter briefly describes outsourcing requirements.

Chapter eight shares lessons learned from a series of case studies using FWDs.

Chapter nine discusses FWD-related research projects, which were either recently concluded or ongoing at the time of the preparation of this report.

Chapter ten concludes the synthesis with a summary of findings and suggestions for further study.

These chapters are followed by References, a bibliography, a list of abbreviations, and two appendices. Appendix A includes a copy of the print version of the survey questionnaire. Appendix B describes the survey results in tabular and graphical form.

DEFINITIONS

This section defines several key terms that pertain to FWD use and data analysis. These definitions are largely based on ASTM standards ("Standard Guide for General Pavement Deflection Measurements" 2005). Variations of these definitions may be found in literature published by AASHTO, FWD manufacturers, and researchers. Additional terms are defined within the context of their relevant sections.

Back-calculation: An iterative process by which pavement layer moduli, or other stiffness properties, are estimated from FWD deflection data. The process begins with a hypothesis of a given layer's modulus, which is repeatedly compared with the FWD's output using an iterative mathematical model. The iteration stops once a predetermined level of tolerance has been reached between subsequent calculated estimates.

Geophone: An electrical sensor that translates dynamic velocity into electrical voltage. Based on the principle of magnetic induction, these devices translate vibration information into an analog electrical signal. Because of their prevalence with FWDs, the terms "geophone" and "deflection sensor" are used interchangeably. For the sake of brevity, this report refers to the device as a "sensor."

Forward calculation: A noniterative process in which stresses, strains, and displacements are calculated from layer data and applied load.

Deflection basin: The bowl shape of the deformed pavement surface caused by a specialized load as depicted from the peak measurements of a series of deflection sensors placed at radial offsets from the center of the load plate ("Standard Guide for General Pavement Deflection Measurements" 2005).

Deflection basin test: A test with deflection sensors placed at various radial offsets from the center of the load plate. The test is used to record the shape of the deflection basin resulting from an applied pulse load. Information from this test can be used to estimate material properties for a given pavement structure ("Standard Guide for General Pavement Deflection Measurements" 2005).

Deflection sensors: An electronic device(s) capable of measuring the relative vertical movement of a pavement surface and mounted to reduce angular rotation with respect to its measuring axis at the expected movement. Such devices may include seismometers, velocity transducers (geophones), or accelerometers ("Standard Guide for General Pavement Deflection Measurements" 2005).

Load cells: Capable of accurately measuring the load that is applied to load plate and placed in a position to minimize the mass between the load cell and the pavement. The load cell shall be positioned in such a way that it does not restrict the ability to obtain deflection measurements under the center of the load plate. The load cell shall be water resistant and resistant to mechanical shocks from road impacts during testing or traveling ("Standard Guide for General Pavement Deflection Measurements" 2005).

Load plates: Capable of an even distribution of the load over the pavement surface for measurements on conventional roads and airfields or similar stiff pavements. The plate shall be suitably constructed to allow pavement surface deflection measurements at the center of the plate ("Standard Guide for General Pavement Deflection Measurements" 2005).

Load transfer test: A test, usually on portland cement concrete (PCC) pavement, with deflection sensors on both sides of a crack or joint in the pavement. The test is used to determine the ability of the pavement to transfer load from one side of the break to the other. Also, the load deflection data can be used to predict the existence of voids under the pavement ("Standard Guide for General Pavement Deflection Measurements" 2005).

Test location: "The point at which the center of the applied load or loads are located" ("Standard Guide for General Pavement Deflection Measurements" 2005).

CHAPTER TWO

FALLING WEIGHT DEFLECTOMETER EQUIPMENT

This chapter provides information on FWD ownership, types and configurations, manufacturers, and maintenance practices.

FALLING WEIGHT DEFLECTOMETER OWNERSHIP

The 45 SHAs that responded to the survey reported owning 82 FWDs. Most were manufactured by Dynatest, but Carl Bro, JILS, and KUAB were also represented. Table 3 summarizes SHA FWD ownership by manufacturer (Appendix B, Questions 2–6).

TABLE 3
QUANTITIES OF FWDS OWNED BY STATE HIGHWAY AGENCIES, BY MANUFACTURER

Manufacturer	Quantity of FWDs in Service (total)	Ages of FWDs (years, average)
Dynatest	61	14
JILS	15	6
KUAB	6	14
Carl Bro	0	Not applicable
Other	0	Not applicable
Total	82	11

FALLING WEIGHT DEFLECTOMETER TYPES AND CONFIGURATIONS

Falling Weight Deflectometer Components

The basic components of a FWD are defined by reference documents such as AASHTO and ASTM standards. For example, in ASTM D4694-96, the apparatus described is composed of the following ("Standard Guide for General Pavement Deflection Measurements" 2005, pp. 487–488):

- An impulse-generating device with a guide system. This device allows a variable weight to be dropped from a variable height.
- Loading plate, for uniform force distribution on the test layer. When the weight affects this plate, this loading plate ensures that the resulting force is applied perpendicularly to the test layer's surface.
- A load cell for measuring the actual applied impulse.
- One or more deflection sensors. (Note: Deflection basin tests require at least seven sensors.)
- A system for collecting, processing, and storing deflection data.

Recorder systems, discussed in Section 8 of ASTM D4694-96, should display and store load measurements with a 200 N (45 lbf) resolution. Such systems should display and store deflection measurements with ±1 μm (0.039 mil) or less of resolution.

Most of the FWDs used by SHAs are either towed by a vehicle or are built into a vehicle's cargo area. Figures 1 and 2 depict one of each such FWD.

FIGURE 1 Trailer-towed FWD (Courtesy: Carl Bro).

FIGURE 2 Vehicle-mounted FWD (Courtesy: Foundation Mechanics).

Sensor Spacing and Target Loads

The newest version of the LTPP FWD manual details physical setup, loads, test plans, error checks, software, and calibration protocols. Sensor spacings depend on the pavement surface being tested and the number of sensors on the FWD. For basin testing, the LTPP FWD manual (Schmalzer 2006) requires:

- 0, 203, 305, 457, 610, 914, 1,219, 1,524, and −305 mm (0, 8, 12, 18, 24, 36, 48, 60, and −12 in.) for nine-sensor FWDs.
- 0, 203, 305, 457, 610, 914, and 1,524 mm (0, 8, 12, 18, 24, 36, and 60 in.) for seven-sensor FWDs on flexible pavements.
- −305, 0, 305, 457, 610, 914, and 1,524 mm (−12, 0, 12, 18, 24, 36, and 60 in.) for seven-sensor FWDs on rigid pavements.

Additionally, target loads of 26.7, 40.0, 53.4, and 71.2 kN (6,000, 9,000, 12,000, and 16,000 lbf) ±10% are defined for LTPP pavement tests. Test locations are specified for PCC testing at joint approach, joint leave, and corners.

The Florida DOT (FDOT) publishes its own guidelines for FWD use. In addition to intradepartmental report requirements, the document gives FWD apparatus parameters, data analysis techniques, and crew requirements.

Other jurisdictions shared their sensor spacing and load methods in the survey. As the LTPP guidelines suggest, sensor spacing varies depending on test type and pavement surface. Most SHAs, however, follow FWD guidelines of their own creation rather than the LTPP guidelines. For example, FDOT follows LTPP guidelines for sensor spacing, but load levels differ. Additionally, rigid pavements are not tested; "the procedure used by FDOT to predict the embankment M_r is applicable only to flexible pavements . . . [if a request involves composite or rigid pavements] Limerock Bearing Ratio tests will be used in lieu of FWD tests" (Holzschuher and Lee 2006). Figure 3 gives the percentages of SHAs who developed their own spacing and load guidelines. Additionally, histograms of sensor spacings at the project level, at the network level, during research, and during other projects are provided in Appendix B.

FALLING WEIGHT DEFLECTOMETER MANUFACTURERS

Information from four FWD equipment manufacturers was gathered for this synthesis. Those manufacturers were Carl Bro; Dynatest; Foundation Mechanics, who offers FWD equipment through its JILS division; and KUAB. The following paragraphs describe each of those manufacturers' equipment and features based on the information gathered. Because of the ever-evolving technology, other equipment and additional features may be offered by FWD manufacturers.

Carl Bro

The Carl Bro Group, acquired by the Dutch consultancy Grontmij in August 2006, offers three types of FWD: trailer-mounted, vehicle-mounted, and portable FWDs.

The Carl Bro trailer-mounted FWD is the PRI2100. The FWD is mounted to the tow vehicle by a double-axle trailer. According to correspondence with Carl Bro, the mass

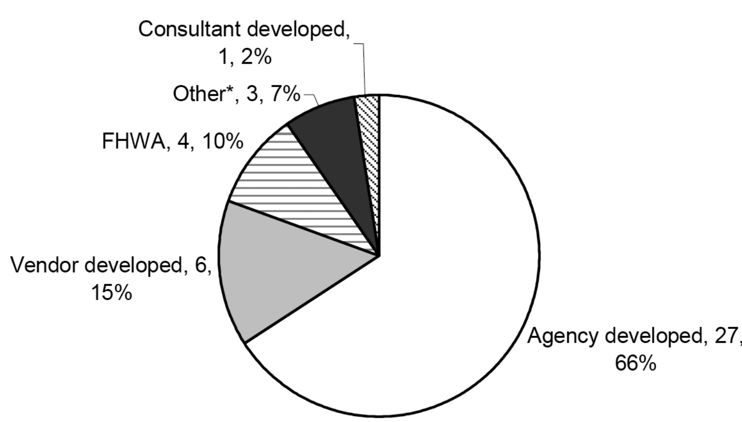


FIGURE 3 Survey response to Question 29, "What kind of flexible pavement field testing manual does your agency use?"

mechanism generates force magnitudes up to 250 kN (56,200 lbf). Carl Bro provides a laptop personal computer (PC) with software, which controls FWD operation and records distance measurement. The company supplies their "RoSy DESIGN" back-calculation software, but the FWD output may be used with other back-calculation packages. Three temperature sensors, nine deflection sensors, a four-split loading plate, a time history module, and warning lights are also supplied (Carl Bro 2006).

The vehicle-mounted Carl Bro PRI2100 is integrated into a van. Otherwise, it is identical to the trailer-mounted PRI2100. The company recommends the vehicle-mounted FWD to reduce "mobilization time" and safety risks associated with trailers.

The PRIMA 100 by Carl Bro is a portable FWD. This device is designed to be carried by one person, with no need for a tow vehicle. Included with the PRIMA 100 are 100 and 300 mm (4 and 12 in.) loading plates and a 10 kg (22 lb) mass. Data are collected onto a personal digital assistant or laptop through a direct cable or Bluetooth wireless connection. A single load cell and up to two additional deflection sensors are supported. The device is powered by four AA-size batteries.

Dynatest

The Dynatest Group of Denmark, the United States, and the United Kingdom manufactured 59 of the 81 FWDs used by survey respondents. In addition to FWD equipment, Dynatest provides FHWA-compliant FWD calibrations at its Starke, Florida, facility. Dynatest's FWDs are either trailer- or vehicle-mounted.

Based on information provided by Dynatest, the Model 8000E FWD supports drop masses from 50 to 350 kg (110 to 770 lb). The resulting applied force thereby ranges from 7 to 120 kN (1,500 to 27,000 lbf). The company supplies loading plates of diameters 305 mm (12 in.) and 450 mm (18 in.), and a segmented loading plate 305 mm (12 in.) in diameter is available for separate purchase. The system supports from 7 to 15 deflection sensors. Additionally, Dynatest supplies a laptop PC with FWD monitoring software. The system's Pavement Deflection Data Exchange (PDDX)-formatted FWD output is compatible with Dynatest's Elmod back-calculation software package.

The Dynatest Model 8081 applies heavier loads than the Model 8000E. Capable of 30 to 240 kN (6,744 to 53,954 lbf) impact loads, the Model 8081 supports load masses between 200 and 700 kg (441 and 1,543 lb). Features and specifications are otherwise similar to the lighter-weight Model 8000E. Similar to Model 8000E, model 8081 outputs to PDDX format.

Foundation Mechanics, Inc.

Based in California, Foundation Mechanics, Inc., sells FWDs under its JILS nameplate. Fifteen of the 81 FWDs used by survey respondents were manufactured by JILS. The company provides FHWA-compliant calibration services at its El Segundo, California, facility. JILS offers trailer-mounted and vehicle-mounted FWDs.

JILS' trailer-mounted FWD is the JILS-20. This FWD includes a 305 mm (12 in.) loading plate, distance measurer, video monitoring system, and temperature measurement hardware. JILS provides a separate gasoline engine for the FWD hydraulic system, allowing for independent vehicle and FWD operation. Up to ten deflection sensors are supported. The company provides a laptop, which includes their JTEST FWD monitoring software. FWD data are output in raw data format, but they can be converted to PDDX format ("JILS, Falling Weight Deflectometers: JILS 20" 2007).

For heavier loads, the company offers the JILS-20HF. While supporting heavier drop loads, the features and specifications are otherwise similar to the JILS-20 ("JILS, Falling Weight Deflectometers: JILS 20HF" 2007).

The company's vehicle-mounted FWD, the JILS-20T, is otherwise identical to the trailer-mounted JILS-20. JILS provides a Ford F350 pickup with dual rear wheels as the carrying vehicle ("JILS, Falling Weight Deflectometers: JILS 20T" 2007).

KUAB

Engineering and Research International, Inc., based in Savoy, Illinois, sells trailer-mounted and vehicle-mounted FWDs under its KUAB nameplate. The company offers FWD repair and calibration services.

According to information provided by KUAB, four models are sold under the KUAB name. All four models support up to seven deflection sensors. The company supplies a 300 mm (12 in.) load plate, which is available either segmented or solid. Additionally, an aluminum cover, automatic ambient temperature sensors, surface temperature sensor, distance measurers, and a laptop are all included. The company provides three days of training to operators. The models are differentiated by their loading capacities and installation types. The KUAB 50, for example, offers a load range from 12 to 50 kN (2,698 to 11,240 lbf). This model is only available as a trailer-mounted FWD. The KUAB 120, conversely, adds a 450 mm (18 in.) solid or segmented load plate and has a load range from 7 to 120 kN (1,574 to 26,977 lbf). The KUAB 150 brings possible loads from 12 to 150 kN (2,698 to 33,721 lbf), and the KUAB 240 supports loads from 20 to 240 kN (4,496 to 53,954 lbf). Furthermore, the KUAB 120, KUAB 150, and KUAB 240 are available as single-axle trailer-mounted FWDs or as vehicle-mounted FWDs.

MAINTENANCE PRACTICES

Most SHAs perform regular maintenance on their FWD equipment and their tow vehicles. These maintenance activities are separate from calibration and can include mechanical lubrication, replacement of consumable parts, leak repair, cleaning, and other activities that keep the mechanical devices in working order.

State Highway Agency Falling Weight Deflectometer Maintenance

Although most SHAs do not have a written FWD maintenance plan (Appendix B, Question 7), maintenance activities are performed by SHA personnel. FWD equipment and tow vehicle maintenance is performed by SHA employees among 87% of survey respondents (Appendix B, Questions 9–10). Seventeen percent of SHAs reported that they follow the manufacturer's guidelines for regular maintenance. Those who did not follow the manufacturer's guidelines usually stated that maintenance activities are done when needed. Twenty-five agencies (listed in Appendix B, Question 11) provided other suggestions on keeping their FWD equipment in working order, including the following (Appendix B, Questions 8 and 11):

- Cleaning the sensors and holders with an emery cloth
- Storing FWD equipment and vehicles in a heated garage when not in use
- Bleeding hydraulic lines annually
- Following a brief maintenance checklist before departing for a job
- Including maintenance activities when FWDs are calibrated
- Giving operators an ownership stake in the FWD equipment they operate
- Overhauling the equipment when needed

A few SHAs reported that their FWDs have not yet needed "significant maintenance."

Manufacturers' Recommendations

FWD equipment manufacturers generally follow LTPP guidelines for equipment maintenance and offer maintenance services on the equipment they sell. For example, Carl Bro supplies a comprehensive maintenance list to its clients, which breaks down maintenance activities by individual FWD component. In their preventative maintenance checklist, Dynatest recommends that brake operation, hand brake pump, load plate lubrication, tires, and belts be inspected on a daily basis; their FWD equipment checklist is summarized in Table 4.

In addition to providing JILS-FWD maintenance services, Foundation Mechanics, Inc.'s maintenance personnel are able to log into their clients' JILS-FWD computers over the Internet to review files and perform diagnostic tests.

KUAB offers a preventative maintenance program as an option with their FWDs, which includes cleaning, inspection, and calibration. The procedures typically take between three and four weeks to complete and are done by KUAB personnel at their Savoy, Illinois, facility.

Merits of Falling Weight Deflectometer Versus Other Nondestructive Testing Devices

The Missouri DOT (MoDOT) detailed the merits of FWD usage in an undersealing study. Before employing FWDs to detect voids, MoDOT used to test load transfer efficiency (LTE) by the "proof-rolling method." A dump truck was filled to give a rear-axle load of 80 kN (18,000 lbf), and its

TABLE 4

DYNATEST RECOMMENDED MAINTENANCE ACTIVITIES AND FREQUENCIES

Frequency	Activities
Daily, or as required	Check brake operation, check hand brake pump for free movement, check load plate for lubrication, clean clamping magnets/disks/springs.
Weekly	Tire pressure (approx. 32 psi), lug nuts tight (75–90 ft-lb), check breakaway feature (actuator), check brake lock operation, inner catch parts lubricated with Teflon, external weight guides lubricated with Teflon, lubricate SD foam guides with silicone spray, check/refill battery level, clean infrared/air sensors.
Monthly	Check brake fluid level (DOT type 3 only), check rubber stabilizers for tightness, nuts and bolts tight, R/L cable checked for bends/breaks, check deflector holders—tips tight, clean sensor cables with soapy water only, check charging system connections, coat terminals with corrosion inhibitor, check hydraulic fluid level, clean/inspect electronic connections, perform relative calibration, wash equipment.
Annually	Change hydraulic fluid, change hydraulic fluid filter, perform reference calibration.

Source: DYNATEST.

rear tire was placed 1 ft past a transverse joint between two slabs. Gauges then gave the deflections generated by the load on each slab. When measured, LTE is less than 65% and loaded side deflections were greater than 0.44 mm (17.5 mils), the slab was undersealed. FWDs are preferred over the proof-rolling method, for the following reasons (Donahue 2004):

- Less manpower is required.
- Lanes are closed for less time.
- "No influence of shoulder movement to apparatus."
- Dynamic FWD impulse loads provide a more realistic simulation of truck movements.
- Multiple load levels are possible.

CHAPTER THREE

FALLING WEIGHT DEFLECTOMETER CALIBRATION

This chapter discusses FWD calibration practices and recommendations. If FWDs are not calibrated, the consequences can be financially significant. According to a study by the Indiana DOT (INDOT) (Yigong and Nantung 2006), overestimating a deflection by 0.0254 mm (1 mil) resulted in 26% more undersealing area. This error resulted in $20,000 in unnecessary drilling and $29,000 in additional asphaltic materials. By simulating a 0.0508 mm (2 mil) deflection overestimate, $37,000 of additional drilling and $54,000 of additional asphaltic materials were deemed necessary, although they were actually unwarranted. Similar trends were observed on an asphalt concrete (AC) overlay project; additional deflections of 0.0254 mm (1 mil) led to additional $11,187.50 per lane-km ($17,900 per lane-mi) for asphaltic materials, and 0.0508 mm (2 mil) errors led to $23,625 per lane-km ($37,800 per lane-mi) of additional materials. Conversely, underestimated deflections led to significantly reduced pavement design life. Underestimating deflections by 0.0254 mm (1 mil) translated to an AC layer 25.4 mm (1 in.) thinner than needed, resulting in a decrease of 2.8 million equivalent single axle load of pavement life.

CALIBRATION TYPES

Relative

Relative calibrations ascertain sensor functionality and relative accuracy. All sensors should produce the same output when in the same position at the same site location ("Standard Test Method for Deflections . . ." 2005). To achieve this, SHAs typically perform relative calibrations once per month (Appendix B, Question 15). A monthly relative calibration is also recommended by LTPP (Schmalzer 2006). Relative calibrations can be performed at any location, in situations in which pavement layers are adequately strong. For example, 44% of survey respondents stated that they perform relative calibrations on a "calibration pad," a specially designed PCC floor, and 33% stated that relative calibrations are done on an "in-service pavement" (Appendix B, Question 16).

Reference

These calibrations are done at specially designed calibration centers. Reference calibrations aim to ensure sensor accuracy according to defined benchmarks. Occasionally, sensors are calibrated individually, but a new reference calibration procedure allows multiple sensors to be calibrated simultaneously. SHAs typically perform reference calibrations once per year (Appendix B, Question 14). An annual reference calibration is also recommended by LTPP (Schmalzer 2006).

CALIBRATION PROCEDURES

Relative

Differences between FWD models, sensor manufacturers, and available technology have led to several relative calibration methods.

According to a survey conducted for this synthesis, 55% of SHAs use a relative calibration procedure developed by Strategic Highway Research Program (SHRP)/LTPP. This procedure is detailed in the *Long-Term Pavement Performance Program FWD Reference and Relative Calibration Manual* (Schmalzer 2006).

Conversely, 35% of respondents said they follow their FWD vendor's relative calibration procedure. If the vendor is Dynatest or JILS, then the LTPP procedure is being followed. According to information provided by KUAB, they recommend that their clients in the United States follow the LTPP procedure and that their Swedish clients follow the Swedish Road Administration (SRA) method. The SRA method places all of the FWD's sensors into a holder and subjects them to five consecutive drops. Calibration is successful if the largest and smallest measured deflections differ by no more than 2 µm (0.0787 mils) plus 1% of the measured value.

Section 7.3.1 of ASTM D4694-96 describes a relative calibration procedure, which uses a vertical sensor holding tower. In a manner similar to the SRA method, five deflections must be measured per sensor, and if they differ by no more than 0.3% from the average deflection then no correction is required. Section 7.3.2 recommends repeating the procedure some distance away from the load plate so that "if any differences in average deflection greater than 2 µm (0.08 mils) are found, the device should be repaired and recalibrated according to the manufacturer's recommendations" ("Standard Test Method for Deflections . . ." 2005).

Reference

Reference calibrations, per LTPP, must be performed at a specialized facility. A pooled fund study was commissioned by the FHWA in 2004 to improve the reference calibration process. Improvement to the original 1994 SHRP reference calibration procedure was needed for the following reasons (Orr et al. 2007):

- The 1994 procedure was designed around Dynatest and KUAB FWDs, the only commercially available FWDs in the United States at the time. Because of differences between FWD manufacturers, the original procedure was not completely compatible with equipment from other manufacturers.
- The 1994 procedure required individual sensor calibration, and took six hours to complete as a result.
- The 1994 procedure used a linear variable displacement transducers (LVDT) for reference deflections, the accuracy of which was occasionally compromised by movement of the mass and beam to which it was mounted. Accelerometers were viable replacements for LVDTs, because they are self-referencing.
- The 1994 procedure used DOS-based software. DOS is no longer the state-of-the-art PC operating system.

The new procedure addresses each of the pooled fund study's points. Universal compatibility is achieved through modified triggering mechanisms. Time is saved by placing all FWD sensors into a single support stand and calibrating them simultaneously. New accelerometer-based control board and data acquisition systems were designed. A new program, WinFWDCal, was written in Microsoft Visual Basic to provide a graphical user interface (GUI) for calibration. Calibration is recommended once per year, but it takes only about two hours to complete (Orr et al. 2007).

By 2006, the updated FWD calibration procedure included an FWD calibration results database, conversions were made to the DOS-based FWDCAL software to work with Microsoft Windows, and software was adapted to work with accelerometers and modern data acquisition boards. Additionally, WinFWDCal was augmented with a utility to convert FWD file formats from the different equipment types to the PDDX format adopted by AASHTO. For sensor calibration, a single support stand was designed so that sensor position was not significant. With such a support stand, all of an FWD's sensors may be tested simultaneously, as opposed to the one-sensor-at-a-time calibration method put forth by the 1994 procedure. The finalized calibration procedure is discussed in a draft final report (Irwin 2006).

Independent of the FHWA-pooled fund study, another calibration procedure was developed at the University of Texas at El Paso (UTEP). With the support of the Texas DOT (TxDOT), UTEP developed a new calibration protocol for TxDOT's FWD fleet. Because TxDOT's FWD units are of varying ages, one FWD may produce differing results than another. To provide better reproducibility, a three-phase calibration plan was created. These phases are as follows (Rocha et al. 2003):

- Physical inspection and component replacement
- Preliminary calibration—a relative calibration is performed and sensors not passing calibration are identified
- Comprehensive calibration—sensors not passing calibration are calibrated more thoroughly and data-gathering issues are troubleshot

These new protocols greatly improved consistency from one FWD to another, and the researchers recommended that "TxDOT implement the new protocol as soon as possible." Section 7 of ASTM D4694-96 acknowledges the UTEP method, which is "more complementary than interchangeable" with the SHRP/LTPP method ("Standard Test Method for Deflections . . ." 2005).

Portable Falling Weight Deflectometer Calibration

Carl Bro's PRIMA 100 PFWD was designed to mimic their existing PRI 2100 trailer-mounted FWD. The design employs three geophones, compared with PRI 2100's nine geophones. Because both models use the same geophones, calibrating the PFWD's geophones uses an identical procedure to the PRI 2100. A time-history system serves as the backbone of Carl Bro's calibration software, which uses a fast Fourier transformation algorithm. Carl Bro calibration equipment employs a test cell connected to an LVDT, and the procedure is verified by means of the SHRP 1994 protocol (Clemen 2003).

CALIBRATION REQUIREMENTS

Calibration Frequencies

For calibration, ASTM D4695-03 recommends that impulse-loading type devices be calibrated "at least once per year using the procedure in Appendix A of SHRP Report SHRP-P-661" for reference calibration and "relative calibration once a month during operation" ("Standard Guide for General Pavement Deflection Measurements" 2005). Additionally, Section 7 of ASTM D4694-96 recommends that deflection sensors be calibrated "at least once a month or in accordance with the manufacturer's recommendations" ("Standard Test Method for Deflections . . ." 2005).

According to the LTPP manual, reference calibration is required once per year, unless the FWD is based in Alaska, Hawaii, or Puerto Rico. Similar requirements are detailed for Georgia (*Pavement Design Manual* 2005) and Florida, which also require that "manuals describing the relative calibration procedure and other aspects of deflection testing should be kept in the vehicle and office" (Holzschuher and Lee 2006). Relative calibrations are required either monthly, if the FWD sees regular usage, or within 42 days of any given data collection operation. Checklists are given for before transit, before operations, and after operations (Schmalzer 2006).

Travel Distances and Costs Associated with Calibration

Because relative calibrations can be performed on any surface where pavement layers are adequately strong, travel distances tend to be short. According to survey data, 52% of SHAs travel 0.62 km (1 mi) or less to a relative calibration site. Additionally, relative calibrations tended to be inexpensive. The same survey showed that 52% of respondents spend less than $100 per relative calibration (Appendix B, Question 19).

Reference calibrations, on the other hand, involve significant expenditures of travel time and money. Because most states require reference calibration once per year at one of the FHWA-certified calibration centers—four LTPP centers, one privately operated by Dynatest, and one privately operated by JILS—57% of survey respondents reported that they travel 805 km (500 mi) or further for their reference calibrations. Similarly, 64% of survey respondents reported that, including total labor, materials, travel, and other incidental expenses, a single reference calibration costs more than $1,000.

CALIBRATION CENTERS

To implement the 1994 calibration procedure, LTPP opened four calibration centers. Currently, those centers are operated by the DOTs in Colorado, Minnesota, Pennsylvania, and Texas. Additionally, the privately operated Dynatest calibration center in Florida and JILS calibration center in California provide calibration services. These calibration centers have since put the 2007 FHWA calibration process into practice. At the Texas calibration center, the TxDOT method can also be used. On average, the Texas and Pennsylvania DOT calibration centers see about 30 FWDs per year, the Colorado calibration center sees about 20, and the Minnesota calibration center sees about 8. None of the calibration centers charge SHAs for calibration services; however, the Colorado, Pennsylvania, and Texas centers charge at least $300 per session to private firms.

Training requirements differ slightly from one calibration center to another. For example, Pennsylvania calibration center technicians are trained by Cornell University and are certified by MACTEC. Minnesota, on the other hand, has not implemented an in-house training program as of the date of this report, but it plans to do so in the future.

Sixty-three percent of survey respondents support the construction of additional calibration centers; however, 76% of survey respondents stated that they are not willing to sponsor such a calibration center (Appendix B, Questions 20–21).

CHAPTER FOUR

DATA COLLECTION, MANAGEMENT, AND STORAGE

This chapter covers FWD operations including data collection, management, and storage.

DATA COLLECTION GUIDELINES

SHAs collect FWD data on a variety of public facilities. Several SHAs contribute FWD data to other state departments, especially in situations in which geotechnical data are needed. Most frequently, state highways are tested; all survey respondents whose states have FWD programs reported testing on SHA highways. Approximately 40% of respondents reported testing city streets and 27% reported performing tests on airport runways (Appendix B, Question 23).

Data collection locations largely depend on the pavement surface type and what sort of data the agency wishes to obtain. On flexible pavements, 91% of survey respondents stated that the right-wheel path is tested. The left-wheel path was tested only by 21% of survey respondents and lane centers by 30%. Lane geometry is dominated by outer lanes in locations where multiple lanes are present, as 63% of survey respondents stated. Inner lanes were tested by 21% of respondents. On rigid pavements, responses were similar to those of flexible pavements. The right-wheel path (56%) and outer lane (40%) were the most prevalent locations to perform FWD tests on rigid pavements. Additionally, slab corners and edges were tested by 38% of respondents.

Preparation

Immediately before testing, the majority of SHAs reported some sort of preparation activity. Of the SHAs surveyed, 55% follow a written equipment inspection checklist before departing for testing and the same percentage follow a written warm-up procedure. Additionally, all testing guides (e.g., LTPP, ASTM, and TxDOT) require a clean surface on which the load plate and sensors should be placed. The ASTM D4695-03 standard, for example, requires that the test location "be free from all rocks and debris to ensure that the load plate . . . will be properly seated" ("Standard Guide for General Pavement Deflection Measurements" 2005).

Testing Procedures and Practices

The FHWA/LTPP program provides a manual for FWD measurements (Schmalzer 2006). In addition, ASTM's "Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device" (2005) covers deflection testing. Many agencies reported using testing protocols that were developed in-house. On flexible pavements, 66% of SHAs reported using agency-developed FWD guidelines (Appendix B, Question 29). Similarly, 29% of SHAs reported using their own FWD testing guidelines for rigid pavement testing (Appendix B, Question 40). The following are a few examples of how different agencies use their FWDs.

The Virginia DOT (VDOT) outlines its FWD testing practices in Test Method 68, "Non-Destructive Pavement Testing . . ." (2007). Tests are done "in accordance with ASTM 4694-96" and VDOT's "Project Evaluation and Pavement Design—Appendix A." On flexible pavements, the Test Method prescribes FWD testing "to assess the structural capacity of the pavement and estimate the strength of subgrade soils. In addition to the structural capacity, the elastic modulus for the surface, base, and subbase layers can be determined" ("Non-Destructive Pavement Testing . . ." 2007). Multilane roads are tested in the outside lane. Sampling is to be done based on 3.2 km (2 mi) intervals, and conducted "in the wheel path closest to the nearest shoulder" ("Non-Destructive Pavement Testing . . ." 2007). For basin testing on AC pavements, for example, the Test Method recommends 11 total drops:

- Two seating drops at 53 kN (12 kips)
- Three recorded drops at 27 kN (6 kips)
- Three recorded drops at 40 kN (9 kips)
- Three recorded drops at 71 kN (16 kips)

Temperature readings should be taken at the surface and at the surface layer's mid-depth.

For all pavement rehabilitation projects, the Idaho Transportation Department considers FWD data or *R*-values. Either may prove that a candidate design has a design life of at least eight years. Additionally, if a candidate design has a design life of more than eight years, and a modicum of additional material and costs would yield a 20-year design life, the 20-year design life is put forth (*Design Manual* 2007).

The Illinois DOT's (IDOT) Bureau of Materials and Physical Research (BMPR) performs FWD tests given the following information ("Pavement Technology Advisory . . ." 2005):

- Marked route
- Contract and section number (if available)
- Location map
- Pavement type and thickness (cores may be needed to verify thickness of pavement layers)
- Contact information for requesting agency and traffic control provider
- Type of investigation desired

If the investigation is for an overlay, agencies must also provide traffic data, design load, design period, and deadline date.

When the California DOT (Caltrans) evaluates a PCC pavement for rehabilitation, it considers replacing individual slabs. To determine whether slab replacement is a viable strategy, Caltrans suggests spacing FWD sensors at 300 mm (12 in.) increments from the load plate.

> In addition, the load transfer efficiency at joints and cracks, as well as the presence of voids at corners, can be evaluated quickly . . . NDT [nondestructive testing] alone cannot, however, completely identify which pavement component is responsible for weaknesses, or whether moisture-related problems exist. A pavement drainage survey and limited coring may also be required ("Slab Replacement Guidelines" 2004, p. 13).

Appendix D of the New Mexico DOT's "Infrastructure Design Directive" (Harris 2006, p. 28) provides the sensor spacings, location requirements, and testing procedures for FWD testing by the agency. The LTPP one year calibration requirement is met, but sensor spacing is unique to the state. Seven sensors should be placed at 0, 203, 305, 457, 610, 762, and 1,219 mm (0, 8, 12, 18, 24, 30, and 48 in.) from the center of the load plate. The load plate should have a 300 mm (12 in.) diameter. Successive measurements should be taken every 76 m (250 ft), using a 40 kN (9,000 lbf) load.

TxDOT explicitly specifies their FWD and FWD data recording system in their specification. Additional equipment, such as a distance measurer, PC, and flat-panel display are described. Elements of the TxDOT specification include the following (Imler 2002):

- Section 2.4. The system shall measure deflections with an absolute accuracy of better than 2% ±2 μm, and with a typical relative accuracy of 0.5% ±1 μm. The resolution of the equipment shall be 1 μm.
- Section 6.1.4. All PC units shall have a multi-boot system installed with boot options for MS-DOS 6.22 and Windows XP.
- Section 7.2.3. Data files shall be created for the FWD tests. The data files shall be composed of 80 character records. A data file shall contain test results and descriptive information by roadway and roadway section. File names for deflection data files shall be in the following specific format: DDPNNNNS.FWD
- The format shown is standard PC DOS format where:
  - DD = District number ranging from 1 to 25,
  - P = Roadway prefix,
  - NNNN = Roadway number ranging from 0001 to 9999, and
  - S = Roadway suffix.

Further details include payment method, acceptance, and warranty.

The Vermont Agency of Transportation (VTrans) uses data from FWD tests for pavement designs. For pavement rehabilitation projects, the VTrans guide lists FWD data along with traffic, climate, materials and soils properties, existing pavement condition, drainage, and safety data as useful inputs. FWD data are used to calculate SN_{eff} for flexible pavements and to calculate effective slab depth D_{eff} for rigid pavements. Data are collected at the following increments:

> [H]alf-mile [805 m] increments in the right wheel path. The opposing lane should be tested at alternating locations so that information is obtained at quarter-mile [0.4 km] increments. Multiple lane highways should be tested across the section to obtain representative information Pavement Design Guide . . . 2003, p. 7).

The Georgia DOT (GDOT) uses sensor spacings identical to the FHWA/LTPP manual for flexible pavements; however, they use a unique set of spacings on rigid pavements. The GDOT spacings are as follows (*Pavement Design Manual* 2005):

- Flexible: 0, 203, 304, 457, 610, 914, and 1,524 mm (0, 8, 12, 18, 24, 36, and 60 in.)
- Rigid and Composite: −304, 0, 304, 610, 914, 1,219, and 1,524 mm (−12, 0, 12, 24, 36, 48, and 60 in.)

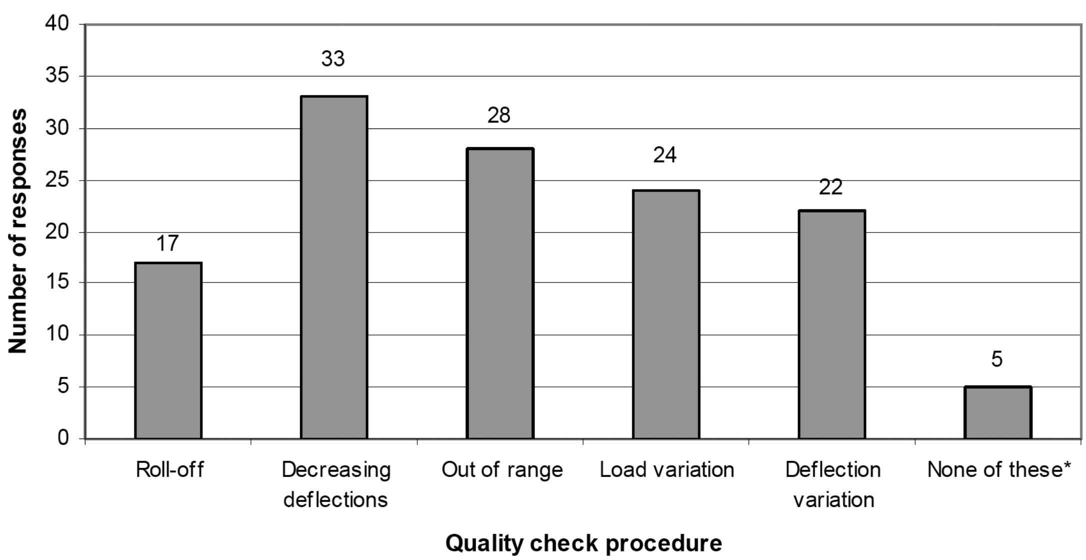
Test locations vary by job type. GDOT's mainline AC pavement testing is done in "the right lane, right wheel path. If there is extensive wheel path cracking then offsetting to the mid-lane path would be acceptable but should be noted." Twenty locations per 1.6 km (1 mi) should be tested in all travel directions. AC shoulders are tested at locations no more than 76 m (250 ft) apart "to help determine if the shoulders are structurally sufficient to carry travel lane traffic during construction." On rigid pavements, FWD tests are done to "determine overall stiffness, material properties, load transfer at the joints, and for void detection." On continuously reinforced concrete pavement (CRCP), tests are conducted in the centers of lanes. Distances between tests are left to engineering and statistical judgment. Testing at cracks on CRCP are done "at cracks that are spalled or have faulted" (*Pavement Design Manual* 2005). On jointed plain concrete (JPC), at least 12 tests should be done per directional kilometer (20 tests per directional mile). Additionally, tests on PCC slabs should be done only when the PCC surface temperature is between 10° and 27°C (50° and 81° F). Composite pavements (i.e., AC over PCC) are treated as rigid pavements where reflection cracks are present.

Field Data Quality Control and Quality Assurance

FWD data gathered in the field are subject to quality checks before being sent to the office for further processing. Five specific error-checking methods are defined by the *Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements* (Schmalzer 2006):

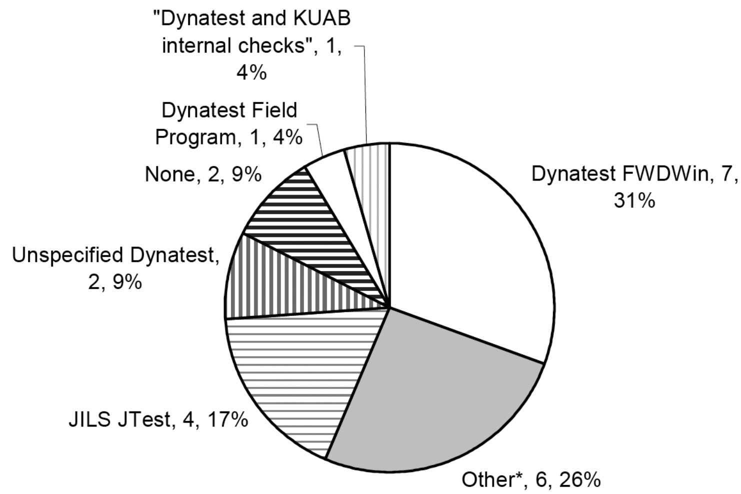
- Roll-off: occurs when a single deflection sensor fails to return to 0 within 60 ms of the weight being dropped.
- Nondecreasing deflections: occurs when deflections measured do not decrease as distance from the load cell increases.
- Overflow: occurs when a deflection sensor measures a deflection beyond its range. Also referred to as an "out-of-range" error.
- Load variation: occurs when the drop load varies by more than 0.18 kN (40.5 lbf) plus 2% of the average load.
- Deflection variation: occurs when the measured deflections from the same drop height vary by more than 2 µm (0.08 mils) plus 1% of the average deflection.

The survey of SHA representatives revealed how frequently these data checks are used. The results are shown in Figures 4 and 5.



* Includes respondents who specified that none of these checks are performed, and those respondents who have an FWD program and did not check any possible response.

FIGURE 4 Survey responses to question 55: "Which of the following data checks are performed by FWD operators?" (Check all that apply.)

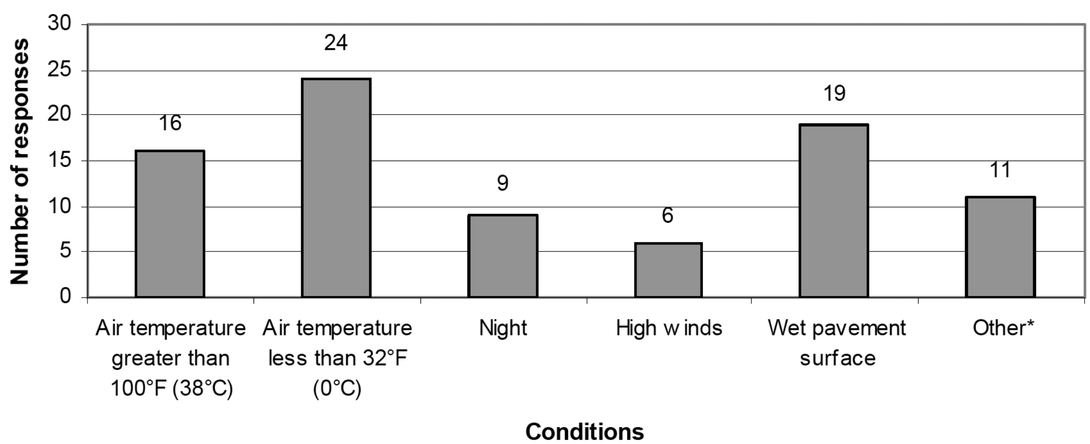


* Other responses: (2) "Dynatest" with no specific software title, (2) FVO, (1) text pad, (1) FHWA

FIGURE 5 Survey response to question 56: “What software is used to perform quality checks in the field?” Responses as reported by SHAs.

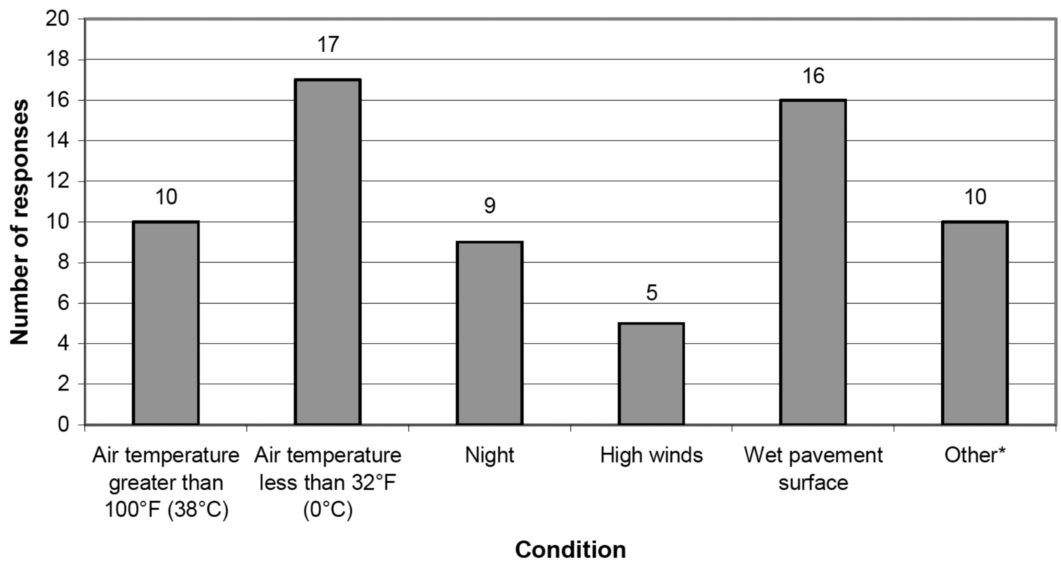
Worker Safety

With the goal of protecting workers and the safety of the motoring public, SHAs institute restrictions on FWD testing depending on environmental conditions. The survey results noting when FWD testing is prohibited are presented in Figure 6 for flexible pavement testing and in Figure 7 for rigid pavement testing.



* Other responses: (1) restricted visibility, (1) pavement distress cracks, (1) high traffic level, (1) safety issues, (1) frozen subgrade, (1) temperature low er than 45°F (7°C), (1) pavement temperature less than 45°F (0°C), (1) pavement temperature less than 40°F (4°C), (1) soil temperature less than 40°F (4°C), (1) subgrade temperature less than 32°F (0°C), (1) pavement temperature higher than 110°F (43°C).
Total responses: 43

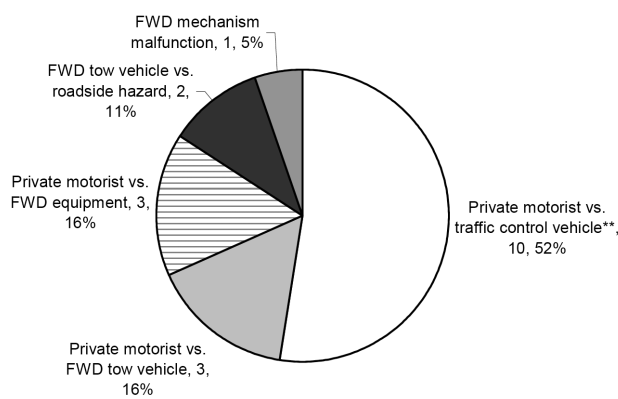
FIGURE 6 Survey responses to question 39: “Under which of these conditions is flexible pavement testing *not* allowed?” (Check all that apply.)



* Other responses: (2) pavement temperature greater than 80°F (27°C), (1) limited visibility, (1) subgrade temperature less than 32°F (0°C), (1) air temperature less than 45°F, (2) temperature greater than 70°F, (1) pavement temperature greater than 100°F (38°C), (1) safety factors.

FIGURE 7 Survey responses to question 50: "Under which of these conditions is rigid pavement testing *not* allowed?" (Check all that apply.)

Despite accident prevention measures such as traffic controls, 29% of survey respondents reported accidents occurring within the past five years. Of the 19 accidents reported, very few of these accidents involved injuries or fatalities. Details for the accidents are summarized in Figure 8.



* Across all accidents, 1 fatality and 2 injuries were reported. FWD crew members were not injured or killed during any of the accidents reported.
** All accidents in this category involved private motorists colliding with an attenuator.

FIGURE 8 Survey responses to question 80: "Please describe the type(s) and severity* of FWD related accidents within the past 5 years."

Recommendations were given for traffic control and flagger placement at the 2001 FWDUG meeting ("FWD: Past Meetings" 2001). Assuming a 3.2 km (2 mi) work zone on a two-lane road, two flaggers should be employed; each flagger should stand 61 m (200 ft) from the traffic-facing fenders of test vehicles (Heath 2001c). For FWD-specific operations, flaggers need only be 15 m (50 ft) away from an FWD vehicle (Heath 2001a). On bridge decks, tapered cones are placed 132 m (435 ft) from the FWD vehicle (Heath 2001b).

DATA MANAGEMENT

Falling Weight Deflectometer Field Data File Types

Although AASHTO recommends the PDDX data format for FWD output files, the survey revealed 12 distinct file formats in use. These formats are shown in Figure 9.

Because so many file formats are in use, analysis software may not be compatible with FWD output from all agencies. PDDX file conversion software, such as PDDX Convert, can be utilized to convert many file formats to PDDX (Orr et al. 2007).

Backups

The *Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements* (Schmalzer 2006) requires that users back up the test data in PDDX format on removable media. These backups should be made at the test site immediately after collection. These data should stay with the tow vehicle until received at the office, where they are uploaded and archived (Schmalzer 2006, p. 41).

In practice, SHAs are backing up data. Seventy-eight percent of SHAs surveyed reported that FWD data files are backed up to removable storage media, such as floppy discs, compact discs, or Universal Serial Bus (USB) flash drives (Appendix B, Question 62).

DATA STORAGE

FWD field data are potentially useful for future applications, especially as analysis technologies evolve. Notably, the survey indicated that 89% of survey respondents keep raw FWD field data for more than five years and 84% keep these data indefinitely (Appendix B, Question 63).

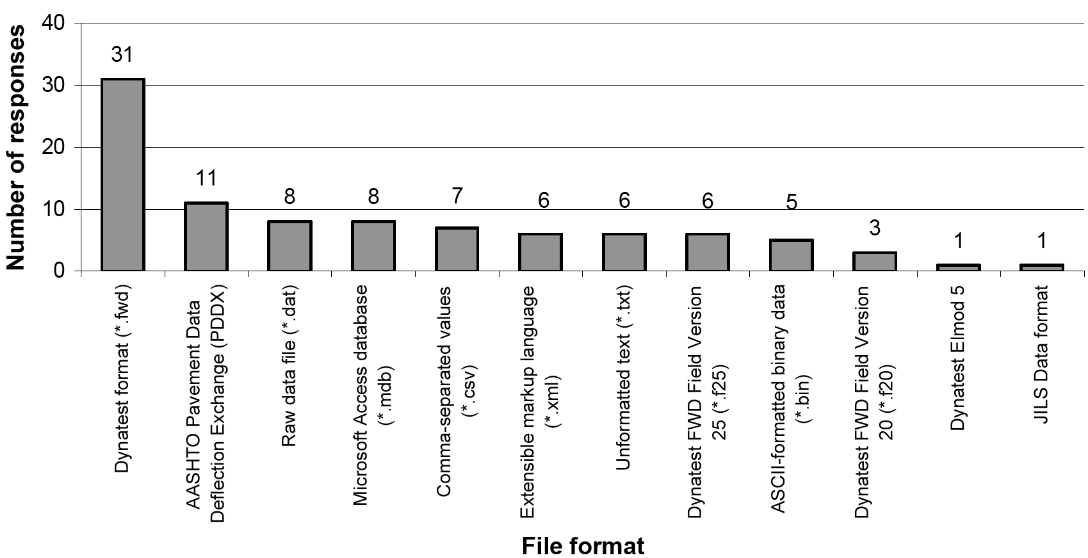


FIGURE 9 Survey response to question 53: "In which format does your FWD equipment give its output?" (Check all that apply.)

CHAPTER FIVE

DATA ANALYSIS

Once FWD data have been collected from the field, multiple analysis tools are available to the SHA. These software packages typically calculate pavement layer modulus, a material parameter that is essential for pavement layer design. According to survey data, 90% of SHAs use FWD data for pavement layer modulus estimation (Appendix B, Question 58). On JPC pavements, FWD data can be used to determine LTE by placing one sensor on one slab and a second sensor on a neighboring slab and determining how each slab moves when the weight is dropped. These data are analyzed with the help of computer software. FWD data analysis software may be provided by FWD vendors, academic institutions, or government bodies. This chapter briefly explores FWD data analysis methods and the software developed around them.

Data analysis tools are not necessarily compatible with data from FWD tests. Sources of incompatibility may be job type (e.g., parking lots vs. highways vs. airports), lack of compatible file formats between FWD models, or differing analysis software configurations. A 2001 study suggests fixing these issues by standardizing file formats among manufacturers, allowing data analysis software to vary test site stationing, and allowing quality controls such as the SLIC transform, nondecreasing deflections, and overflow checks (Schmalzer 2001).

DATA ANALYSIS METHODS

Back-calculation

The most common back-calculation method is an iterative mathematical process. The method assumes that a unique set of layer moduli result in the deflections measured by the FWD. The data analyst, based on experience and judgment, selects seed moduli to calculate deflections. These calculated deflections are compared with the output from the Bossinesq equations, or a two- or three-dimensional finite-element model. After the first calculation, the seed moduli are adjusted and the calculation is repeated. The iteration stops once a predetermined level of tolerance has been reached between the measured and calculated deflections. From this iteration, layer moduli are estimated.

Forward Calculation

Forward calculation is a process of using the equations of elastic layer theory to calculate stresses, strains, and deflections caused by surface loads at any point in a pavement system. Computer programs such as BISAR, CHEVLAY2, and ELSYM5 are used for forward calculation. The process is "forward" in the sense that it is closed form. By contrast, back-calculation uses forward calculation iteratively, together with numerical methods to assist with convergence, to "back out" the pavement layer moduli from measured surface deflections.

Hogg and DELMAT Methods

Hogg (Stubstad et al. 2006) and DELMAT (Hossain 2006) methods have been used as checks and balances for backcalculated data. As an example, Florida uses the Hogg model and has shown reasonable agreement with backcalculated moduli for asphalt and subgrade layers.

Load Transfer Efficiency

Adjacent JPC slabs should move together when a load is applied to one of them; faulting can result if they do not. The degree to which adjacent slabs move together is defined as LTE. LTE is calculated from FWD deflections by placing the load cell on one PCC slab and then placing a sensor on an adjacent unloaded slab. When the weight is dropped, the measured deflections are used to calculate LTE with Eq. (1),

$$LTE = \frac{D_{unloaded}}{D_{loaded}} \times 100\% \qquad (1)$$

where D_{unloaded} represents the deflection of the unloaded PCC slab, and D_{loaded} represents the deflection of the loaded PCC slab (Pierce et al. 2003).

The work done by Gawedzinski (2005) for IDOT provides a comprehensive example of load transfer analysis and contains a discussion of the state of the practice for LTE.

Quality Control/Quality Assurance of Analyzed Data

The *Long-Term Pavement Performance Program Manual for Falling Weight Deflectometer Measurements* (Schmalzer 2006) lists the software data checks required. These data checks are discussed in greater detail in chapter four:

- Roll-off
- Nondecreasing deflections
- Overflow
- Load variation—set to ±18 kN + 0.02X (±4,000 lbf + 0.02X), where X represents successive drop loads
- Deflection variation—set to ±2µm + 0.01X (±0.0787 mils + 0.01X), where X represents successive measured deflections

FWD data should be processed onsite using FWDConvert and FWDScan (Schmalzer 2006). Once at the office for processing, the data are subjected to a variety of software and correction algorithms.

Other Findings

In the early 1960s, California began measuring pavement deflections using a device of its own design. Known as the California Traveling Deflectometer, the device exerted a simulated 80 kN (18,000 lbf) single-axle force, while a Benkelman Beam measured the resulting deflections. This unique device is a fundamental standard by which California compares all other nondestructive pavement deflection testing devices. While using the Caltrans flexible pavement rehabilitation design method, deflections are correlated to the California Deflectometer. Additionally, FWD data are correlated to a standardized reference FWD load, FWD_{ref}, which transmits a 40 kN (9,000 lbf) load to a loading plate 305 mm (12 in.) in diameter. The correlation function is illustrated in Eq. (2),

$$D(CD) = 1.2D\left(FWD_{ref}\right) \qquad (2)$$

where $D(CD)$ is the California Deflectometer equivalent deflection and $D(FWD_{ref})$ represents deflections measured by the reference FWD. Additionally, any FWDs must possess a valid calibration certificate issued by an FWD calibration center ("California Test 356 . . ." 2004).

DATA ANALYSIS SOFTWARE

FWD manufacturers bundle their own software with the FWDs they sell, but each software package is available for separate purchase. The following sections describe the various software packages available.

AASHTO DARWin

Used by 21% of survey respondents (Appendix B, Question 59), DARWin automates the processes in the 1993 *AASHTO Guide for the Design of Pavement Structures*. Version 3.1, the most recent version, is designed for 32-bit versions of Windows operating systems. Back-calculation is based on a mathematical iteration. As inputs, the program accepts Dynatest version 20, KUAB, and PDDX files, but it cannot use Dynatest version 25 files ("AASHTOWare DARWin Product Features" 2005).

Carl Bro RoSy DESIGN for Roads

Based on a fast Fourier transformation algorithm, Carl Bro's RoSy DESIGN software calculates pavement layer stresses and strains in a 32-bit Windows environment. Additionally, RoSy DESIGN is able to link backcalculated data to a geospatial database. The program is compatible with "data from any FWD equipment" ("Carl Bro RoSy DESIGN Product Data Sheet" 2006). Despite its availability with all Carl Bro FWDs, no SHAs reported using RoSy DESIGN (Appendix B, Question 59).

Dynatest ELMOD

A plurality of SHAs surveyed reported that Dynatest's ELMOD (an acronym for Evaluation of Layer Moduli and Overlay Design) is their FWD analysis package of choice. Used by 21% of survey respondents, ELMOD is currently at version five. Back-calculation is based on a mathematical iteration, and the user may choose between the finite-element, linear elastic theory or a nonlinear subgrade algorithm by means of add-ons. The program operates in a 32-bit Windows environment. ELMOD 5 is able to read Dynatest versions 9, 10, 20, and 25 files, as well as Microsoft Access database files generated by Dynatest WinFWD.

KUAB ERIDA

For FWD data analysis, KUAB provides the ERIDA software package. KUAB's pavement analysis software is compatible with Dynatest FWD equipment ("Pavement Analysis Software" 2003). The program supports KUAB's FWD format, Unicode text files, and PDDX files. Despite its compatibility and possible bundling with KUAB FWDs, no SHAs reported using ERIDA for data analysis (Appendix B, Question 59).

MODCOMP

Currently in version 6, MODCOMP was reported as the data analysis package of choice by two SHAs. The program supports linear and nonlinear modeling criteria (Stubstad et al. 2000). MODCOMP is freely available and was developed by

Cornell University. It is designed to work in a command line environment under DOS (Schmalzer et al. 2007).

Virginia Department of Transportation ModTag

VDOT added a GUI to MODCOMP. The resulting program, ModTag, is currently in its third major revision. The program operates in a 32-bit Windows environment, but the calculation methods are identical to MODCOMP. ModTag incorporates several data quality assurance measures, including the SLIC transform.

Texas Transportation Institute MODULUS

The Texas Transportation Institute, a collaborative facility operated by Texas A&M University and the TxDOT, developed the graphical FWD data analysis package MODULUS. Among survey respondents, 14% reported MODULUS as their data analysis package of choice. MODULUS is currently at version six (Liu and Scullion 2001). The program operates in a 32-bit Windows environment. Back-calculation techniques are based on the linear elastic model. The program reads Dynatest FWD files and is freely available (Schmalzer et al. 2007).

EVERCALC

Developed by the Washington State DOT (WSDOT), EVERCALC was reported by 15% of survey respondents as their primary FWD data analysis package. Version 5.0, the most recent version, operates in a 32-bit Windows environment. Back-calculation techniques are based on the linear elastic model. As inputs, EVERCALC accepts Dynatest versions 20 and 25 FWD output files. The program is freely available.

SLIC Transform

SLIC is an algorithm for finding errors in FWD data. The algorithm compensates for misplaced sensors and other data issues by applying a logarithmic normalization. The SLIC algorithm can easily be added to FWD field software such as VDOT's ModTag and WSDOT's FWD AREA (Stubstad 2006).

During the development of the Asphalt Layer Condition Assessment Program pavement layer condition software, the program's outputs were compared with MODULUS 5.1 at two locations. Both programs accept raw FWD data, including sensor spacing, as inputs. Unlike MODULUS, however, this program applies the SLIC method to screen out invalid data (Xu et al. 2003).

Other Software Packages

Fourteen percent of survey respondents reported using in-house developed software packages for their FWD data analysis.

CalBack

Caltrans, the University of California at Berkeley, and the University of California at Davis are developing a Java-based back-calculation software package. CalBack, currently at version 0.9, provides a GUI to linear elastic model calculations. The program accepts raw FWD data from JILS and Dynatest FWDs and operates in a 32-bit Windows environment (*CalBack Manual* 2006).

Falling Weight Deflectometer AREA

WSDOT developed FWD AREA, a software program that takes Dynatest FWD Field Program output files, sensor offsets, pavement material type, temperature correction factor, plate radius, and geographic information as inputs. Using these inputs, FWD AREA calculates load deflections, deflections normalized to the 40 kN (9,000 lbf) reference FWD, loading area, and deflections normalized for temperature. FWD AREA can display the deflection data in plots of deflection versus sensor spacing ("Falling Weight Deflectometer" 2007).

Microsoft Excel

The FDOT FWD handbook describes data analysis in the office using Microsoft Excel. It provides proprietary macros for forward estimation and "Greenbar" forms, as well as milepost versus deflection tables (Holzschuher and Lee 2006).

ANALYSIS OUTPUT FILE TYPES

Data analysis output files are a function of the analysis software that creates them. From the literature review and survey, little relevant information was found. CalBack and ModTag explicitly show a button labeled "Export to Excel" (*CalBack Manual* 2006).

CHAPTER SIX

PERSONNEL TRAINING

For FWD data to be useful to pavement designers, it must be collected properly. Without proper training between FWD operators, data analysts, and pavement designers, miscommunications may result. Furthermore, training prevents minor mechanical difficulties from becoming major operational obstacles. In this chapter, training of FWD operators and data analysts is discussed.

QUALIFICATIONS

Falling Weight Deflectometer Operators Qualifications

When asked about their FWD operator training practices, 66% of SHAs responded that they provide training to new FWD operators. When asked about training duration, 37% of survey respondents stated that before a newly hired FWD operator is on the job, one month or less is devoted to training. Conversely, 30% gave training intervals of from 4 to 6 months. On elaboration, 33% of SHAs explicitly stated that training is provided on the job. Additionally, three states—Nevada, North Carolina, and South Carolina—require new operators to demonstrate proficiency, either by successfully completing data-gathering operations under supervision or by passing a test (Appendix B, Questions 64–68).

SHA operator training may be complemented or substituted with vendor-provided training. The purchase of an FWD from any of the four manufacturers includes a training session. Durations and content of training sessions are summarized in Table 5.

Although some localities have unique needs, certain skill sets are universally desirable for FWD operators. According to Martin (2006), these skill sets are as follows:

- Equipment setup and operation familiarity,

TABLE 5

FWD VENDOR-PROVIDED OPERATOR TRAINING SUMMARY

FWD Vendor	Training Duration	Concepts Covered	Certificate Available?
Carl Bro	5 days	Included with purchase of new FWD equipment	Yes
		Introduction to equipment, including setup and shutdown	
		Data collection software use	
		Basic maintenance and troubleshooting	
Dynatest	—	Included with purchase of new FWD equipment Refresher courses available for newly hired operators	—
		Tow vehicle tour	
		Introduction to equipment, including setup and shutdown	
		User manual overview	
		Data collection software use	
		Basic maintenance and troubleshooting	
		Support contact information	—
JILS	7 days	—	—
KUAB	3 days	Included with purchase of new FWD equipment Ongoing telephone support is provided	—
		Introduction to equipment, including setup and shutdown	
		Equipment operation, including testing patterns	
		Data collection software use	
		Basic maintenance and troubleshooting	
		Equipment calibration	

Note: — = no response given.

- Basic familiarity with signal processing,
- Automotive maintenance, and
- Computer skills.

In addition to those skills, FWD operators should be able to clearly communicate with the office and take direction. Furthermore, FWD operators should be exposed to data processing and analysis techniques. With these skills, operators can spot erroneous data before the errors have a chance to propagate, thus saving agencies time and money.

Falling Weight Deflectometer Data Analysts Qualifications

Sixty-six percent of SHAs reported that they provide training to new FWD data analysts. Training duration mostly fell into one of two responses; 31% stated 1 month or less of training was provided, and 27% stated that training was provided for 6 months. When asked for more details, six SHAs explicitly stated that training is provided on the job. Additionally, two states—Nevada and North Carolina—require new analysts to demonstrate proficiency, either by successfully completing data-gathering operations under supervision or by passing a test (Appendix B, Questions 66, 68–69).

Three SHAs stated that vendors provided at least some training. New FWD equipment purchases include training sessions. Details of these training sessions are described in Table 6.

Calibration Center Operator Qualifications

Training requirements differ slightly from one calibration center to another. For example, Pennsylvania calibration center technicians are trained by Cornell University and are certified by MACTEC. The calibration center in Minnesota, on the other hand, has not yet implemented an in-house training program, but it plans to do so in the future.

TRAINING CERTIFICATIONS

Certificate programs for FWD operators and data analysts are rare. One state—South Carolina—and one FWD vendor—Carl Bro—stated explicitly that a certification program is in place for FWD operators (Appendix B, Questions 70). The South Carolina certificate is earned when a new operator rides "with a certified operator for a period of time to show proficiency, and pass a test" (Appendix B, Questions 71).

ADDITIONAL TRAINING OPPORTUNITIES

Falling Weight Deflectometer User's Group

Sixty-one percent of SHAs surveyed send representatives to the annual FWDUG meeting (Appendix B, Questions 72). The FWDUG was started in 1992 as a forum to "share information and experiences in the practical aspects of FWD

TABLE 6

FWD VENDOR-PROVIDED DATA ANALYST TRAINING SUMMARY

FWD Vendor	Training Duration	Concepts Covered
Carl Bro	5 days	Introduction to road design software, including data import, quality check, and calculation
		Basic pavement design theory
		Presentation of calculation results
		Basic troubleshooting
Dynatest	—	Included with purchase of new FWD equipment
		Refresher courses available for newly hired operators
		Smoothing
		User manual overview
		Support contact information
JILS	—	—
KUAB	—	Development of a FWD test pattern
		Data acquisition and data reduction
		Pavement section definition
		Load and temperature normalization of data
		Back-calculation of layer moduli values
		Load transfer and void detection in PCC pavements
		Structural evaluation of existing pavements
		Determining remaining structural life and overlay thickness design

Note: — = no response given.

testing and data analysis." Meetings are held once per year in various cities across the United States. Free exchange of ideas is encouraged. Currently, Patricia Polish of the Nevada DOT serves as the FWDUG's executive secretary. Meetings are typically held in October or November (*FWD: Introduction* 2007).

National Highway Institute

A division of FHWA, the National Highway Institute (NHI), is a clearinghouse for highway construction and maintenance education materials. NHI currently does not offer a training course for FWD usage, but 85% of SHAs surveyed would support one. A course previously offered by NHI discussed pavement deflection analysis, including FWD usage (*Pavement Deflection Analysis* 1994).

CHAPTER SEVEN

FALLING WEIGHT DEFLECTOMETER PROGRAM ADMINISTRATION

FWD program administration is the discipline of organizing and managing resources (i.e., people, equipment, schedules, and money) in such a way that FWD testing can be completed within the defined constraints of scope, quality, time, and cost. Each SHA program administrator endeavors to work within the limitations of their resources.

Among SHAs with an FWD program, an average of 2,194 lane-km (1,363 lane-mi)—with a median of 644 lane-km (400 lane-mi)—are tested annually. Tested lane distances are shown in Figure 10. Additionally, 187 full-time employees work for these programs (Appendix B, Question 87).

ANNUAL BUDGETING

From the survey results, the responding SHAs' expenditures varied widely for their FWD program budgets. Three states—Connecticut, Kentucky, and New Hampshire—stated that no SHA FWD program was in place. On the opposite end of the spectrum, California reported spending $850,000 annually on its FWD program. A histogram of annual budgets is shown in Figure 11. The majority of these budgets were primarily spent on project-level testing, including forensics. On average, 65% of program budgets were applied to project-level testing, compared with 22% for research and 11% for network-level testing (Appendix B, Question 82).

OUTSOURCING REQUIREMENTS

Although most FWD activity is performed by SHA staff, some work is outsourced. The budgets of three responding states—Florida, New Jersey, and Rhode Island—are dominated by outsourcing activities, which respectively make up 75%, 90%, and 70% of each SHA FWD program budget (Appendix B, Question 83). Typically, outsourced work must follow the local SHA's procedures; Florida reported that contractors must "Follow FDOT procedures including training, equipment used, calibration, data quality checks, and deliverables." Additionally, one state—Alaska—serves as an FWD services provider for other agencies such as the U.S. Army Corps of Engineers (Appendix B, Question 85).

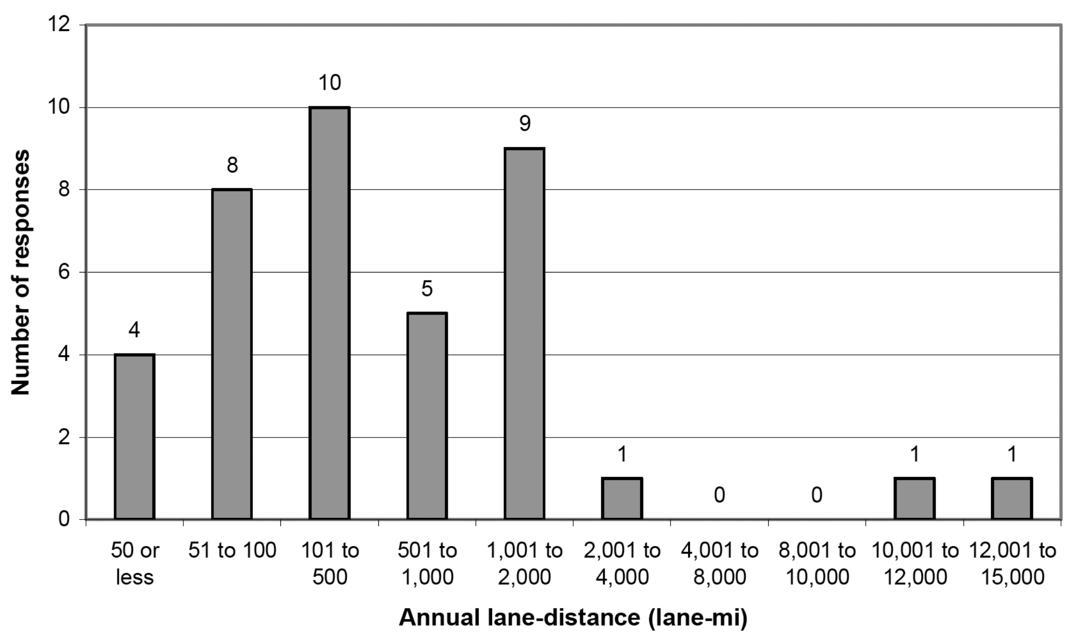
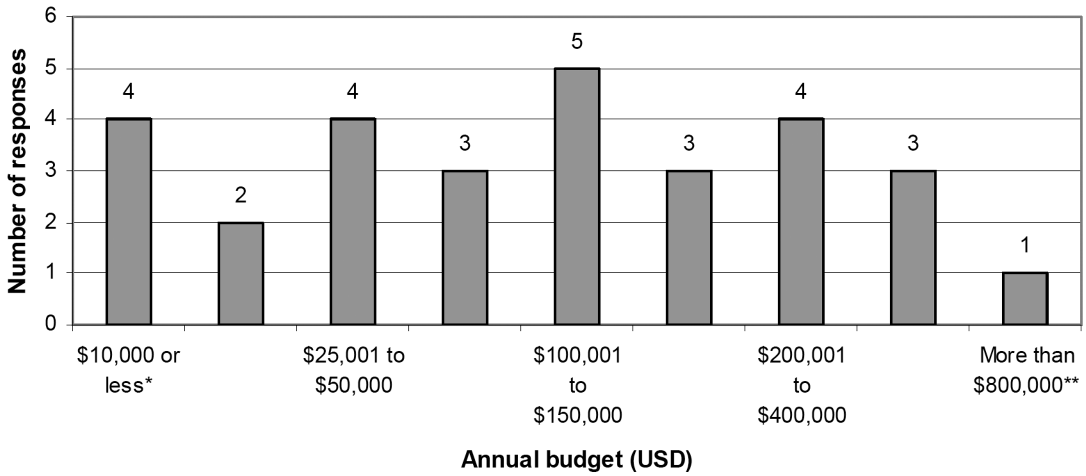


FIGURE 10 Survey response to Question 87: "Approximately what lane-distance does your FWD program test annually?"



* Responses: (2) $10,000; (1) $5,000; (1) $1
** Response: (1) $850,000

FIGURE 11 Survey responses to question 82: “What is the average annual operating budget—including labor, materials, travel, etc.—for your FWD field testing program?”

CHAPTER EIGHT

APPLICATIONS OF FALLING WEIGHT DEFLECTOMETER DATA—CASE STUDIES

This chapter discusses how FWD data has been applied to various agency activities. The case studies cover the following topics:

- Data collection and analysis refinement
- Pavement rehabilitation and overlay
- PCC joint sealing evaluation
- Pavement management systems
- Load transfer efficiency
- Void detection
- Spring load restrictions
- Nonresilient pavement layer behavior
- Utility cuts
- Experimental paving materials
- Project acceptance and evaluation
- Conversion of data from other NDT devices
- International practices

CASE 1. DATA COLLECTION AND ANALYSIS REFINEMENT

The Kansas DOT sponsored a study of LTE and temperature, during which FWD planning lessons were learned. FWD data were collected at one site along Interstate 70 at various times through the year. Because temperature has such significant effects on LTE and other pavement properties, the Kansas DOT drafted the following recommendations (Corn 2005):

- Plan FWD data collection operations with climatic conditions in mind.
- Test during temperate climate months.
- Test approach and leave slabs.
- Do not test while the ambient temperature is higher than 27° C (80° F), per the AASHTO recommendation.
- "Don't expect the expected."

VDOT uses FWD pavement testing at the project level, at the network level, and for forensic investigation of pavement failures. AC, jointed concrete pavement (JCP), CRCP, and composite pavements are all subject to FWD testing. At the project level, VDOT derives PCC elastic moduli, composite modulus of subgrade reaction (*k*-value), LTE, and presence of voids from FWD rigid pavement testing. On flexible pavements, they derive SN_{eff}, layer moduli, and resilient moduli of subgrades. A presentation by VDOT describes its FWD testing on its entire Interstate highway network. To provide a structural component to Virginia's pavement management system (PMS), FWD data were collected on Interstate 77 every 0.3 km (0.2 mi) and at three load levels. Additionally, FWD data were used to determine project acceptance. On Interstate 64, FWD testing was done at early-age cracking sites. The data showed "weak structure" and the contractor was "asked to remove and replace unaccepted pavement sections" (Habib 2006).

TxDOT owned 15 FWDs in 2003 and used them to test 5%–10% of network-level highways for their PMS. On the project level, TxDOT collected FWD data for "load zoning, design, forensic studies, joint load transfer on Jointed Concrete Pavement (JCP), and many projects for determining structural adequacy" (Beck 2003).

The Pennsylvania DOT outlines its pavement design procedures in its *Pavement Policy Manual* (*2007*), including new pavement designs. According to procedures outlined in chapter six, "Pavement Design Procedures," new pavement design submissions must include a table of M_r values backed up by either FWD data or lab tests. Additionally, federal-aid pavement preservation projects require patching percentages generated by FWD and by visual inspection. Back-calculation of M_r values is permissible only under five scenarios:

- Full depth bituminous pavement sections,
- Existing bituminous overlays on thin concrete pavements (original concrete pavements less than 8 inches in depth or any parabolic sections),
- Existing bituminous overlays on concrete pavements which suffer from severe alkali silica reaction (ASR) degradation, [and]
- Directly on subgrade and subbase (this situation is rare) (Pavement Policy Manual 2007).

CASE 2. PAVEMENT REHABILITATION AND OVERLAY

When contractors perform pavement resurfacing projects in the state of Alabama, an FWD test is required ("ALDOT Procedure 390 . . ." 2004, p. 14).

In a technology brief by IDOT's BMPR, specific uses of FWD data were listed. On rigid pavements, the brief lists the following uses ("Pavement Technology Advisory . . ." 2005):

- Locating areas of poor support beneath jointed concrete pavements
- Determining load transfer across transverse and longitudinal joints
- Estimating subgrade and pavement layer elastic moduli values (E1, E2, etc.)
- Developing cost-effective maintenance and rehabilitation alternatives

On flexible pavements, the IDOT brief lists the following uses ("Pavement Technology Advisory . . ." 2005):

- Determining the structural adequacy of a pavement and identify causes of failure
- Determining uniformity of support along a project and identify weak areas
- Estimating subgrade and pavement layer elastic moduli values (E1, E2, etc.)
- Developing cost-effective maintenance and rehabilitation alternatives

When conditions warrant, California's PCC roadways may be rehabilitated by replacing individual slabs. These slabs, which must measure at least 3.6 m (12 ft) in width and 2 m (6.6 ft) in length, are considered good candidates for replacement if a visual inspection shows two or more corner breaks; if they contain "third-stage cracking," segments that move relative to each other, longitudinal or transverse cracks wider than 13 mm (0.5 in.), or cracks with 150 mm (6 in.) or more of spalling; or if they are no longer supported because of settlement, base failure, or excessive curling. Once a visual inspection is done, the guidelines recommend FWD usage, along with drainage analysis and coring, to determine pavement condition ("Slab Replacement Guidelines" 2004).

The New York State DOT (NYSDOT) evaluates pavement structural capacity using FWD, but not on the project level. Additionally, tests are done only in the following situations (*Comprehensive Pavement Design Manual* 2000):

- Deflection survey of 50 statewide sites as a part of pavement performance monitoring program
- Deflection survey of 48 statewide sites as part of a SUPERPAVE performance monitoring program
- Determination of load transfer efficiencies at joints and cracks of PCC pavements
- Determination of the appropriateness and effectiveness of cracking and seating, and rubblizing operations

The YONAPAVE algorithms for evaluating the effective structural number (SN_{eff}), and thereby the thickness of an AC overlay, were developed at YONA Engineering Consulting & Management in Israel. This method reduces SN_{eff} calculations into five equations. Previously, SN_{eff} determination was done through an empirical process developed by AASHTO. Deflection basins measured by FWDs form the first step in the YONAPAVE process. The area under a plot of FWD deflections versus distance forms the basis for a characteristic length l_0 equation, whose value is then carried through a calculation of subgrade modulus of elasticity E_{sg}. SN_{eff} can then be determined from the l_0 and E_{sg} values. The SN_{eff} values generated by the YONAPAVE process correspond "in generally good agreement" with values calculated by the MODULUS or AASHTO NDT interpretation approach (Hoffman 2003).

To accomplish the elimination of spring load restrictions by 2002, the Alaska DOT and Public Facilities (Alaska DOT&PF) conducted FWD tests on all roads where spring load restrictions had been practiced. In all cases, recommendations were made for AC overlays on the existing AC pavements based on the FWD data (Bush and Tohme 2003).

CASE 3. JOINT SEALING EVALUATION

The Concrete Pavement Technology Program Task 9 research study, *Cost-Effectiveness of Sealing Transverse Contraction Joints in Concrete Pavements* (Hall et al. 2004), utilizes FWD analysis of joint load transfer and voids to analyze the performance of PCC pavements with sealed and unsealed joints. According to the authors, the study is expected to answer the following questions:

- What are the effects on long-term performance of unsealed transverse joints in concrete pavements with different pavement cross sections and slab dimensions, traffic levels, and climatic conditions?
- What are the effects of different transverse joint sealant materials and configurations on the long-term performance of concrete pavement in various climatic conditions (climatic zones)?
- Is sealing transverse contraction joints cost-effective for different pavement designs and materials over a range of climatic zones and traffic levels (Hall et al. 2004)?

CASE 4. PAVEMENT MANAGEMENT SYSTEMS

Several states include FWD data in their PMSs. For example, Nebraska's PMS stores FWD data that are collected by the Materials and Research Division. These data are used for "structural capacity analysis, evaluation of existing subgrade strength, and overlay analysis." Deflection test locations and frequency will vary according to project conditions (*State of Nebraska Pavement Management Systems* 2007).

CASE 5. LOAD TRANSFER EFFICIENCY

An example of a forensic study using LTE was conducted in Michigan (Peng et al. 2005). A time history analysis of the deflection data showed that the dowels were likely loose. Deflection testing showed that permanent loss of slab contact with the base (void) existed near the doweled joint.

CASE 6. VOID DETECTION

FWD data are used to detect voids where pavement layers have no support.

Undersealing

To fill voids under a PCC pavement, injection holes are drilled into the pavement and a grout of cement, fly ash, and water is pumped through the holes. This procedure is referred to as "undersealing" by the South Dakota DOT (SDDOT). Before and after drilling holes, voids in the pavement are detected using FWD data. The FWD loading plate is placed as close as possible to the slab corner, and the LTE to the adjacent joint is measured. If the measured deflections fall out of a range determined by the state engineer as acceptable, undersealing procedures begin (*Standard Specifications for Roads & Bridges* 2004).

In a research report, MoDOT disseminates their FWD void detection efficiency findings. Because voids under PCC-bridge approach slabs contribute to premature cracking, early detection of these voids is crucial to avoid costly replacement and rehabilitation measures. Based on the study's findings, MoDOT recommends that FWD should be used to determine voids under PCC slabs. This recommendation assumes that the FWD and operator are available, undersealing is being considered as a preventive maintenance treatment, and one or more of the following conditions are met ("Void Detection with the Falling Weight Deflectometer" 2004):

- Long lane closures for proof-roll testing are not desirable (e.g., at bridge approaches with reduced shoulder widths and high-volume routes).
- Fewer personnel than required with proof rolling are available for testing.
- The pavement shoulder is unstable for accurate proof-rolling measurements.
- More clear and quantifiable indications of undersealing improvements than proof rolling can provide are desired (i.e., AASHTO rapid void detection procedure).

Abandoned Mine Detection

The Ohio DOT is experimenting with the use of FWD data to supplement investigations of abandoned mine detection. The procedure is documented in ODOT's *Manual for Abandoned Mine Inventory and Risk Assessment* (1998).

CASE 7. SPRING LOAD RESTRICTIONS

The North Dakota DOT imposes limits on the per-axle weight trucks may carry during the spring thaw. These spring load restrictions are imposed to save the pavement layers from otherwise-avoidable and significant damage. A North Dakota DOT website ("Implementation of Spring Load Restrictions . . ." 2007) details the three main factors used to determine when the restrictions should be posted. Direct strength measurements, interpreted from FWD data, are combined with long-range weather forecasts and temperature probes.

SDDOT adopted using FWD data for spring load restrictions in 1996. SDDOT had recorded centerline miles subjected to spring load restrictions since 1969. In the years since spring load limits were instituted in South Dakota, the percentage of road network mileage requiring load restrictions during the spring thaw has generally decreased. When FWD data became a criterion for spring load restrictions in 1996, the number of lane-miles subject to restriction increased temporarily (12.7% of the roadway network in 1996 versus 11.1% in 1994 and 1995), but continued their downward trend thereafter. By 2007, 3.5% of SDDOT's roadway network was subject to spring load restrictions. SDDOT attributes the additional limits to FWD data ("2007 Spring Load Restriction Summary" 2007).

NYSDOT utilized FWDs to study the seasonal variability of pavement layer moduli. Regions experiencing winter-freeze, spring-thaw conditions in the soil undergo severely weakened subgrade layers during the thaw season. Because such seasonal differences in pavement layer moduli severely affect pavement surfaces, pavement designers must compensate for them. Six possible seasons were identified (Orr 2006):

- Freezing, when frost is present in less than 100 mm (4 in.) of the subgrade layer.
- Winter, when at least 100 mm (4 in.) of the subgrade layer contains frost and no thaw is present.
- Spring thaw, when any thaw in the unbound layers is present and some portion remains frozen.
- Spring recovery, when resilient modulus increases quickly because of drainage.
- Spring, when all frost has thawed, but precipitation outpaces evaporation.
- Summer, when evaporation outpaces precipitation.

To identify when such seasonal parameters are necessary, Cornell University and NYSDOT developed a geographical model that shows which portions of New York are subject to significant seasonal variation. FWD data were gathered at varying sites throughout the year. The model was then built using backcalculated FWD moduli. Additionally, the seasonal model was used to design a 20-year AC overlay in Arcadia, New York.

CASE 8. NONRESILIENT PAVEMENT LAYER BEHAVIOR

Because the FWD has replaced the Benkelman beam as the primary pavement analysis and design device, measured layer moduli now include plastic deformations as well as recoverable deformations. Mechanistic design practices assume that all layers behave resiliently. In the past, these additional plastic deformations were assumed negligible; however, nonresilient behavior may be observed given a load of significant magnitude. The practice of "16 (FWD weight) drops at four load levels with four replicates at each drop height or load level" may result in nonresilient behavior. Such behavior can be detected by statistical tests. Two statistical methods of nonresilient behavior detection were tested using FWD tests at Cornell University. Tests were performed from February until May 2003. No trends were observed through ANOVA (analysis of variance) tests but chi-squared variance tests on the center sensor data revealed nonresiliency during the spring-thaw season. ANOVA tests "will detect systematic variations; however, if the deflections are not always generally increasing or decreasing for a given load level, the test does not detect when nonresilient behavior is occurring" (Orr 2003).

CASE 9. UTILITY CUTS

The Iowa DOT sought to improve utility cut repair techniques. Utility cuts often settle over time, which leads to "uneven pavement surfaces, annoyance to drivers and, ultimately, further maintenance." Causes of the settlement include differing backfill material between jurisdictions, excessive volumes of backfill materials "placed at bulking moisture contents," and the lack of quality assurance or control. FWD data showed that backfill materials within utility cuts—as well as an area 0.6 to 0.9 m (2 to 3 ft) beyond the cut perimeter—were susceptible to settlement. The Iowa DOT will continue to monitor its utility cuts using FWD tests, as well as nuclear gauges, dynamic cone penetrometers (DCPs), Clegg hammers, and laboratory tests. These data "will be studied with the goal of increasing pavement patch life and reducing the maintenance of the repaired areas" (*Research News* 2007).

CASE 10. EXPERIMENTAL PAVING MATERIALS

Crushed aggregate, a popular base course for pavements, became progressively more expensive. To save money on base courses, FDOT has sponsored recycling concrete aggregate (RCA) research. FWD data were used to test various RCA mixes and the results show RCA to be a viable base course for roadway pavements ("Guidelines and Specifications for the Use of Reclaimed Aggregates . . ." 2001).

Ultra-thin whitetopping (UTW) was evaluated using FWD data in Minnesota. FWD data were collected one year after an experimental UTW pavement test section was constructed at the Minnesota Road Research test facility. PCC thickness varied from section to section; the study's intent is to determine an ideal PCC thickness. Strain data captured by the FWD showed a good bonding condition between the lower bituminous surface and the new PCC wearing course. Although an optimal UTW overlay design is not yet determined, "the dynamic strain measurements indicate that there is a better bond between the asphalt and the overlay in the thinner sections." It was also observed that the magnitude of the strains in the thinner sections were more dependent on the stiffness of the asphalt than the number of equivalent single axle loads accumulated (Vandenbossche and Rettner 1998).

CASE 11. PROJECT ACCEPTANCE AND EVALUATION

FWD tests have potential for use during construction. FWD data may be used for the following (Clark 2005):

- Subgrade strength improvements before structural section construction.
- Subbase and base layer monitoring after structural section construction.
- LTE on jointed plain concrete pavement.
- Baseline development.

As an example, FWD tests on Virginia State Highway 288 showed where a cement-treated base needed to be placed during construction. A second example, where CRCP was placed, showed deflections greater than 0.14 mm (5.5 mils). These deflections indicated poor construction joints, and further investigation showed reinforcing steel at the wrong depth. FWD was again used as a diagnostic tool along U.S. Highway 29, where two stations showed poor support. Although FWD could be used as an acceptance criterion, contractors would have to be familiar with their use and be able to afford one.

In a research report for VDOT (Diefenderfer and Bryant 2005), pavement warranty contracts are suggested for future rehabilitation projects. VDOT considered requiring pavement contractors to enter into warranty contracts. Such warranties ensure quality pavements over the course of a pavement's design life. In some cases, however, competition between contractors was reduced. As a potential study case, an AC overlay project was chosen. FWD data were employed in the AC overlay design phase and before acceptance. FWD data collection included using four load levels spaced at locations 22.9 m (75 ft) apart.

After a jointed reinforced concrete pavement rehabilitation was completed along Interstate 287 in New Jersey, FWD data were used for "assessing the existing condition of the mainline pavement, investigating the causes of premature distresses in the mainline pavement, and monitoring the effectiveness of slab undersealing at joint locations." For example, after a pavement rehabilitation project was complete, low- to medium-severity transverse cracks appeared. "The FWD, DCP, and compressive strength test results were used to evaluate the condition of the various pavement layers. A normalization load of 40 kN (9,000 lbf) was used for the analysis of the FWD test results. That is, the FWD deflections from the actual applied loads were normalized or adjusted to the values that would have resulted if a 40 kN (9,000 lbf) loading had been applied." The FWD and compressive strength test results revealed that the PCC layer was in fair-to-good condition. The average backcalculated PCC layer modulus (*E*PCC) was almost 34,500 MPa (5,000 ksi), whereas the average compressive strength of the PCC layer was 60 MPa (8,700 psi). The FWD results indicated that the support to the PCC layer was adequate at midslab locations, because the average backcalculated modulus of subgrade reaction (*k*) value was 5.5 kg/cm^3 (200 pci), a "fair value." However, the DCP test results indicated low California Bearing Ratio (CBR) values (average CBR = 46%) for the nonstabilized open graded (NSOG) layer. Notwithstanding the LTE values (92% on average), the FWD joint test results indicated that the pavement was not performing well at joint locations. The joint deflection (i.e., deflection directly beneath the center of the FWD load plate during joint testing) and joint intercept values (indicative of slab support) were fairly high—average values of 9.6 mils and 2.1 mils, respectively. These results suggest that voids likely exist beneath the slabs near joints, and excessive vertical slab movement consequently occurs at these locations. These voids were promptly undersealed. Additionally, high degrees of nighttime slab curl were confirmed by FWD testing, exacerbated by the nonstabilized open graded base layer instead of a more densely graded base material. The researchers concluded that "the FWD can thus act as an evaluative and investigative tool during the early stages of a project and as a quality control instrument to ensure that the desired final pavement product is achieved after the pavement work has been performed" (Frabizzio et al. 2002).

In Kentucky, a 5.1 km (3.17 mi) section of Interstate 265 was examined following a pavement reconstruction project. In addition to FWD data, ground-penetrating radar (GPR) testing and coring were completed along the segment. The PCC slabs showed transverse cracks and differential settlement. The FWD data were used to determine layer stiffness and LTE. Although the Kentucky Transportation Cabinet accepts LTE values of 90% or greater, all slabs in the study area had less than 90% LTE (Rister et al. 2003).

CASE 12. CONVERSION OF DATA FROM OTHER NONDESTRUCTIVE TESTING DEVICES

FDOT elected to replace its entire Dynaflect fleet with FWDs. This decision is attributable to FWD providing a more accurate simulation of actual traffic loads, its use as a pavement research tool, and its adoption by LTPP. Because FDOT testing data were collected by means of Dynaflect before FWD adoption, conversion from Dynaflect to FWD was needed. A linear correlation was found to make the conversion, and this study refines this correlation. FWD, Seismic Pavement Analyzer, and Dynaflect data were collected at pavement sites throughout Florida, and statistical correlations were determined. Additionally, the researchers conducted a state-of-the-practice literature review, as well as a survey of SHAs. FWD data were processed into M_r and soil support value using MODULUS, EVERCALC, the AASHTO method, and a finite-element modeling program. FWD M_r data backcalculated through MODULUS showed a strong correlation to M_r values collected by the Dynaflect (R_2 = 0.867). Similarly, Dynaflect M_r values correlated strongly with FWD data processed through EVERCALC (R_2 = 0.742) and through the AASHTO method (R_2 = 0.925) along 483 km (300 mi) pavement sections. In cases in which pavement testing had been performed by LTPP, the LTPP database was "found to be the best database available to deduce general patterns of the pavement behavior during field testing." The researchers reached 16 conclusions. The following 11 conclusions were relevant to this synthesis (Tawfiq 2003):

- FWDs accurately simulated vehicle loads on pavements.
- Other NDT devices did not accurately simulate vehicle loads.
- Thick AC layers, very thin AC layers, shallow bedrock, and heavier loads may have given unrealistic data and should be compensated for before performing backcalculation.
- Calibration was crucial.

- MODULUS gave no indication of invalid FWD data, whereas EVERCALC gave an error message.
- MODULUS and EVERCALC gave similar results, but EVERCALC worked within the Windows GUI and MODULUS required a DOS command line interface. Additionally, EVERCALC was more sensitive to seed moduli. Furthermore, EVERCALC was accompanied by software for overlay design and stress simulation but had poor user manuals.
- Sensor D6—placed 36 in. from the load plate—better measured subgrade response than sensor D7. This observation may have been unique to Florida.
- While finite-element analysis was generally reliable, bedrock and subgrade moduli were occasionally overestimated.
- Soil moisture was not considered for back-calculation strategies, but it can drastically change soil properties.
- Bedrock depth was not considered for back-calculation techniques, but it can be determined through finite-element analysis.
- FWD data should be coupled with other data to be useful. Such data include bedrock depth and layer thickness.

CASE 13. INTERNATIONAL PRACTICES

A nation-by-nation assessment of FWD usage and nondestructive testing was provided in a report by the European Cooperation in the Field of Scientific and Technical Research (COST), under the auspices of the European Union. The following are some of the findings (Beuving 2000):

- Spain—At the project level, FWDs were used exclusively on rigid pavements; flexible pavements were tested using either Lacroix deflection measurement devices or FWDs. Measurements are taken every 200 m (656 ft), and surveys are completed every 4 years.
- Finland—Structural assessments are performed using KUAB FWD data. Measurements are taken "not further apart than 500 m (1,640 ft)" and are completed every 3 to 5 years. The primary parameter derived from FWD data is the spring Bearing Capacity Ratio; however, plans were under way to switch to the Structural Condition Index.
- Denmark—Deflection data from FWD and average daily traffic are used to determine structural pavement capacity. Denmark's PMS, in place since 1988, included deflection data taken at 200 m (656 ft) distances in both directions and moduli are backcalculated using an "equivalent thickness approach."
- Ireland—FWD data are collected in 200 m (656 ft) sections "with measuring distances of 25 to 50 m (82 to 164 ft)." These data are used to classify pavement layer bearing capacity, subgrade layer bearing capacity, and AC overlay thickness.

In the state of Western Australia, FWD testing has gradually replaced the Benkelman beam as the standard deflection testing mechanism since the 1990s. Two FWDs are present in Western Australia. "With the arrival of FWDs, Main Roads Western Australia (MRWA) commenced conducting network level FWD deflection survey together with profilometer survey for roughness, rutting, and texture measurements in annual basis." Annual calibration was required and a calibration center based on the SHRP 1994 protocol was built in Perth. Traffic control was performed by a "driver operator" with an escort vehicle warning sign behind the FWD trailer. Test methods followed the ASTM D4694-96 protocol. Sensors were located at 0, 203, 305, 406, 508, 610, 762, 914, 1,524 mm (0, 8, 12, 16, 20, 24, 30, 36, and 60 in.) from the load plate. Tests were conducted at 50 kN (11,200 lbf) to simulate Western Australia tire pressure loads. Data were collected every 0.8 km (0.5 mi) in the outer wheel path. The data gathered were used "together with Rutting, Roughness, Surface Texture, and Skid Resistance to the key pavement performance indicators for the Road Network Maintenance Contracts," and thereby to determine payment to contractors. Furthermore, "based on the network deflection data the Contractors select the sections requiring project level pavement investigation for rehabilitation works." The presence of FWDs has greatly increased testing efficiency. "Average production rate was 250 deflection tests per day. Typical production rate of Benkelman Beam tests is 80 to 100 per day." Testing integrity is validated through calibration, data auditing, marking the test point, and accounting for environmental factors. Additionally—

> Deflection data from the tests carried out on or close to the outer wheel path after the rainy season were generally high. This reflected wetting of subgrade and weakening pavement edges. Seasonal effects on deflection data between the successive surveys can be reduced if deflection testing is carried out around the same time of the year (Sapkota 2003).

CHAPTER NINE

CURRENT RESEARCH

This synthesis study identified the following FWD research project topics. Each topic represents several research projects, some of which were recently concluded as of this writing.

IN-MOTION DEFLECTION TESTING

Although the FWD is a useful tool to determine layer stiffness and detect voids, it must be stationary during its operation. This feature inconveniences agencies, as lanes must be closed to perform network-level testing. Ideally, a deflection measuring device should travel at highway speeds. In 1997, SweRoad under the tutelage of the Swedish government developed the Swedish Road Deflection Tester. The device was tested on roads in Sweden and the United Kingdom and found to correlate closely with the FWD. Additional sections of the report give brief histories of roads, profilers, and deflection devices (Andrén 2006).

In a TxDOT study (Jitin et al. 2006), a suitable replacement for the FWD was sought. Because the FWD must be stationary while in operation, the device is potentially unsafe to use on network-level pavements. A handful of in-motion deflection detection devices have been developed and this project reviews those that are readily available to TxDOT. The researchers reviewed University of Texas at Austin's Rolling Dynamic Deflectometer, Dynatest's Airfield Rolling Weight Deflectometer, Applied Research Associates' Rolling Wheel Deflectometer, SweRoad's Road Deflection Tester, and Greenwood Engineering's High Speed Deflectograph. The researchers found the High Speed Deflectograph to be the device most in keeping with TxDOT guidelines, because it is the only candidate device that takes multiple deflection measurements in the same location.

PORTABLE FALLING WEIGHT DEFLECTOMETER

In a research study by INDOT (Kim et al. 2006), a portable FWD (PFWD) was evaluated for its correlation with a standard plate bearing load test. Tests were done at 22 highway construction sites. The coefficient of subgrade reaction k_{30} was measured using the plate bearing load test and the PFWD measured the dynamic deflection modulus. A linear correlation ($R_2 = 0.77$) was found between the two devices. Furthermore, the research found the error between the two tests to be about 28.5%, but this error was greatly reduced by repeating the PFWD test.

Carl Bro's PRIMA 100 lightweight FWD (LFWD) is compared in another study with a standard FWD and to a plate load test (Nazzal et al. 2004). Tests were conducted at three stations on U.S. Highway 190 and at four stations along Louisiana State Highway 182. The LFWD-measured elastic modulus E_{LFWD} showed a statistically significant correlation to the standard FWD-measured resilient modulus ($M_{FWD} = 0.97E_{LFWD}$, $R_2 = 0.94$). Plate load tests showed similarly strong correlations to E_{LFWD} in the PLT device's initial and reloaded cases ($E_{PLT(i)} = 22 + 0.7\ E_{LFWD;}\ R_2 = 0.92$ and $E_{PLT(R2)} = 20.9 + 0.69\ E_{LFWD}$, $R_2 = 0.94$). Based on these strong correlations, the LFWD is a suitable device for evaluating pavement layer moduli.

Because traditional trailer or vehicle-mounted FWDs can be expensive and cumbersome, an agency's testing ability may be limited. In areas prone to freeze-thaw conditions, these limits may lead to incomplete network-level tests. One solution, a PFWD, was tested in this study for its compliance with traditional FWDs. The PRIMA 100, formerly manufactured by Dynatest, was compared with a JILS 20C FWD provided by the Maine DOT and two Dynatest 8000 FWDs, one provided by VTrans and the other provided by the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory. Although the VTrans FWD was operated per the FHWA/LTPP manual, the Cold Regions Research and Engineering Laboratory added one sensor 8 in. from the load plate. The study reached three conclusions (Steinert et al. 2006):

- PFWD composite moduli follow similar trends to composite moduli and subbase moduli as determined from FWD measurements on asphalt surfaced roads.
- The correlation between composite modulus derived by the PFWD and traditional FWD increases with decreasing asphalt thickness.
- The PFWD can be used as a tool to evaluate whether specific roadways experience strength loss during the spring thaw and thus warrant load restrictions.

For roads where load restrictions are placed, the PFWD can be used as an aid to determine when restrictions should be placed and removed.

GROUND-PENETRATING RADAR INTEGRATION

INDOT evaluated network-level FWD and GPR testing feasibility. The report recommended that Indiana perform complete network-level tests on 3,541 lane-km (2,200 lane-mi) of its Interstate highways annually, which would complete the state's entire network in five years. Back-calculation of pavement layer moduli followed the ASTM D5858 standard, and FWD operation followed ASTM D4694. FWD and GPR should be included with the state's PMS, along with "international roughness index, pavement condition rating, rut depth, pavement quality index, texture and skid resistance". FWD and GPR data can provide information to operators, which may prevent unnecessary coring. Furthermore, the following research is recommended by this INDOT study (Noureldin et al. 2005):

- Develop prediction models using FWD center deflection as a pavement performance indicator.
- Develop an automated structural adequacy index employing both the FWD data and automated distress identification data (especially the structural-related distress component of the pavement condition rating) for pavement management purposes.
- Use the GPR to characterize the dielectric characteristics of pavement surfaces, especially those with potential to trap moisture.

NETWORK-LEVEL TESTING

Members of the European Union commissioned a study of FWD usage. Confined to network-level testing, the study conducted a literature review, found other pertinent data from COST studies, Lisbon's FWD workshop presentations, and FWD owners in Europe. Network-level activity was divided into four subcategories: budgeting, planning, programming, and prioritization. From the Lisbon workshop, COST learned the need for network-level FWD testing was subject to six criteria (*Use of Falling Weight Deflectometers at Network Level* . . . 1998):

- Road network size
- Quality of bearing capacity data within the agency's pavement database
- Importance given to particular parameters within a PMS
- Testing budget including time required
- Customer requirements
- Historic reasons, such as frequency of maintenance

MECHANISTIC-EMPIRICAL PAVEMENT DESIGN

FWD data are essential to mechanistic–empirical pavement design, and two research projects are in progress, the first of which, Use of Deflection Testing with the MPEDG, is investigating

> [T]he current state of the practice and art in routine back-calculation of FWD data and develop[ing] recommendations for advancing FWD data analysis and interpretation, particularly in relevance to the rehabilitation procedures in the Mechanistic–Empirical Pavement Design Guide (MEPDG) developed under the NCHRP 1-37A project. This project will also develop best practices guideline for analyzing and interpreting FWD data for project level analyses with particular emphasis on the effective and efficient use of FWD data with the MEPDG (Sivaneswaran 2007).

The second research project is entitled Evaluation of State Highway Agency Adoption of Practices for Implementing Mechanistic Empirical Pavement Design (FHWA contract number DTFH61-06-P-00198).

CHAPTER TEN

CONCLUSIONS

Falling weight deflectometers FWDs have been in use since the 1980s and over time have become the predominant pavement deflection measurement device. Interpretation of FWD data helps state highway agencies SHAs evaluate the structural capacity of pavements for research, design, rehabilitation, and pavement management purposes. The number of FWDs in use and the importance of their role in pavement engineering practice are expected to rise as agencies move toward mechanistically based pavement design. Based on work carried out in this synthesis, the following conclusions can be made:

- SHAs are currently using 82 FWDs. Most were manufactured by Dynatest, but Carl Bro, JILS, and KUAB were also represented.
- Most SHAs are currently following FWD guidelines of their own creation rather than the Long Term Pavement Performance (LTPP) guidelines.
- Although most SHAs do not have written FWD maintenance plans, maintenance activities are being performed.
- The 1994 Strategic Highway Research Program/ LTPP FWD reference calibration procedure has been replaced by a newly developed 2007 FHWA calibration procedure, which has been adopted by FHWA/LTPP Regional Calibration Centers and several independent calibration facilities.
- Of the SHAs surveyed, 55% review a written equipment inspection checklist before departing for testing and the same percentage follow a written warm-up procedure.
- Despite accident prevention measures such as traffic controls, 29% of survey respondents reported accidents occurring within the past five years during FWD testing operations.
- There is no standard for data storage time among SHAs. The survey indicated that 89% of survey respondents keep raw FWD field data for more than five years and 84% keep these data indefinitely.
- Among SHAs with an FWD program, an average of 2,194 lane-km (1,363 lane-mi)—with a median of 644 lane-km (400 lane-miles)—are tested annually. Additionally, 187 full-time employees work for these programs.
- From the survey results, the responding SHAs' expenditures varied widely (ranging from no program to $850,000 annually) for their FWD programs.

Based on work carried out in this synthesis, the following future activities are suggested:

- Network-level FWD data collection could be more standardized as SHAs implement FWD testing and data analysis into their pavement management systems.
- FWD data, along with the international roughness index and visual inspections, could be developed into a comprehensive program for construction project acceptance.
- The reference calibration method, as well as the various calibration, data analysis, and FWD operation software packages, should continue to be refined, especially as new technologies become available.
- FWD data analytical software creators should provide their product to the open-source development community to expedite software development, increase peer review, develop algorithm standardization, and increase user acceptance. They should incorporate the Pavement Deflection Data Exchange file format as a main input file format option for the FWD data analysis.
- Traffic control guidelines for moving work zones, such as FWD field activities, should be developed.
- The collection and use of time history data should be investigated.

The following future synthesis topic was proposed by the panel members of this study. Synthesis of FWD Testing Protocols: The purpose for collecting FWD data has a major influence on the SHA's pavement testing protocol. This proposed synthesis of SHA practices for FWD testing could provide information needed to support guidelines that advance SHA data collection practices. Information needed to quantify and document the various FWD data collection practices should include, but not be limited to, the following:

- Purpose of the FWD Testing and the Data Analysis Requirements, which may also be applied in categories by pavement type such as hot mix asphalt (HMA), portland cement concrete (PCC), and composite (HMA over PCC) pavements:

  - Project-level requirements
  - Network-level requirements
  - Research-level requirements
  - Why is the LTPP testing protocol not applicable (e.g., was it too rigorous of a research-level protocol and not needed for design purposes)?
  - Are the SHAs continuing to use existing testing protocols or developing new versions?
  - What are the SHA specified testing protocols for project level, network level, or research level (e.g., specific HMA, PCC, or composite pavement testing for evaluation of pavement performance, pavement management, forensic investigation, and overlay design)?
  - What are the SHA-specified testing protocols for specific data analysis techniques (e.g., back-calculation, load transfer, and void detection)?
- FWD and Auxiliary Equipment Requirements
  - Pavement load levels and load sequencing capabilities
  - Deflection sensor configuration (i.e., number of sensors and spacing)
  - Data file management, file formats, onboard error checking, data quality control methods, and file storage/transfer capabilities
  - Auxiliary data collection equipment needed for analysis (e.g., temperature data, global positioning system data, distance measurement instrument data, etc.)
- FWD Equipment Calibration and Maintenance Requirements
  - SHA requirement (e.g., frequency)
  - SHA procedure for FWD calibration certification and verification
  - SHA procedure for FWD maintenance record check (e.g., in-vehicle documentation)
- Personnel Qualification and Training Records
  - SHA requirement for FWD operator qualifications
  - SHA procedure for FWD operator training record verification
  - Other record verification procedures

For each of the levels of testing (project, network, and research), the testing protocol for specific analysis may require separation by pavement categories. The testing protocol's purpose may not always apply to a different pavement type or to another level of testing.

- Data Collection Methodologies for HMA Pavements
  - Equipment check guidelines (e.g., preparation, field, and return checks)
  - Testing protocol specifying load levels, load sequencing, data to record, and data collection pattern (e.g., HMA pavement rehabilitation/overlay design)
  - Auxiliary data collection [e.g., cores, ground penetrating radar (GPR), dynamic cone penetrometer (DCP), and temperature vs. depth]
  - Safety considerations (e.g., traffic control)
- Data Collection Methodologies for PCC Pavements
  - Equipment check guidelines (e.g., preparation, field, and return checks)
  - Testing protocol specifying load levels, load sequencing, data to record, and data collection pattern (e.g., PCC pavement rehabilitation/overlay design)
  - Auxiliary data collection (e.g., cores, GPR, DCP, and temperature vs. depth)
  - Safety considerations (e.g., traffic control)
- Data Collection Methodologies for Composite Pavements
  - Equipment check guidelines (e.g., preparation, field, and return checks)
  - Testing protocol specifying load levels, load sequencing, data to record, and data collection pattern (e.g., composite pavement rehabilitation/overlay design)
  - Auxiliary data collection (e.g., cores, GPR, DCP, and temperature vs. depth)
  - Safety considerations (e.g., traffic control)
- Data Collection Methodologies for Specific Analytical Techniques
  - Equipment check guidelines (e.g., preparation, field, and return checks)
  - Testing protocol specifying load levels, load sequencing, data to record, and data collection pattern (e.g., back-calculation analysis and Mechanistic–Empirical Pavement Design Guide requirements)
  - Auxiliary data collection (e.g., cores, GPR, DCP, and temperature vs. depth)
  - Safety considerations (e.g., traffic control)

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ABBREVIATIONS

AC	Asphalt concrete
ADOT	Arizona Department of Transportation
ALDOT	Alabama Department of Transportation
ASR	Alkali-silicate reaction
BMPR	Bureau of Materials and Physical Research
Caltrans	California Department of Transportation
CBR	California Bearing Ratio
COST	European Cooperation in the Field of Scientific and Technical Research
CRCP	Continuously reinforced concrete pavement
DCP	Dynamic cone penetrometer
D_{eff}	Effective slab depth
DOS	Disk Operating System (Microsoft)
ERI	Engineering Research International
FDOT	Florida Department of Transportation
FWD	Falling weight deflectometer
FWDUG	Falling Weight Deflectometer User's Group
GDOT	Georgia Department of Transportation
GPR	Ground-penetrating radar
GUI	Graphical user interface
HMA	Hot-mix asphalt
HWD	Heavy weight deflectometer
IDOT	Illinois Department of Transportation
INDOT	Indiana Department of Transportation
ITD	Idaho Transportation Department
ITRD	International Transport Research Documentation
JCP	Jointed concrete pavement
JPC	Jointed plain concrete
k	*k*-value
LFWD	Lightweight FWD
LTE	Load transfer efficiency
LTPP	Long-Term Pavement Performance
LVDT	Linear variable displacement transducers
M_r	Resilient modulus
MEPDG	Mechanistic–Empirical Pavement Design Guide
MoDOT	Missouri Department of Transportation
MRWA	Main Roads Western Australia
NDT	Nondestructive testing
NHI	National Highway Institute
NYSDOT	New York State DOT
PCC	Portland cement concrete
PDDX	Pavement Deflection Data Exchange
PFWD	Portable falling weight deflectometer
PLT	Plate load test
PMS	Pavement management system
R_2	Coefficient of determination
RCA	Recycling concrete aggregate
SDDOT	South Dakota Department of Transportation
SHA	State highway agency
SHRP	Strategic Highway Research Program
SN	Structural number
SN_{eff}	Effective structural number
SRA	Swedish Road Administration
TRIS	Transportation Research Information Services
TxDOT	Texas Department of Transportation
UTEP	University of Texas at El Paso
UTW	Ultra-thin whitetopping
VDOT	Virginia Department of Transportation
VTrans	Vermont Agency of Transportation
WSDOT	Washington State DOT

UNITS OF MEASURE

cm	centimeter
ft	foot
in.	inch
km	kilometer
kN	kilonewton
ksi	kips per square inch
lbf	pounds force
mi	mile
mils	milli-inch (0.0001 in.)
MPa	megapascal
µm	micrometer
pci	pound per cubic inch
psi	pounds per square inch

APPENDIX A

SURVEY QUESTIONNAIRE

The survey questionnaire was prepared for this synthesis and reviewed initially by the panel members. Invitations to take the survey were sent to falling weight deflectometer (FWD) administrators in each of the 50 state highway agencies (SHAs) in the United States. Continuous communication with SHA representatives resulted in 45 of those 50 invitees responding, for a response rate of 90%. One response was submitted by mail. All other responses were submitted by means of an online form.

The survey contained a total of 88 separate questions. The questions are grouped into 12 broad categories: (1) Background Information, where the respondents' contact information was collected; (2) FWD Equipment Types; (3) FWD Equipment Maintenance; (4) FWD Equipment Calibration; (5) General FWD Testing Procedures; (6) FWD Field Testing—Flexible Pavements; (7) FWD Field Testing—Rigid Pavements; (8) FWD Computers; (9) Data Analysis; (10) Data Management and Storage; (11) Personnel Training; and (12) FWD Program Administration, which was split into two sections for the benefit of online responses.

A summary of the individual states that replied and their responses is given in Appendix B.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

National Academy of Sciences
National Academy of Engineering
Institute of Medicine
National Research Council

TRB
Transportation Research Board

Falling Weight Deflectometer Usage (NCHRP Project 20-5, Synthesis Topic 38-15)

Sierra Transportation Engineers, Inc. (STE) is conducting this web based survey for NCHRP Project 20-5, Synthesis Topic 38-15 Falling Weight Deflectometer (FWD) Usage. A synthesis of highway agency FWD usage will provide information needed for advancing the state-of-the-practice. We would appreciate your time and effort in completing this survey by May 8, 2007.

We highly recommend responding to this survey using WebSurveyor/Vovici's Internet site. The address is:

http://www.trb.org/ss/wsb.dll/25/fwd38-15.htm

If you choose not to use the web site, please fill out this form, and send it—along with any supporting materials—to:

Dr. Sirous Alavi, P.E.
Sierra Transportation Engineers
1005 Terminal Way Suite 125
Reno NV 89502

This survey is divided into 13 parts.

Please allow about one hour to complete this survey.

PART 1: BACKGROUND INFORMATION

1) Respondent's Contact Information

Agency/organization reporting	
Respondent's name	
Respondent's title	
Mailing address	
City	
State	
Zip code	
Telephone	
Email address	

PART 2: FWD EQUIPMENT TYPES

How many FWDs does your agency use? How old are they?

2) Carl Bro

Quantity of FWDs in service	
Ages of FWDs (years, separated by commas)	

3) Dynatest

Quantity of FWDs in service	
Ages of FWDs (years, separated by commas)	

4) JILS

Quantity of FWDs in service	
Ages of FWDs (years, separated by commas)	

5) KUAB

Quantity of FWDs in service	
Ages of FWDs (years, separated by commas)	

6) Other

Manufacturer name	
Quantity of FWDs in service	
Ages of FWDs (years, separated by commas)	

PART 3: FWD EQUIPMENT MAINTENANCE

7) Does your agency have a written FWD maintenance plan?

❍ Yes *(please provide a copy to fwdsurvey@ste-group.com)*
❍ No

8) If not, please describe your FWD maintenance activities. Include scheduling and activity descriptions.

9) Who performs maintenance activities on the FWD equipment your agency uses? (Check all that apply)

❑ In-house
❑ Vendor
❑ Other (please describe below)

If you selected other, please specify: ______________________________

10) Who performs maintenance activities on the FWD vehicles your agency uses? (Check all that apply)

❑ In-house
❑ FWD vendor
❑ Vehicle dealership
❑ Other (please describe below)

If you selected other, please specify: ______________________________

11) Please describe any additional practices which have kept your FWD equipment in good working order.

PART 4: FWD EQUIPMENT CALIBRATION

12) Does your agency require calibration of FWD equipment?*

❍ Yes
❍ No

13) If yes, how often do you perform relative calibrations?

(number)	per	(month/year)
Other (please specify)		

14) If yes, how often do you perform reference calibrations?

(number)	per	(month/year)
Other (please specify)		

15) Whose procedure do you follow to perform a relative calibration? (If you choose other, please specify your procedure—including load magnitudes and repetitions—in the space below, or provide a copy to *fwdsurvey@ste-group.com*)

❍ Vendor
❍ FHWA/LTTP
❍ Other (please specify)

If you selected other, please specify: ____

16) What surface do you use to conduct a periodic relative calibration test?

❍ In-service pavement
❍ Calibration pad
❍ Other (please specify)

If you selected other, please specify: ____

17) Where do you have your reference calibrations done? (Organization name, city, and state)

18) If your agency does require calibration, how far must the equipment typically travel?

Relative calibration travel distance	
Reference calibration travel distance	
Distance units (mi or km)	

19) If your agency does require calibration, what is the approximate cost per calibration session, including total labor, materials, travel, and incidental expenses?

Relative calibration cost (dollars)	
Reference calibration cost (dollars)	

20) Would your agency favor additional calibration centers?

❍ Yes
❍ No

21) Would your agency sponsor such a calibration facility?

❍ Yes
❍ No

PART 5: GENERAL FWD TESTING PROCEDURES

22) How many crew members do you use to operate an FWD unit on a typical project?

- ❍ 1
- ❍ 2
- ❍ 3
- ❍ Other (please specify)

If you selected other, please specify: ______________________________

23) What facilities do you test with the FWD? (Check all that apply)

- ❑ Agency highways
- ❑ City streets
- ❑ Airports
- ❑ Other (please specify)

If you selected other, please specify: ______________________________

24) What is the average lead time from the date you receive a request to the date of testing?

(number)	(days/weeks/months/years)

25) What is the average turn-around time from the date of testing to the date the results are submitted to your customer?

(number)	(days/weeks/months/years)

26) Is there an equipment inspection checklist prior to testing?

- ❍ Yes
- ❍ No

27) Is there a written warm-up procedure prior to testing?

- ❍ Yes
- ❍ No

28) Who provides traffic control?

- ❍ Agency
- ❍ Contractor
- ❍ Other (please specify)

If you selected other, please specify: ______________________________

PART 6: FWD FIELD TESTING—FLEXIBLE PAVEMENTS

All responses in this section should specifically refer to your agency's testing methods on asphalt concrete pavements.

29) What kind of flexible pavement field testing manual does your agency use?

❍ FHWA
❍ Agency-developed
❍ Consultant-developed
❍ Vendor-developed
❍ Other (please specify)

If you selected other, please specify: ____

30) How much time does a complete flexible pavement network level FWD testing cycle take?

(number)	(days/weeks/months/years)

31) For flexible pavement at the network level, are FWD tests done before the project starts, after the project is completed, or both? (Check all that apply)

❑ Before the project starts
❑ After the project is completed
❑ Additional testing is done during construction

Additional comments: ____

32) For any given flexible pavement project, approximately how soon *before the project starts* does your agency perform FWD tests?

(number)	(days/weeks/months/years)

33) For any given flexible pavement project, approximately how soon *after the project is completed* does your agency perform FWD tests?

(number)	(days/weeks/months/years)

34) Where on flexible pavements are data collected? (Check all that apply)

❑ Right wheel path
❑ Left wheel path
❑ Center of lane
❑ Outer lane (where multiple lanes are present)
❑ Inner lane (where multiple lanes are present)

For each of the following levels, describe your flexible pavement measurement variables, where applicable.

35) Project level (including forensics)

Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

36) Network level

Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

37) Research

Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

38) Other levels

Other level name	
Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

39) Under which of these conditions is flexible pavement testing *not* allowed? (Check all that apply)

- ❑ Air temperature greater than 100°F (38°C)
- ❑ Air temperature less than 32°F (0°C)
- ❑ Night
- ❑ High winds
- ❑ Wet pavement surface
- ❑ Other (please specify)

If you selected other, please specify: ____

PART 7: FWD FIELD TESTING—RIGID PAVEMENTS

All responses in this section should specifically refer to your agency's testing methods on portland cement concrete pavements.

40) What kind of rigid pavement field testing manual does your agency use?

- ❍ FHWA
- ❍ Agency-developed
- ❍ Consultant-developed
- ❍ Vendor-developed
- ❍ Other (please specify)

If you selected other, please specify: ____________________

41) How much time does a complete rigid pavement network level FWD testing cycle take?

(number)	(days/weeks/months/years)

42) For rigid pavement at the network level, are FWD tests done before the project starts, after the project is completed, or both? (Check all that apply)

- ❑ Before the project starts
- ❑ After the project is completed
- ❑ Additional testing is done during construction

Additional comments: ____________________

43) For any given rigid pavement project, approximately how soon *before the project starts* does your agency perform FWD tests?

(number)	(days/weeks/months/years)

44) For any given rigid pavement project, approximately how soon *after the project is completed* does your agency perform FWD tests?

(number)	(days/weeks/months/years)

45) Where on rigid pavements are data collected? (Check all that apply)

- ❑ Right wheel path
- ❑ Left wheel path
- ❑ Center of lane
- ❑ Slab corner
- ❑ Slab edge
- ❑ Outer lane (where multiple lanes are present)
- ❑ Inner lane (where multiple lanes are present)

For each of the following levels, describe your rigid pavement measurement variables, where applicable.

46) Project level (including forensics)

Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

47) Network level

Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

48) Research

Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

49) Other levels

Other level name	
Number of replicate drops required	
Drop load (separate values with commas)	
Drop load units (lb, kip, kg, N, kN)	
Sensor spacing from center (separate values with commas)	
Sensor spacing units (in or mm)	
Number of temperature gradient holes	
Temperature gradient hole depths (separate values/descriptions with commas)	
Temperature gradient hole depth units (in or mm)	
Temperature gradient hole measurement frequency (minutes)	
Other testing variables	

50) Under which of these conditions is rigid pavement testing *not* allowed? (Check all that apply)

- ❑ Air temperature greater than 100°F (38°C)
- ❑ Air temperature less than 32°F (0°C)
- ❑ Night
- ❑ High winds
- ❑ Wet pavement surface
- ❑ Other (please specify)

If you selected other, please specify: ____

PART 8: FWD COMPUTERS

51) What type of field data collection computers are most commonly used?

❍ Desktops
❍ Laptops
❍ Other (please specify)

If you selected other, please specify: ____________________

52) What is the name of the FWD data collection software used in the field? (Separate multiple names and versions with commas)

Name	
Version	

53) In which format does your FWD equipment give its output? (Check all that apply)

❑ AASHTO Pavement Data Deflection Exchange (PDDX)
❑ ASCII-format binary data (*.bin)
❑ Comma-separated values (*.csv)
❑ Dynatest format (*.fwd)
❑ Extensible markup language (*.xml)
❑ Raw data file (*.dat)
❑ Unformatted text (*.txt)
❑ Other (please specify)

If you selected other, please specify: ____________________

54) What operating system does your FWD unit(s) use?

❍ MS-DOS 6 or prior
❍ Windows 3.1x
❍ Windows 95/98/Me/NT 4.0
❍ Windows 2000/2003/XP/Vista
❍ Mac OS 8/9
❍ Mac OS X
❍ Linux (any distribution)
❍ Other (please specify)

If you selected other, please specify: ____________________

PART 9: DATA ANALYSIS

55) Which of the following quality checks are performed by FWD operators? (Check all that apply)

- ❑ Roll-off
- ❑ Decreasing deflections
- ❑ Out of range
- ❑ Load variation
- ❑ Deflection variation
- ❑ Other (please specify)

If you selected other, please specify: ______________________________

56) What software is used to perform data quality checks in the field? (Separate multiple names and versions with commas)

Name	
Version	

57) What software is used to perform data quality checks in the office? (Separate multiple names and versions with commas)

Name	
Version	

58) Does your agency use FWD data to estimate pavement layer moduli?

- ❍ Yes
- ❍ No

59) What software is used to perform layer modulus calculations using FWD data? (Separate multiple names and versions with commas)

Name	
Version	

60) Does your agency use a seasonal and/or temperature adjustment factor(s) in determining layer moduli using FWD data?

- ❍ Yes
- ❍ No

PART 10: DATA MANAGEMENT AND STORAGE

61) Are FWD program and configuration backups stored in the FWD vehicle?

- ❍ Yes
- ❍ No

62) Does the FWD Operator back up FWD data files to any external media (e.g., floppy disks, CD-ROM, USB flash drive, etc.) prior to leaving the test site?

- ❍ Yes
- ❍ No

63) How long are raw FWD field data stored?

(number)	(weeks/months/years/indefinite)

PART 11: PERSONNEL TRAINING

64) How many months of training is required for new FWD operators?

65) How many months of training is required for new FWD data analysts?

66) Does your agency provide training to FWD operators?

- ❍ Yes
- ❍ No

67) If yes, please describe.

68) Does your agency provide training to FWD data analysts?

- ❍ Yes
- ❍ No

69) If yes, please describe.

70) Does your agency have a certification program for FWD operators?

- ❍ Yes
- ❍ No

71) If yes, please describe.

72) Does your agency have a certification program for FWD data analysts?

❍ Yes

❍ No

73) If yes, please describe.

74) Does your agency send representatives to the annual FWD User's Group meeting?

❍ Yes

❍ No

75) Would your agency support a National Highway Institute (NHI) course on FWD usage?

❍ Yes

❍ No

PART 12: FWD PROGRAM ADMINISTRATION—PART 1 OF 2

76) How many full-time staff are involved with your FWD program?

Technicians	
Engineers	
Others (please describe)	

77) If you answered others above, please describe.

78) Have there been any FWD-related accidents within the past 5 years?

- ❍ Yes
- ❍ No

79) If yes, how many?

80) Please describe the type(s) and severity of FWD-related accidents within the past 5 years.

PART 13: FWD PROGRAM ADMINISTRATION—PART 2 OF 2

81) Does your agency have an FWD Quality Control and/or Quality Assurance plan(s) in effect for the entire FWD program (e.g., data collection, data analysis, data storage, maintenance, etc.)?

- ❍ Yes *(please provide a copy to fwdsurvey@ste-group.com)*
- ❍ No

82) What is the average annual operating budget—including labor, materials, travel, etc.—for your FWD testing program?

(dollars)

83) What fraction of your FWD program budget is applied to:

In-house activities	(percent)
Outsourced activities	(percent)

84) If outsourced, what are the contract requirements for personnel training, equipment calibration, data quality, and other deliverables?

85) What percentage of your FWD program budget is dedicated to each of the following levels?

Project level (including forensics)	(percent)
Network level	(percent)
Research	(percent)
Other (please describe)	(percent)

86) If you answered other above, please describe.

87) Approximately what lane-distance does your FWD program test annually?

Lane-distance	(number)
Lane-distance units	(lane-mi or lane-km)

88) Please provide any additional comments on the advantages of FWD use in your agency.

APPENDIX B

SUMMARY OF SURVEY RESULTS

The responses to the survey questionnaire are presented in this appendix.

The data were processed using a spreadsheet. If a state highway agency (SHA) contributed two or more responses, those responses were combined into a single response. Except where explicitly noted, responses not from SHAs were excluded from the analysis. Additionally, SHAs that do not have falling weight deflectometer (FWD) programs were excluded from analysis.

Questions with verbose answers were quantified, where mathematically and logically possible. However, responses of "not applicable," "invalid," or notes to delete answers to previous questions were not considered for analysis.

PART 1: BACKGROUND INFORMATION

Question 1: Respondent's Contact Information

TABLE B1

SURVEY QUESTION 1: RESPONDENT'S CONTACT INFORMATION

Agency/Organization Reporting	Respondent's Title
Alabama Department of Transportation	Assistant Pavement Management Engineer
Alaska Department of Transportation and Public Facilities	State Pavement Engineer
Arizona Department of Transportation	Supervisor
Arkansas Highway and Transportation Department	Staff Planning Engineer
California Department of Transportation	Senior Transportation Engineer
Colorado Department of Transportation	E/PS Technician II
Colorado Department of Transportation	PE I
Connecticut Department of Transportation	Transportation Supervising Engineer (Pvt. Mgmt.)
Florida Department of Transportation	Pavement Performance Engineer
Hawaii Department of Transportation, Highways Division	Civil Engineer
Idaho Transportation Department	Assistant Materials Engineer
Illinois Department of Transportation	Pavement Analysis Engineer
Indiana Department of Transportation	Section Manager
Iowa Department of Transportation	Special Investigations Engineer
Kansas Department of Transportation	Pavement Evaluation Specialist
Louisiana Transportation Research Center (Louisiana Department of Transportation and Development)	Senior Pavement Research Engineer
Maine Department of Transportation	Falling Weight Deflectometer Coordinator
Maryland State Highway Administration	Assistant Division Chief
Michigan Department of Transportation	FWD Specialist, Pavement Performance Engineer
Minnesota Department of Transportation	Deflection Testing and Analysis
Mississippi Department of Transportation	FWD and Field Operations EIT
Missouri Department of Transportation	Pavement Engineer
Montana Department of Transportation	NDT Supervisor
Nevada Department of Transportation	Senior Materials Supervisor
New Mexico Department of Transportation	Geologist Manager
New Jersey Department of Transportation	Principal Engineer
North Carolina Department of Transportation, Pavement Management Unit	TE II—Pavement Design/ Analysis Engineer
North Dakota Department of Transportation	Transportation Engineer
New York State Department of Transportation	Civil Engineer 2
Ohio Department of Transportation	Pavement Research Engineer
Oregon Department of Transportation	Pavement Design Engineer
Pennsylvania Department of Transportation, Bureau of Maintenance and Operations	Roadway Programs Specialist
Rhode Island Department of Transportation	Principal Civil Engineer

continued

TABLE B1 (*continued*)

Agency/Organization Reporting	Respondent's Title
South Dakota Department of Transportation	Engineering Supervisor
South Carolina Department of Transportation	State Pavement Design Engineer
Tennessee Department of Transportation	CE Manager II
Texas Department of Transportation	Pavement Engineering Specialist
Utah Department of Transportation	Pavement Management Engineer
Vermont Agency of Transportation	Transportation Tech IV
Virginia Department of Transportation	NDT Manager
Washington State Department of Transportation	Engineer 4
West Virginia Department of Transportation	HE4
Wisconsin Department of Transportation	Engineering Specialist
Dynatest Consulting, Inc.	Marketing Manager

Note*:* CE = Civil Engineer; E/PS = Engineering/Physical Science; HE = Highway Engineer; PE = Project Engineer; TE = Transportation Engineer; EIT = Engineer-in-Training.

PART 2: FWD EQUIPMENT TYPES

Questions 2–6: How many FWDs does your agency use? How old are they?

TABLE B2

SURVEY QUESTIONS 2–6: "HOW MANY FWDS DOES YOUR AGENCY USE? HOW OLD ARE THEY?"

FWD Manufacturer	Quantity of FWDs in Service (total)	Ages of FWDs (years, average)
Dynatest	61	14.33
Foundation Mechanics	15	5.71
KUAB	6	13.50
Carl Bro	0	Not applicable
Other	0	Not applicable
Total	82	11.18

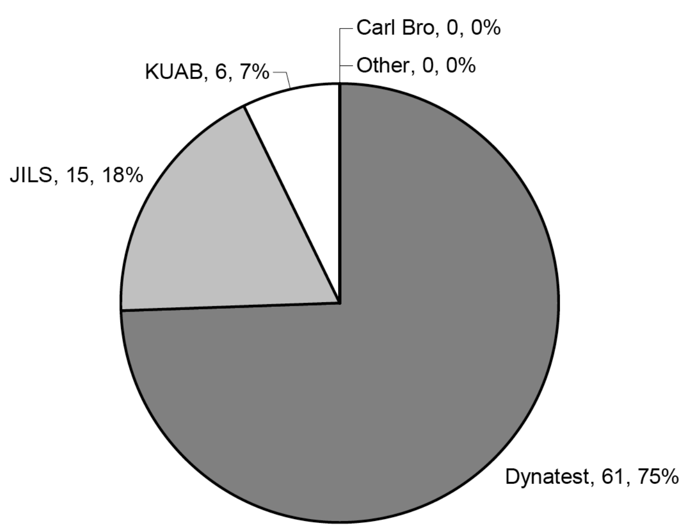


FIGURE B1 Survey response to Questions 2-6: "How many FWDs does your agency use? How old are they?"

PART 3: FWD EQUIPMENT MAINTENANCE

Question 7: Does your agency have a written FWD maintenance plan?

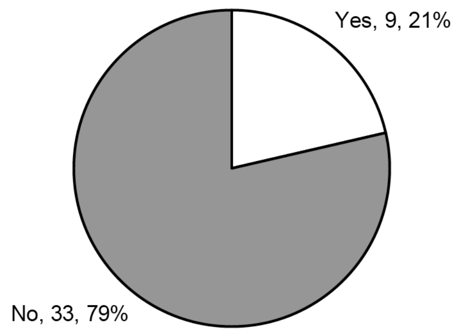


FIGURE B2 Survey response to Question 7: "Does your agency have a written FWD maintenance plan?"

Question 8: If not, please describe your FWD maintenance activities. Include scheduling and activity descriptions.

TABLE B3

SURVEY QUESTION 8: "IF NOT, PLEASE DESCRIBE YOUR FWD MAINTENANCE ACTIVITIES: INCLUDE SCHEDULING AND ACTIVITY DESCRIPTIONS"

State	Response
Alaska	Lubrication once a year. Relative calibration annually.
Arizona	Weekly system maintenance.
California	For FWD maintenance documentation we use the manufacturer's manual. We have annual preventative maintenance performed at the manufacturer's facility prior to the annual calibration. Routine maintenance activities are performed by FWD operators and equipment shop mechanics.
Colorado	Follow manufacturer's schedule. The JILS is fairly maintenance free. • Annual maintenance checks and service • Fluid check/change • Brakes • Tires • Mechanical check (FWD equipment)
Idaho	Every 2 weeks the crew bleeds the hydraulic system. They do a daily check of the FWD trailer and schedule other maintenance as needed.
Illinois	Routine maintenance of tow vehicle. Repair operational problems with FWD as they arise.
Indiana	Winter maintenance activities include (maintenance procedures on) data acquisition, computer, sensors, cabling, mechanical, monitoring devices, and vehicles.
Iowa	• Geosensor stability spring replacement annually • Load spring (bumper) replacement every 2 years • Cleaning, wiring maintenance, inspection annually
Kansas	We check (our FWDs) out before each season looking for worn or broken parts, and we test them for proper operation.
Louisiana	Calibrated at manufacturer once a year, plus monthly relative calibration.

continued

TABLE B3 (*continued*)

State	Response
Maine	Overall maintenance is completed on an as-needed basis. Greasing, oil changes, etc., are completed on a schedule.
Maryland	(We follow) manufacturers' manual suggestions.
Michigan	Yearly preventive maintenance program with ERI, Inc., the U.S. KUAB representative.
Minnesota	Routine—performed weekly or as needed by the FWD operator. Annual—performed yearly by agency personnel. Major—performed by vendor.
Missouri	We fix problems as they come up. Usually, we have to bleed air out of the hydraulic lines about once a year.
Montana	The vehicle maintenance is performed by our own mechanics, based on amount of mileage driven, and our operators. Our mechanics perform scheduled maintenance every 5,000 and 30,000 miles. Once a year, they are inspected by the vendor during yearly SHRP calibration.
Nebraska	We do project maintenance and annually we send it to KUAB for maintenance.
Nevada	Vehicles (both tow vehicle and FWD) are checked out prior to leaving for the job. In addition, our Equipment Division has preventive maintenance checks that come due every 6 months.
New Mexico	(We perform) quarterly servicing, using service and maintenance manuals. Velocity transducer calibrations and technical support for maintenance and repairs (are provided by the) vendor.
New York	Our Equipment Management Facility at Waterford performs regular maintenance of FWD vehicles. We usually send (FWD trailers) to KUAB and Dynatest for maintenance; not every year, but at an interval of several years.
North Dakota	• Monthly—clean the sensor bases and holders with an emery cloth. • Every other day—lubricate the sensor guides. • Once a month—grease the load cell. • Daily—check hydraulic fluid level. • A draft manual of FWD procedures has been started but not finalized.
Ohio	One day a week is set aside for data processing and maintenance, if needed. During the off season, equipment is inspected and preventive maintenance performed.
Oregon	Trailer serviced at 5,000-mile intervals with scheduled tow vehicle maintenance. Weekly calibration checks at five known locations—two on PCC and three on AC. Sensor stack calibration check done every 8 weeks.
Rhode Island	Our FWD is not used very often and has not yet required any significant maintenance.
South Carolina	Monthly relative calibration, lubrication, and visual inspection. Biennial service visits to manufacturer.
South Dakota	Maintenance (is performed) in-house.
Tennessee	We do not currently utilize our FWD on a regular basis.
Utah	(We follow) manufacturers' recommendations.
Vermont	Relative calibrations are done by operator, trailer maintenance by operator and state agency.
Virginia	Vehicle maintenance is done by the local VDOT shop on a maintenance schedule set up by the equipment division. Maintenance on the trailer and electronics is performed by the operator in accordance with guidelines established by the vendor.
Washington State	Yearly maintenance service is performed on hydraulic system, catch assembly, batteries, and calibration of load cell and sensors.
Wisconsin	Greasing, oiling, sensor calibration, DMI (distance measuring instrument) calibration, troubleshooting electronics, and battery testing.

Question 9: Who performs maintenance activities on the FWD equipment your agency uses? (Check all that apply.)

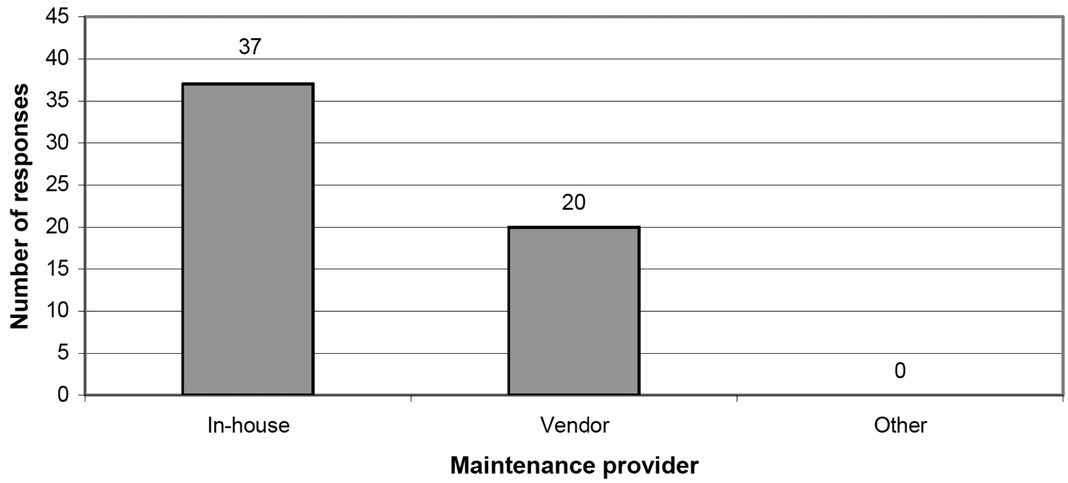
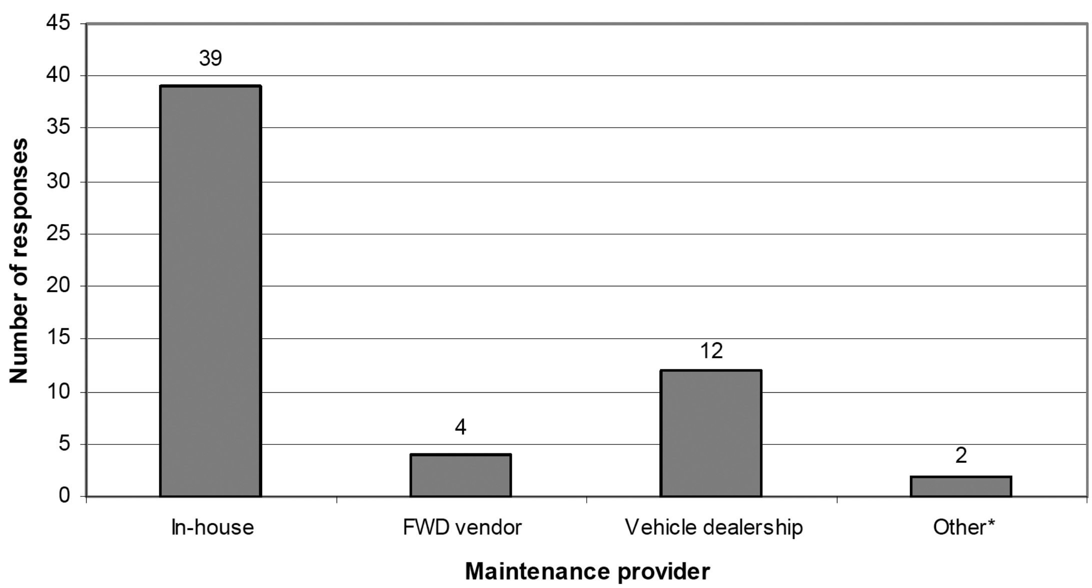


FIGURE 3 Survey response to Question 29, "What kind of flexible pavement field testing manual does your agency use?"

Question 10: Who performs maintenance activities on the FWD vehicles your agency uses? (Check all that apply.)



* Other response: (1) state garage, (1) did not answ er

FIGURE B4 Survey response to Question 10: "Who performs maintenance activities on the FWD vehicles your agency uses?" (Check all that apply.)

Question 11: Please describe any additional practices that have kept your FWD equipment in good working order.

TABLE B4

SURVEY QUESTION 11: "PLEASE DESCRIBE ANY ADDITIONAL PRACTICES THAT HAVE KEPT YOUR FWD EQUIPMENT IN GOOD WORKING ORDER"

State/Manufacturer	Response
Alabama	Technicians perform weekly walk-around prior to taking equipment out.
Alaska	Check lube, tightness of bolts and connections.
Arizona	Weekly system service.
California	We have a vehicle usage and/or time limit for vehicle maintenance. Routine inspection of the FWD equipment is also performed at those maintenance intervals. FWD problems are either fixed in-house or sent to the manufacturer to fix.
Colorado	Garaged to protect it from weather when not in use. Continuous operator maintenance during use.
Florida	Monthly visual checks for all general items such as lights, tires, sun degradation of electrical components, and general corrosion of exposed components.
Idaho	We perform relative calibrations to check for problems. Check and replace worn or damaged parts.
Indiana	No winter testing.
Iowa	Replacement of geosensors every 3 years. Replacement of transducer approx. 5 years (depending on usage/wear). Annual calibration at Denver, Colorado, facility. Monthly relative calibrations of geosensors.
Louisiana	We have a full-time mechanic who keeps all of our equipment in working condition.
Maryland	Operator involvement (ownership).
Michigan	Common sense.
Missouri	We try to house the equipment indoors as much as possible.
Montana	Our FWDs and their vehicles are pressure washed and the inside of the vehicle is wiped down every Thursday. This helps with dust in the computer systems and then all of the hydraulic rams can be inspected and lubed.
Nevada	Vehicles are kept clean. Any signs of leaks are fixed ASAP. If we have any operating problems that we cannot resolve, we call the manufacturer for assistance.
New Jersey	We also perform in-house maintenance as necessary.
New Mexico	Operational standards are set for testing. Daily walk-around inspection of the working parts for unit.
New York	Our operator attends the FWD User Group meeting where operators discuss FWD maintenance. FWD Calibration Center Operator also provides tips regarding good maintenance habits.
North Carolina	Sheltered storage and washed regularly.
Oregon	Services are done at 5,000-mile intervals at same time the towing vehicle is serviced.
Pennsylvania	Keeping all the components clean and the FWD units indoors when they are not being used.
South Carolina	Our oldest unit was overhauled and updated by the manufacturer approximately 10 years ago.
Utah	Annual calibration.
Vermont	Stored in a heated garage.
Washington	Daily pre-inspection inspection of working operation.
Wisconsin	Strive to gain rudimentary knowledge of electrical symbols and components to help in trouble shooting.
Dynatest Consulting, Inc.	We have several different maintenance/overhaul/upgrade plans to meet customer needs and budgets.

PART 4: FWD EQUIPMENT CALIBRATION

Question 12: Does your agency require calibration of FWD equipment?

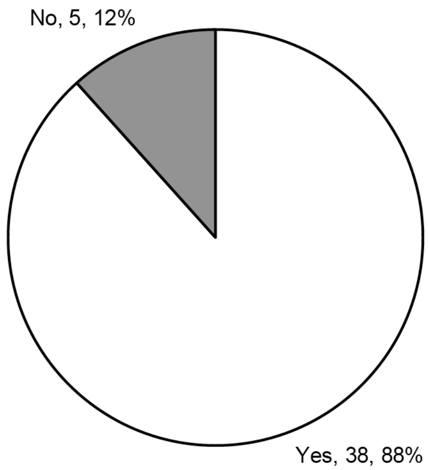


FIGURE B5 Survey response to Question 12: "Does your agency require calibration of FWD equipment?"

Question 13: If yes, how often do you perform relative calibrations?

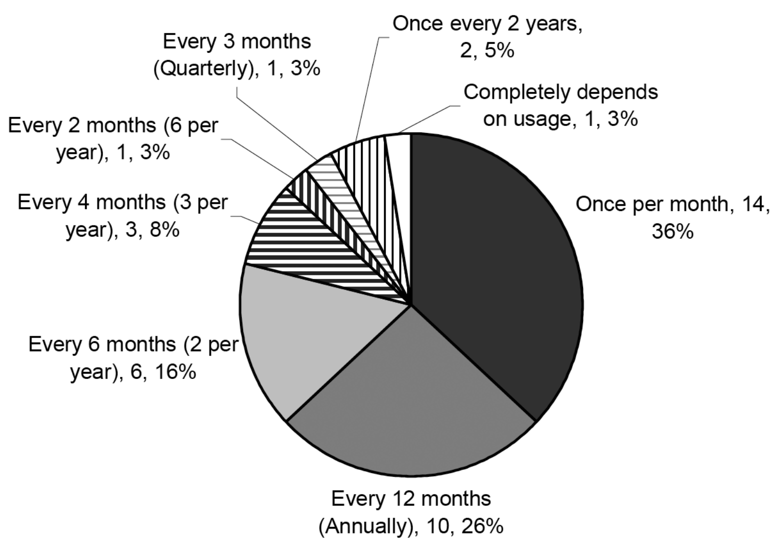


FIGURE B6 Survey response to Question 13: "If yes, how often do you perform relative calibrations?"

Question 14: If yes, how often do you perform reference calibrations?

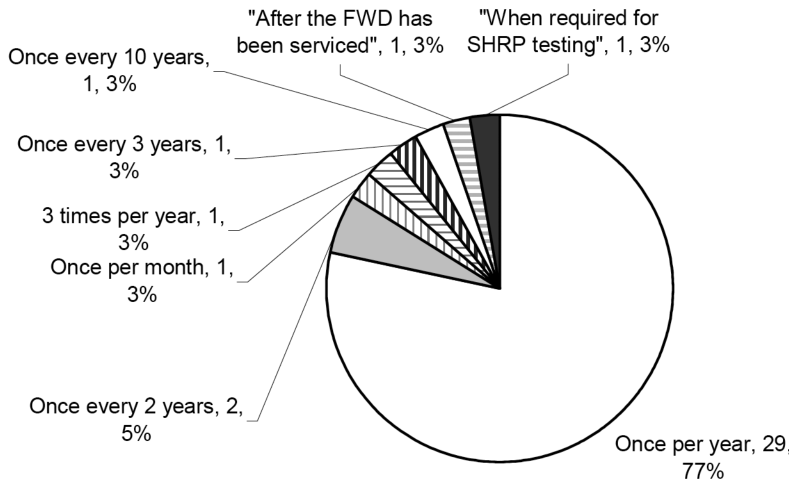
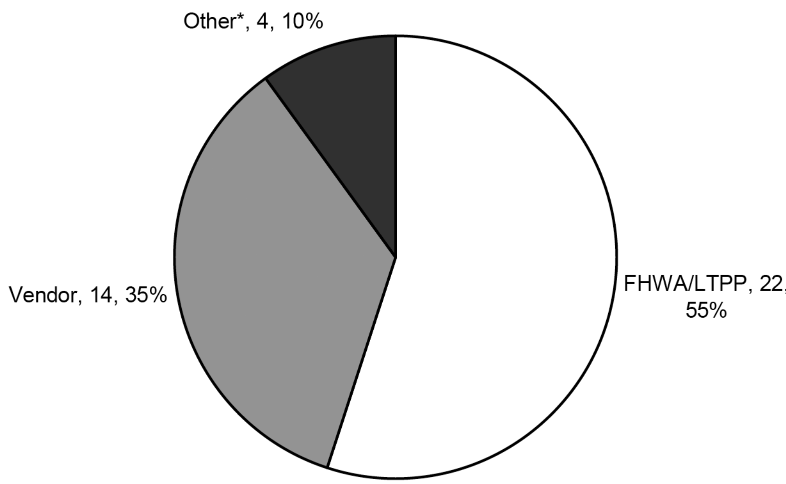


FIGURE B7 Survey response to Question 14: "If yes, how often do you perform reference calibrations?"

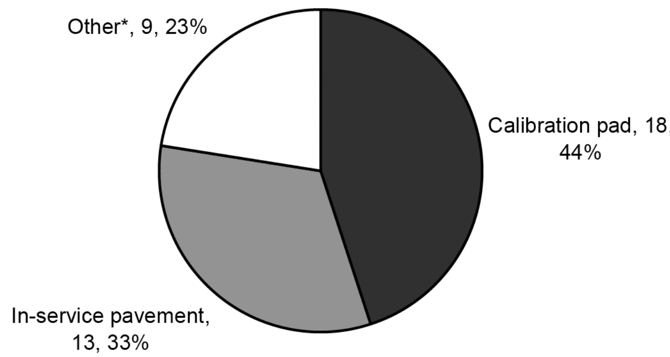
Question 15: Whose procedure do you follow to perform a relative calibration? (If you choose other, please specify your procedure—including load magnitudes and repetitions—in the space below or provide a copy to fwdsurvey@ste-group.com.)



* Other responses: (2) ASTM D4694, (1) TxDOT calibration protocol, (1) (internal) informal process, local testing.

FIGURE B8 Survey response to Question 15: "Whose procedure do you follow to perform a relative calibration?" (If you choose other, please specify your procedure—including load magnitudes and repetitions—in the space below, or provide a copy to fwdsurvey@ste-group.com.)

Question 16: What surface do you use to conduct a periodic relative calibration test?



* Other responses: (4) parking area, (3) unspecified concrete slab or floor, (1) concrete pad at manufacturer's facility, (1) no additional information

FIGURE B9 Survey response to Question 16: “What surface do you use to conduct a periodic relative calibration test?”

Question 17: Where do you have your reference calibrations done (organization name, city, and state)?

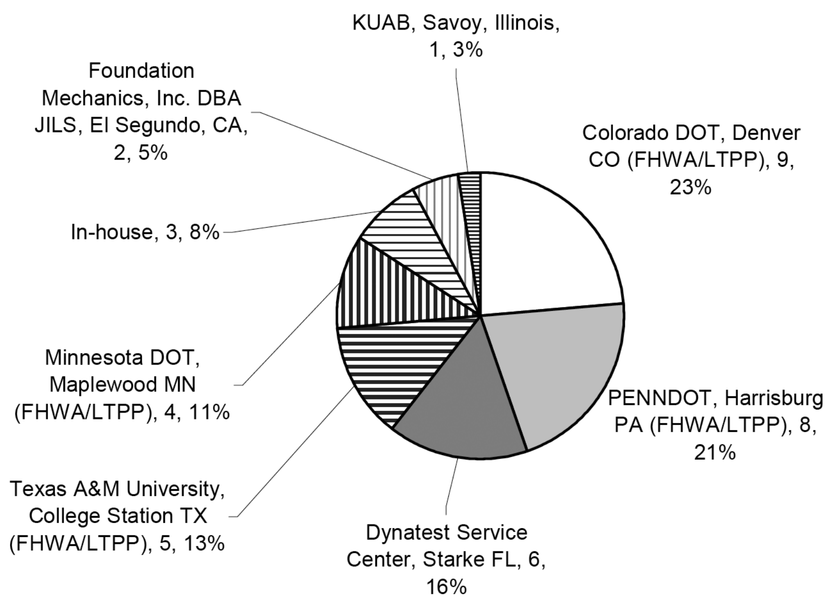


FIGURE B10 Survey response to Question 17, organized by facility name and location: “Where do you have your reference calibrations done?” (Organization name, city, and state)

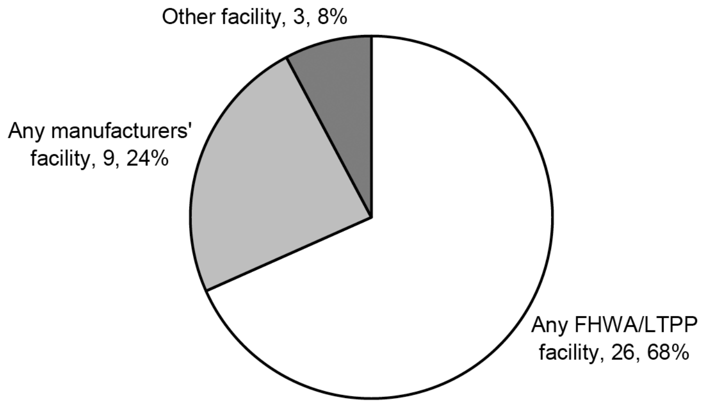


FIGURE B11 Survey response to Question 17, organized by facility operator: "Where do you have your reference calibrations done?" (Organization name, city, and state)

Question 18: If your agency does require calibration, how far must the equipment typically travel?

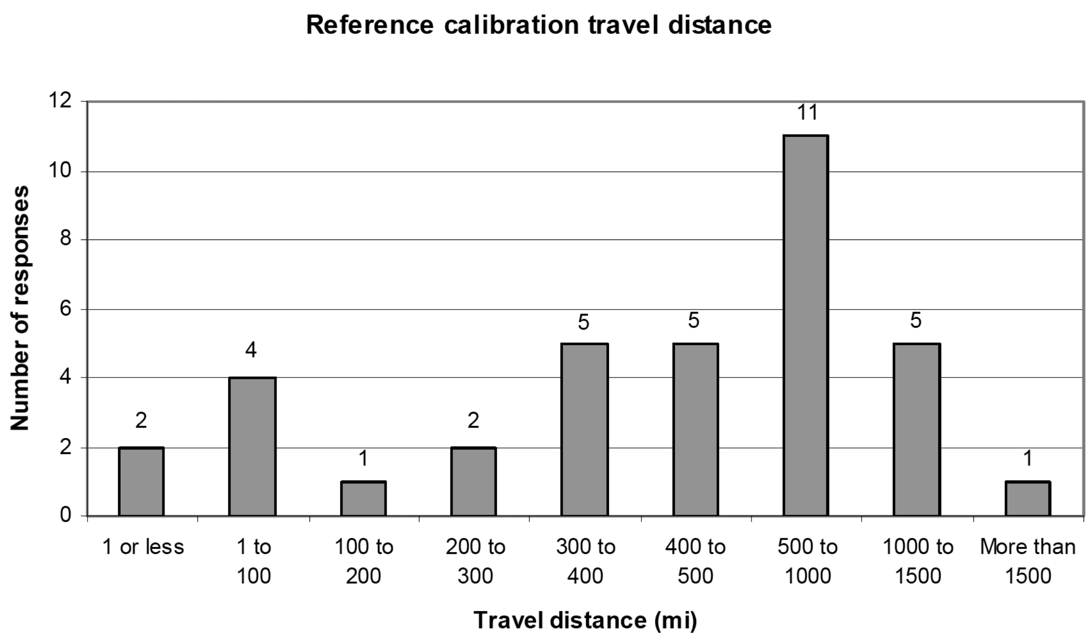


FIGURE B12 Survey response to Question 18, reference calibrations: "If your agency does require calibration, how far must the equipment typically travel?"

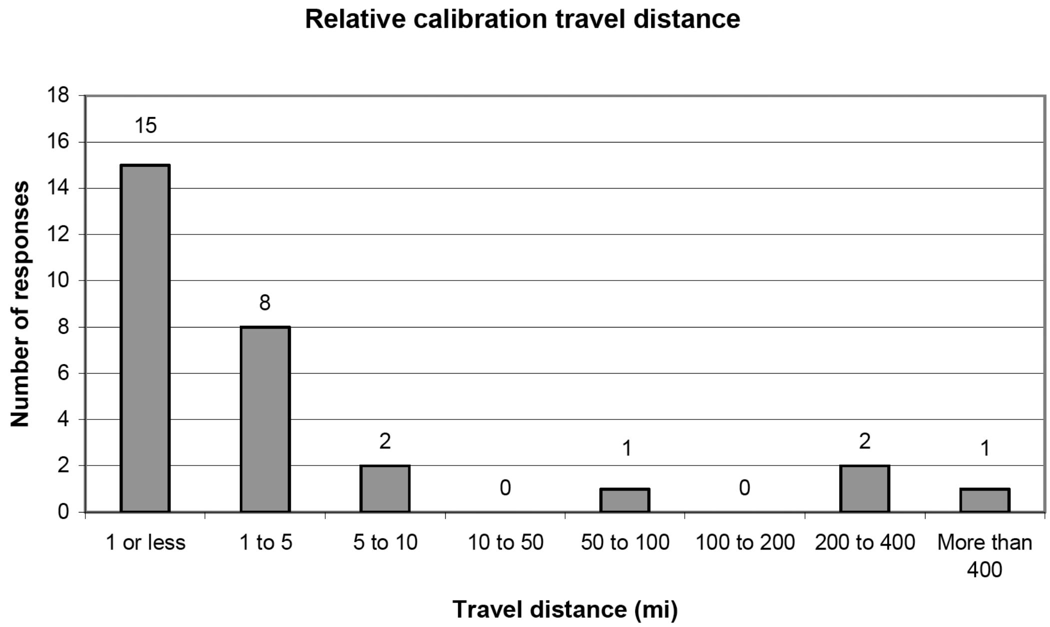


FIGURE B13 Survey response to Question 18, relative calibrations: "If your agency does require calibration, how far must the equipment typically travel?"

Question 19: If your agency does require calibration, what is the approximate cost per calibration session, including total labor, materials, travel, and incidental expenses?

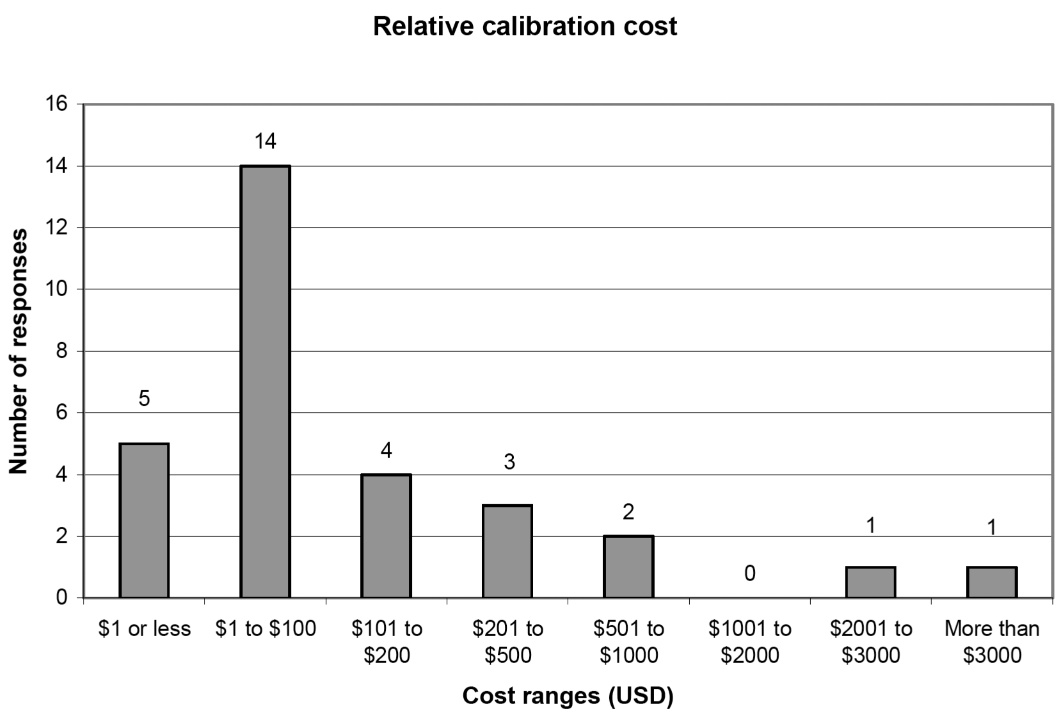


FIGURE B14 Survey response to Question 19, relative calibrations: "If your agency does require calibration, what is the approximate cost per calibration session, including total labor, materials, travel, and incidental expenses?"

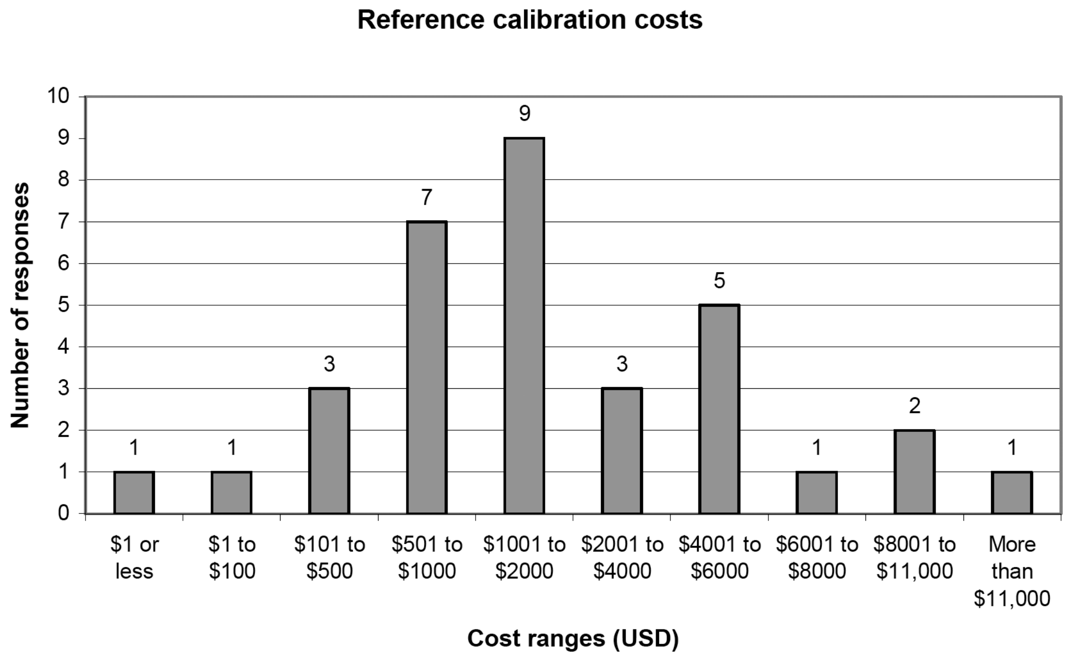


FIGURE B15 Survey response to Question 19, reference calibrations: "If your agency does require calibration, what is the approximate cost per calibration session, including total labor, materials, travel, and incidental expenses?"

Question 20: Would your agency favor additional calibration centers?

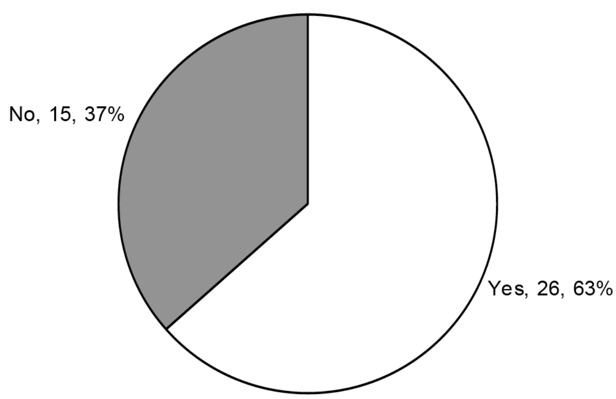


FIGURE B16 Survey response to Question 20: "Would your agency favor additional calibration centers?"

Question 21: Would your agency sponsor such a calibration facility?

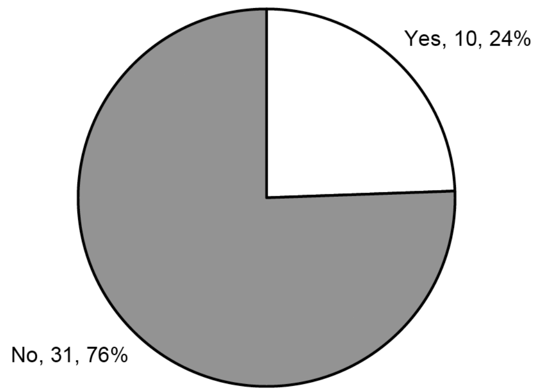


FIGURE B17 Survey response to Question 21: "Would your agency sponsor such a calibration facility?"

PART 5: GENERAL FWD TESTING PROCEDURES

Question 22: How many crew members do you use to operate an FWD unit on a typical project?

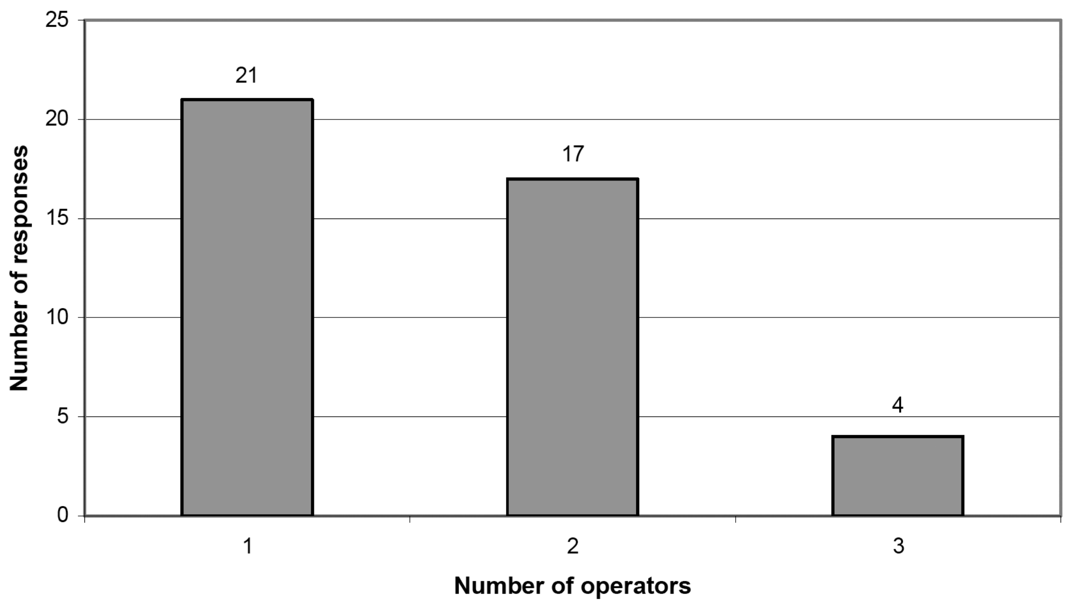


FIGURE B18 Survey response to Question 22: "How many crew members do you use to operate an FWD unit on a typical project?"

Question 23: What facilities do you test with the FWD? (Check all that apply.)

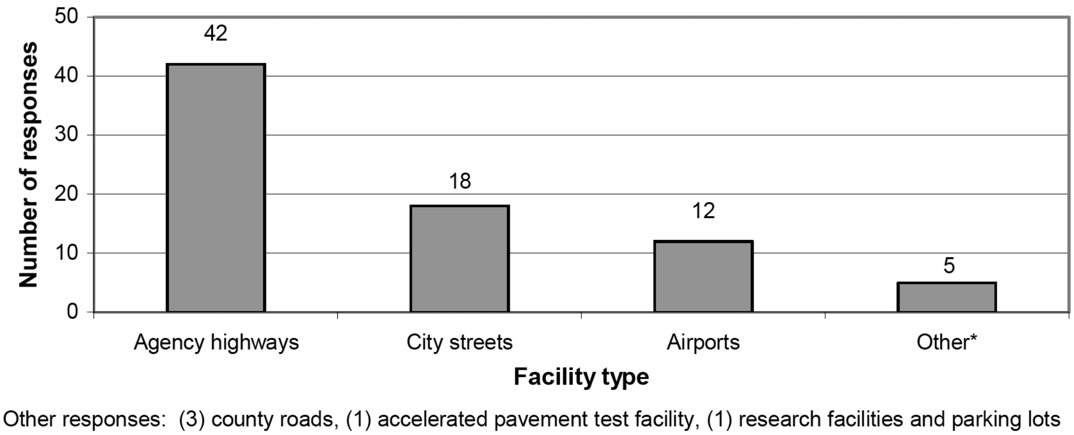


FIGURE B19 Survey response to Question 23: "What facilities do you test with the FWD?" (Check all that apply.)

Question 24: What is the average lead time from the date you receive a request to the date of testing?

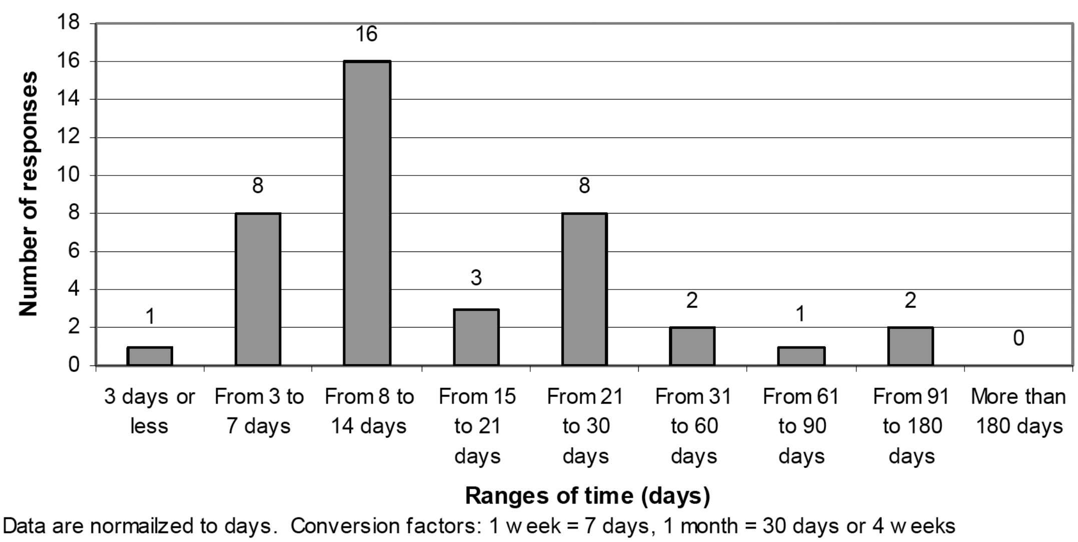


FIGURE B20 Survey response to Question 24: "What is the average lead time from the date you receive a request to the date of testing?"

Question 25: What is the average turnaround time from the date of testing to the date the results are submitted to your customer?

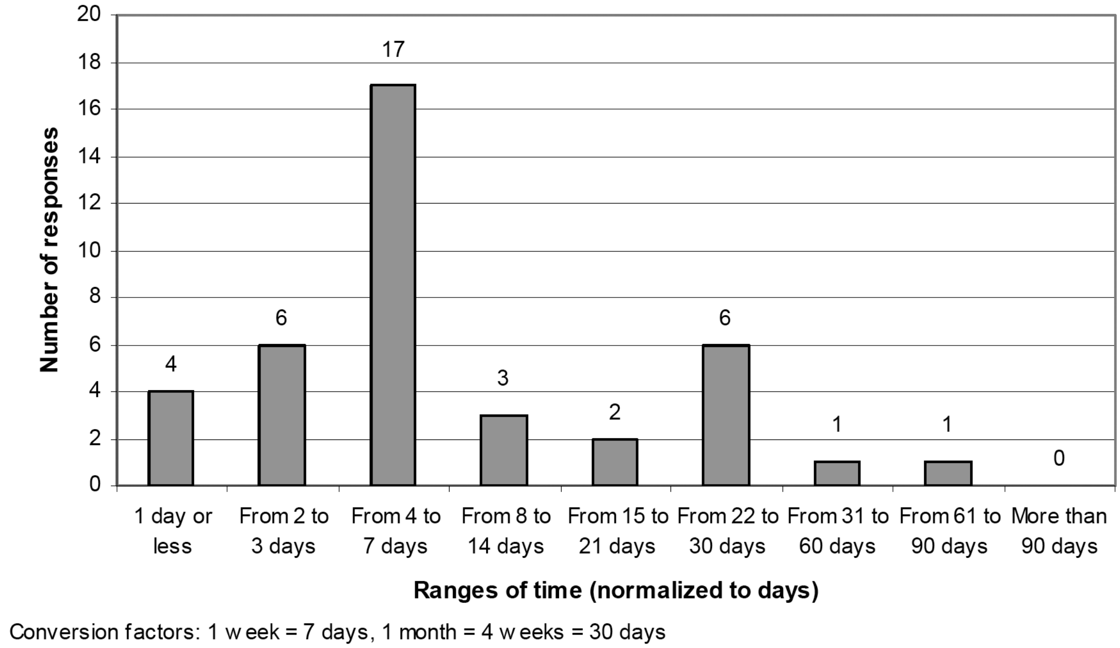


FIGURE B21 Survey response to Question 25: "What is the average turn-around time from the date of testing to the date the results are submitted to your customer?"

Question 26: Is there an equipment inspection checklist prior to testing?

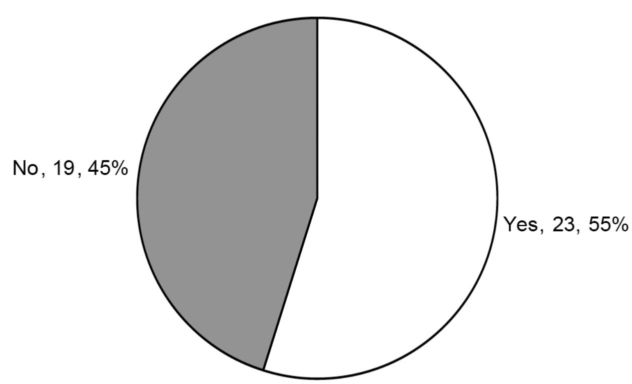


FIGURE B22 Survey response to Question 26: "Is there an equipment inspection checklist prior to testing?"

Question 27: Is there a written warm-up procedure prior to testing?

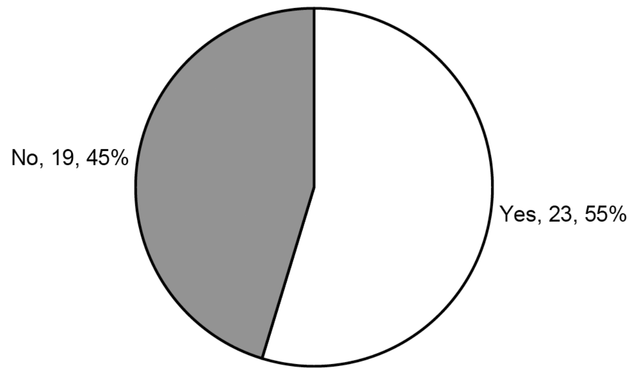
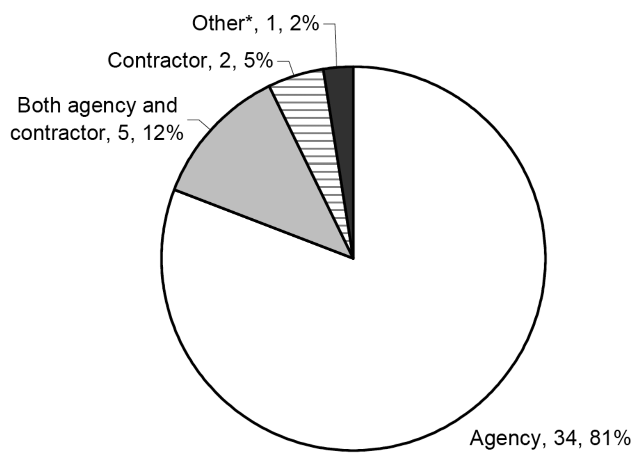


FIGURE B23 Survey response to Question 27: “Is there a written warm-up procedure prior to testing?”

Question 28: Who provides traffic control?

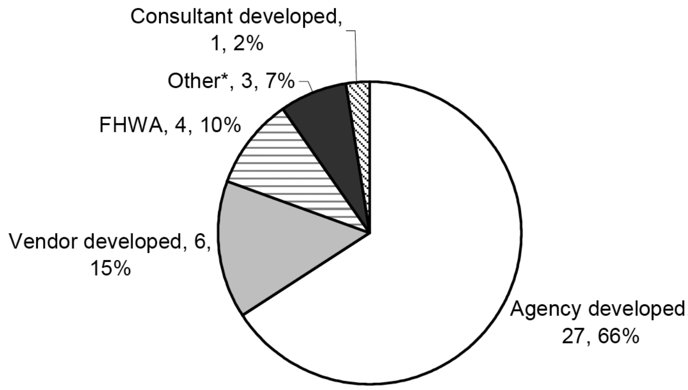


* Other response: (1) "Crew conducts own traffic control."

FIGURE B24 Survey response to Question 28: “Who provides traffic control?”

PART 6: FWD FIELD TESTING—FLEXIBLE PAVEMENTS

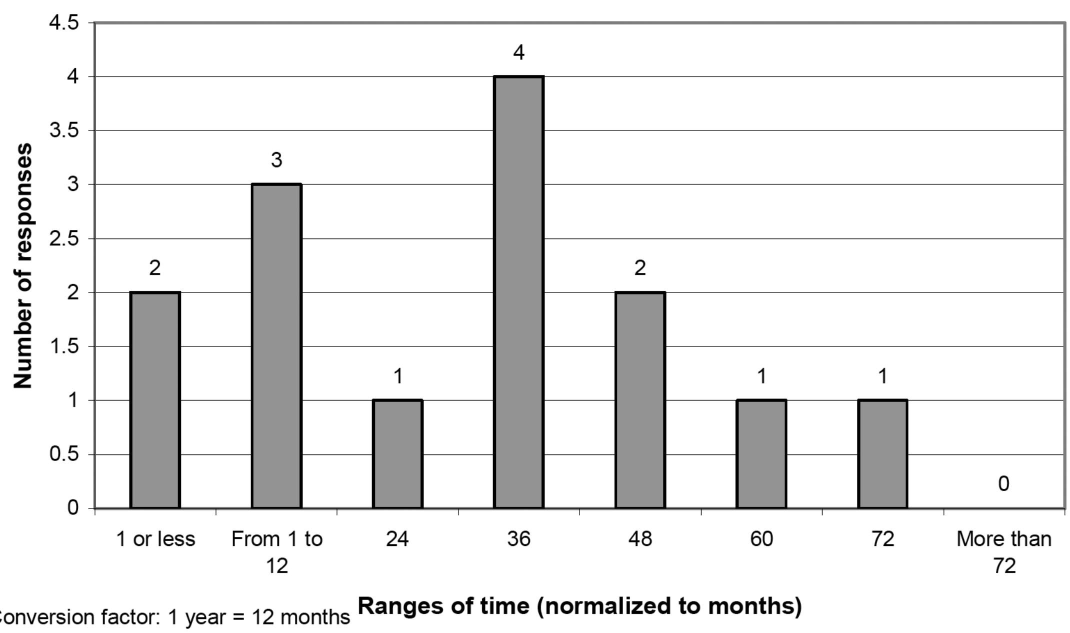
Question 29: What kind of flexible pavement field testing manual does your agency use?



* Other responses: (2) none, (1) ASTM

FIGURE B25 Survey response to Question 29: "What kind of flexible pavement field testing manual does your agency use?"

Question 30: How much time does a complete flexible pavement network-level FWD testing cycle take?



Conversion factor: 1 year = 12 months

FIGURE B26 Survey response to Question 30: "How much time does a complete flexible pavement network level FWD testing cycle take?"

Question 31: For flexible pavement at the network level, are FWD tests done before the project starts, after the project is completed, or both?

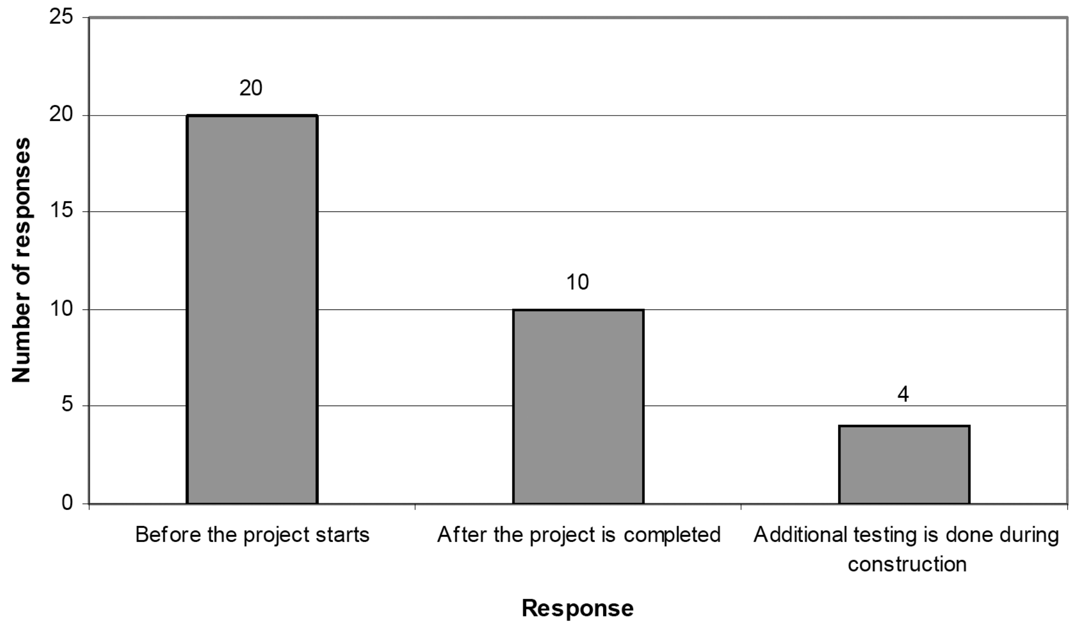


FIGURE B27 Survey response to Question 31: "For flexible pavement at the network level, are FWD tests done before the project starts, after the project is completed, or both?"

Question 32: For any given flexible pavement project, approximately how soon *before the project starts* does your agency perform FWD tests?

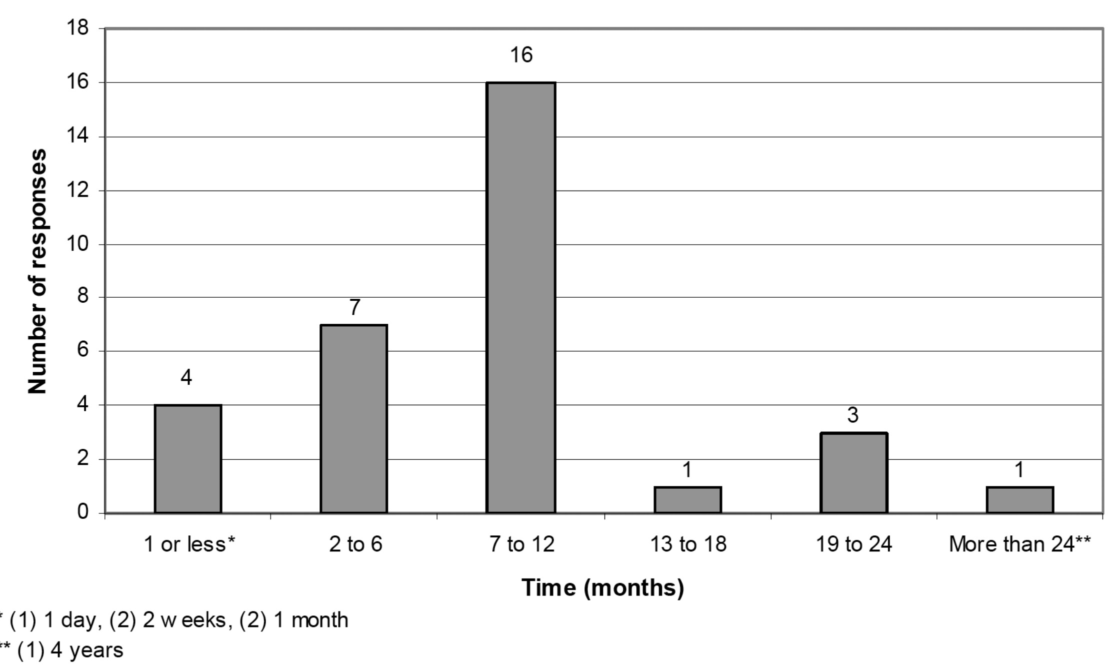
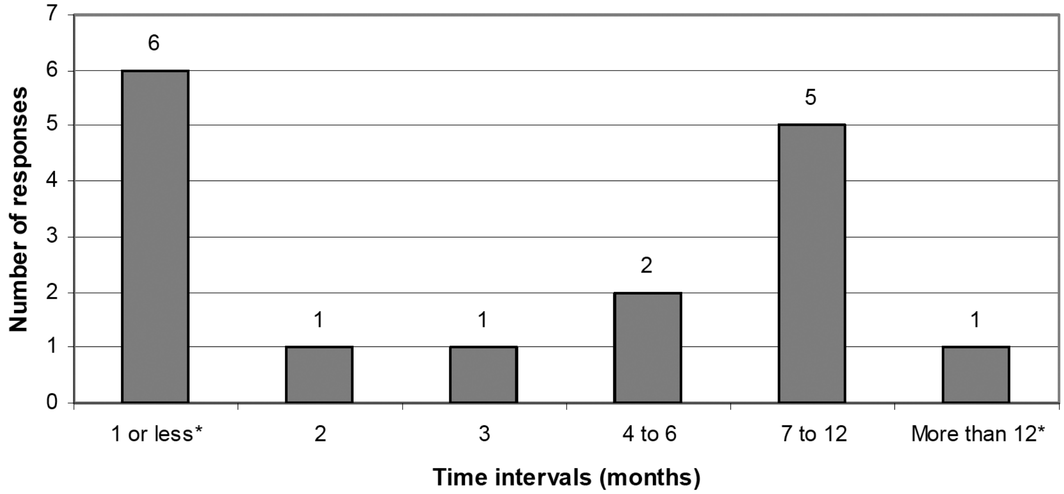


FIGURE B28 Survey response to Question 32: "For any given flexible pavement project, approximately how soon before the project starts does your agency perform FWD tests?"

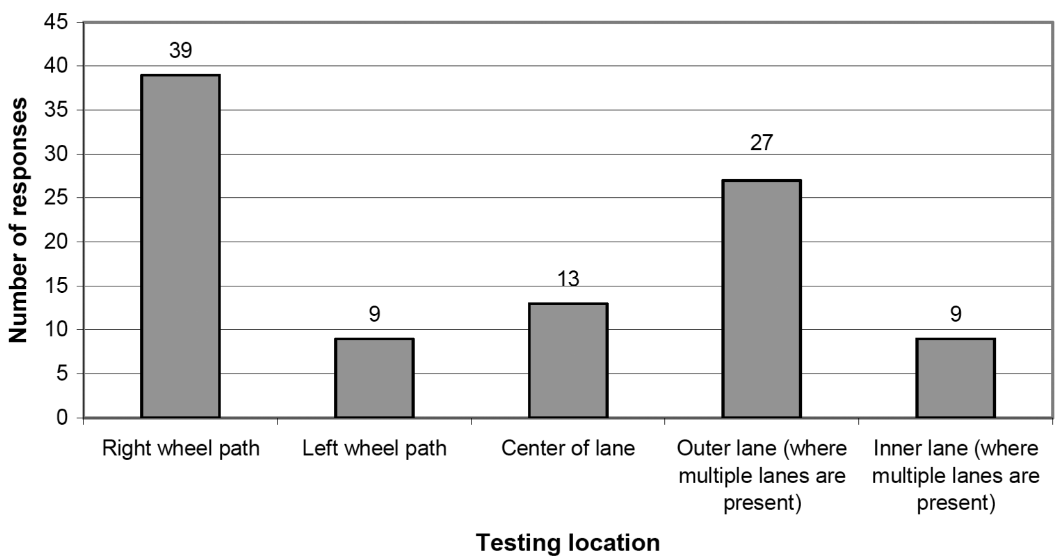
Question 33: For any given flexible pavement project, approximately how soon *after the project is completed* does your agency perform FWD tests?



* (1) 1 day, (1) 1 w eek, (1) 2 w eeks, (3) 1 month
** (1) 5 years

FIGURE B29 Survey response to Question 33: "For any given flexible pavement project, approximately how soon after the project is completed does your agency perform FWD tests?"

Question 34: Where on flexible pavements are data collected? (Check all that apply.)

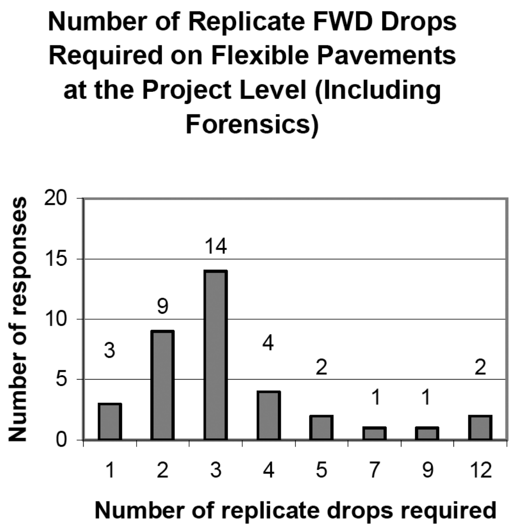


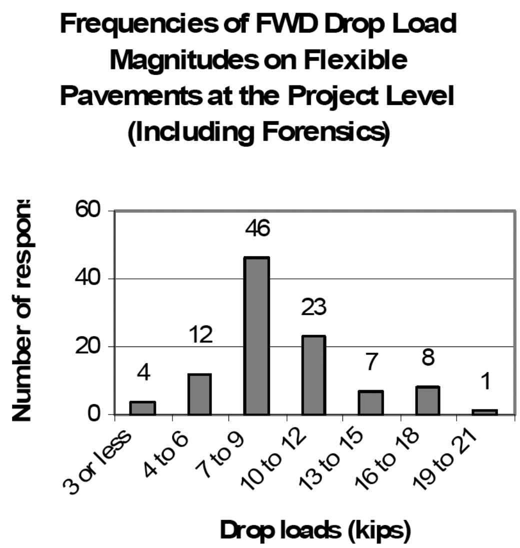
41 total responses

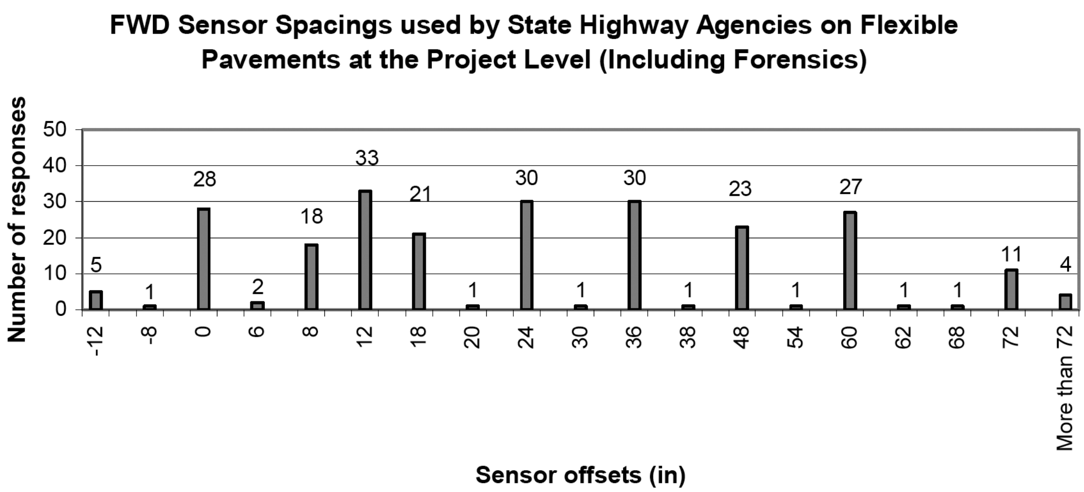
FIGURE B30 Survey response to Question 34: "Where on flexible pavements are data collected?" (Check all that apply.)

Questions 35–38: For each of the following levels, describe your flexible pavement measurement variables, where applicable.

Question 35: Project level (including forensics)







* Responses greater than 72 inches: (1) 98, (1) 146, (1) 206, (1) 278

FIGURE B31 Survey responses to Question 35, Project Level (Including Forensics): “For each of the following levels, describe your flexible pavement measurement variables, where applicable.”

TABLE B5

SURVEY QUESTION 35: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR FLEXIBLE PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE." FLEXIBLE PAVEMENT TEMPERATURE GRADIENT HOLES AT THE PROJECT LEVEL (INCLUDING FORENSICS)

Responding State	No. of Temperature Gradient Holes	Temperature Gradient Hole Depth(s)	Temperature Gradient Hole Measurement Frequency
Alabama	1	Pavement mid-depth	1 min
Idaho	1	3 in.	20 min
Louisiana	1	1 in.	1 min
Nebraska	1	Pavement mid-depth	20 min
New Mexico	3	—	—
Pennsylvania	1	1 in.	1 min
Texas	2	1 in.	20 min
Vermont	1 or 2	Pavement mid-depth	120 min

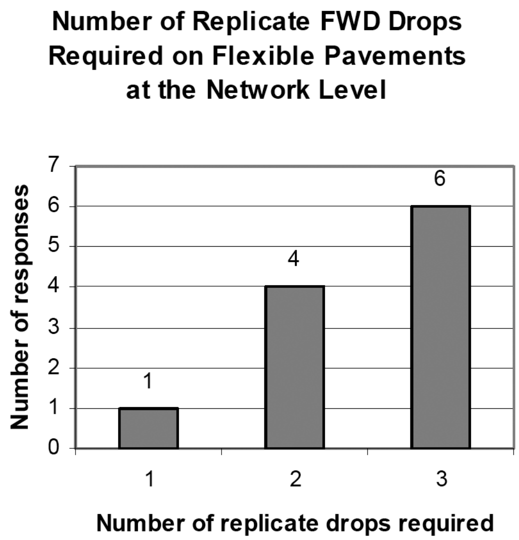
Note: — = no response given.

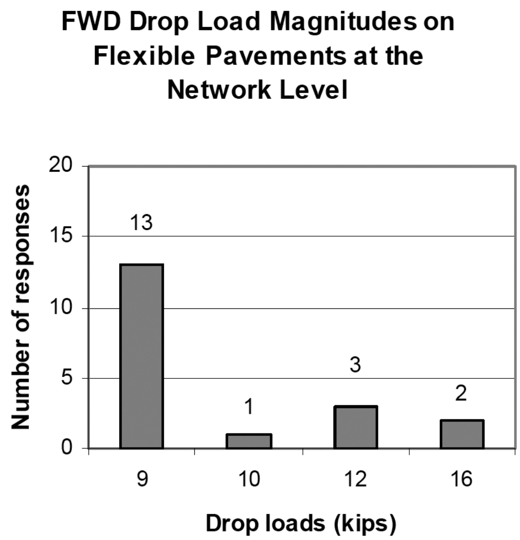
TABLE B6

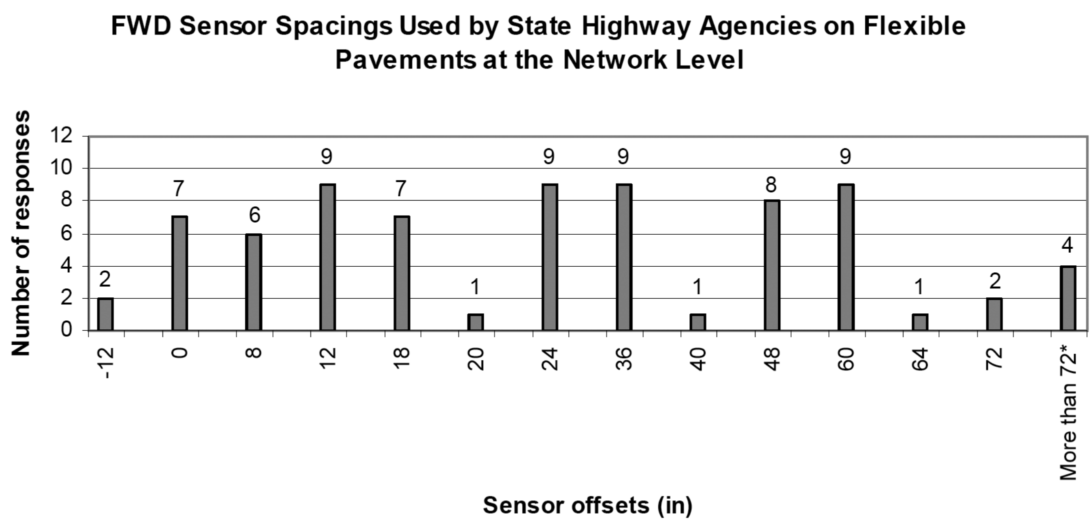
SURVEY QUESTION 35: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR FLEXIBLE PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE." OTHER FLEXIBLE PAVEMENT TESTING VARIABLES AT THE PROJECT LEVEL (INCLUDING FORENSICS)

Responding State	Other Testing Variables
Alabama	All projects more than 1 mile in length are tested every two-tenths of a mile. Projects less then 1 mile are tested every tenth of a mile.
Alaska	No temp gradient holes are done. Air and surface temperatures.
California	Recorded data for temperature is ambient and pavement surface.
Colorado	We follow LTPP drop sequence and sensor spacing.
Florida	Temperatures are only measured for research projects where the bound surface layer needs evaluation.
Idaho	Temperatures taken at mid-depth of pavement a minimum of once per hour.
Indiana	Only surface temperature is measured.
Iowa	Surface temperatures are obtained with the temperature sensor on the FWD unit at time of test.
Kansas	Varies.
Maine	We do not use gradient holes.
Maryland	The drop weights, sequence, etc., are project-specific depending on information required.
Michigan	Air and surface temperature.
Mississippi	Temperature of air and surface of the pavement.
Montana	We use previous day mean temperatures for our temperature correction. No temperature holes are drilled.
Nevada	We use infrared surface temperatures for gathering temperature data. This measurement is taken at every test location.
New Jersey	Various LTPP setups (are employed).
New York	We perform load transfer efficiency tests on PCC joints.
North Carolina	Asphalt surface temperature is measured at every drop location.
Pennsylvania	We do not drill any holes for temperatures.
Utah	We measure surface temperature.
Washington	Infrared measurement per location and conversion using the bell method.

Question 36: Network level







* Responses greater than 72 inches: (1) 98, (1) 146, (1) 206, (1) 278

FIGURE B32 Survey responses to Question 36, Network Level: "For each of the following levels, describe your flexible pavement measurement variables, where applicable."

TABLE B7

SURVEY QUESTION 36: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR FLEXIBLE PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE." FLEXIBLE PAVEMENT TEMPERATURE GRADIENT HOLES AT THE NETWORK LEVEL

Responding State	No. of Temperature Gradient Holes	Temperature Gradient Hole Depth(s)	Temperature Gradient Hole Measurement Frequency
New Mexico	3	—	—
Montana	1	1 in.	1 min
Texas	1	1 in.	20 min

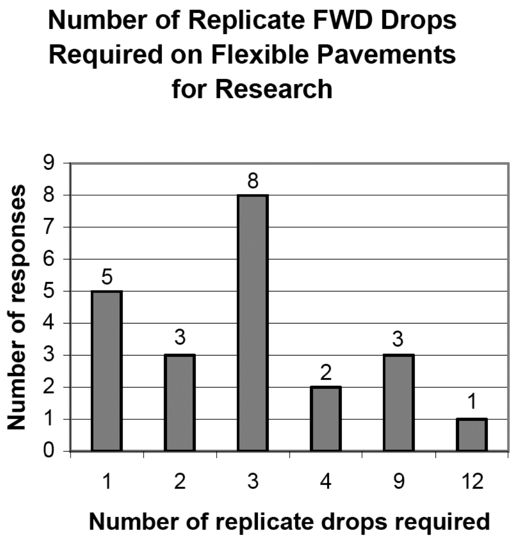
Note: — = no response given.

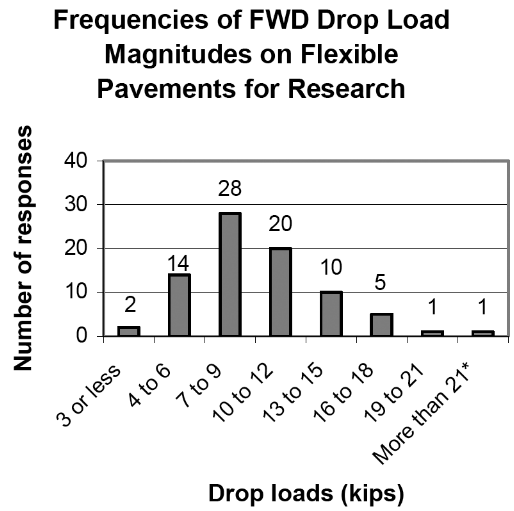
TABLE B8

SURVEY QUESTION 36: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR FLEXIBLE PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE" OTHER FLEXIBLE PAVEMENT TESTING VARIABLES AT THE NETWORK LEVEL

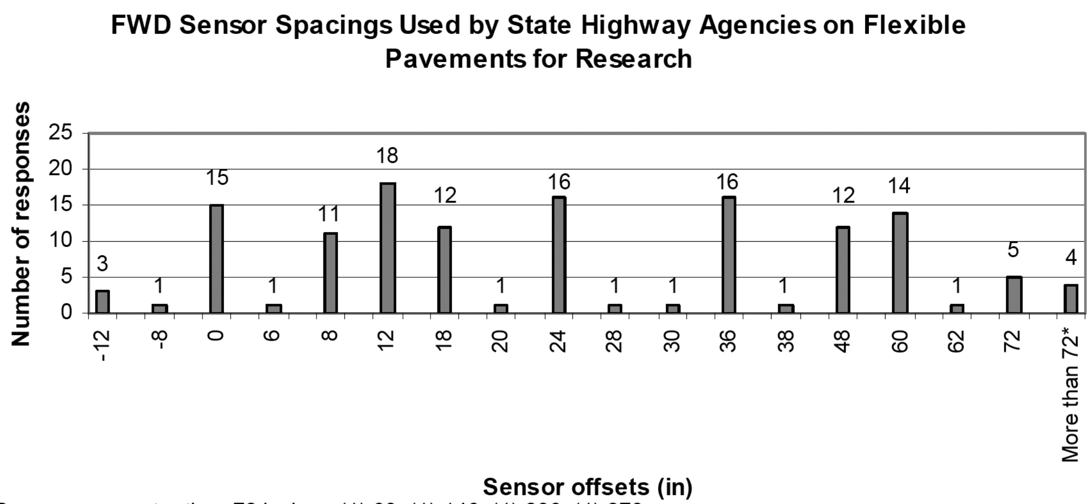
Responding State	Other Testing Variables
Alaska	No temp gradient holes are done. We measure surface and air temperatures.
California	Network-level testing is not performed.
Florida	FDOT only evaluates project-level tests, and does not conduct network-level testing.
Hawaii	Network-level testing is not currently being conducted.
Indiana	Only surface temperature is measured.
Iowa	Surface temperatures are obtained with temperature sensor on the FWD unit at test time.
Maine	We do not use gradient holes.
Michigan	Surface and air temperature.
New Jersey	LTPP setups are used. We do not do in-house network Heavy Weight Deflectometer testing. Stantec consulting did some network-level testing for us a few years back.
Pennsylvania	We only perform project-level FWD testing.
Utah	We measure surface temperature.
Wisconsin	No testing is done on network level.

Question 37: Research level





* 1 respondent noted 120 kips



* Responses greater than 72 inches: (1) 98, (1) 146, (1) 206, (1) 278

FIGURE B33 Survey responses to Question 37, Research: “For each of the following levels, describe your flexible pavement measurement variables, where applicable.”

TABLE B9

SURVEY QUESTION 37: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR FLEXIBLE PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE." FLEXIBLE PAVEMENT TEMPERATURE GRADIENT HOLES FOR RESEARCH

Responding State	No. of Temperature Gradient Holes	Temperature Gradient Hole Depth(s)	Temperature Gradient Hole Measurement Frequency
Florida	3	2 in.	—
Idaho	1	3 in.	20 min
Illinois	1	5 in.	—
Louisiana	1	1 in.	1 min
Montana	1	1 in.	1 min
Vermont	2	Mid-depth	120 min

Note: — = no response given.

TABLE B10

SURVEY QUESTION 37: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR FLEXIBLE PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE." OTHER FLEXIBLE PAVEMENT TESTING VARIABLES FOR RESEARCH

Responding State	Other Testing Variables
California	Recorded data for temperature is ambient and pavement surface.
Colorado	We do what is requested by the customer. No set procedure for research.
Idaho	If the test section is short, test (temperature gradient) hole at the beginning and end of testing but not less than once per hour.
Iowa	Everything varies by project.
Kansas	Varies (by project).
Maryland	Extremely variable dependent on requirements.
Nevada	We use infrared surface temperatures for gathering temperature data. This measurement is taken at every test location.
New York	Load transfer efficiency tests are performed on PCC joints.
North Carolina	Asphalt surface temperature is measured at every drop location.
Texas	Many variables.
Utah	Same testing procedure (as project level) unless something specific is asked for.
Virginia	Drop sequence and sensor spacing is as requested.

Question 38: Other levels

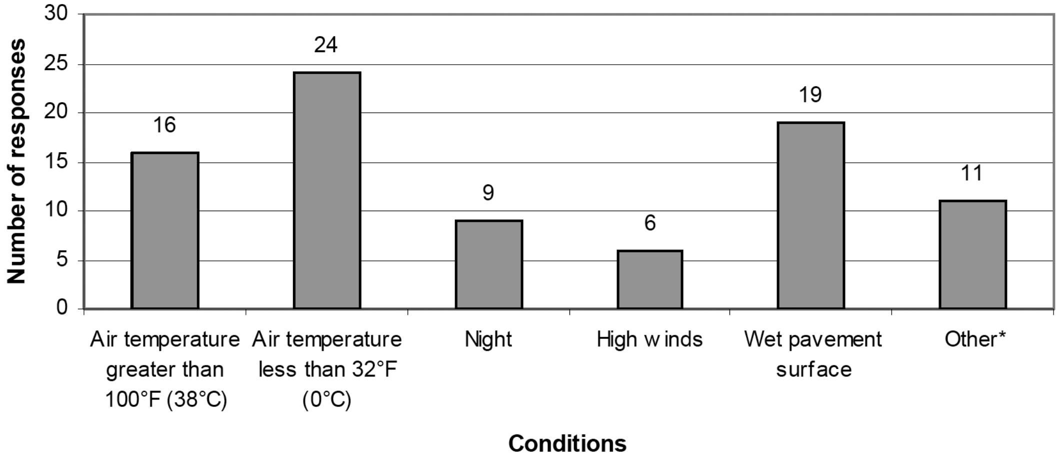
TABLE B11

SURVEY QUESTION 38: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR FLEXIBLE PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE" (OTHER LEVELS USED)

Responding State	Description	Loading Conditions	Sensor Spacings	Temperature Gradient Holes	Other Testing Variables
Alaska	Airport—B747	4 replicate drops at 55 kips each	0, 8, 12, 24, 36, 48, 60, and 72 in.	None	Surface and air temperatures are measured
North Dakota	Spring load restrictions	3 replicate drops at 7, 9, and 9 kips	0, 8, 12, 18, 24, 30, 36, 48, and 60 in.	None	—
Washington	Load transfer	2 replicate drops at 4 lb each	−12, 0, and 12 in.	None	Infrared (temperature measurement)

Note: — = no response given.

Question 39: Under which of these conditions is flexible pavement testing not allowed? (Check all that apply.)

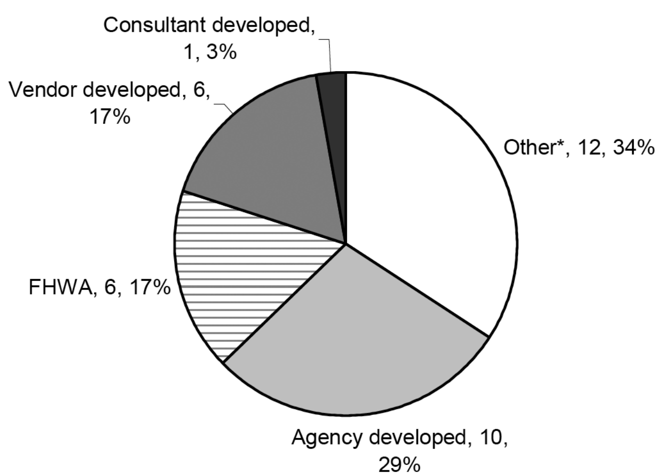


* Other responses: (1) restricted visibility, (1) pavement distress cracks, (1) high traffic level, (1) safety issues, (1) frozen subgrade, (1) temperature low er than 45°F (7°C), (1) pavement temperature less than 45°F (0°C), (1) pavement temperature less than 40°F (4°C), (1) soil temperature less than 40°F (4°C), (1) subgrade temperature less than 32°F (0°C), (1) pavement temperature higher than 110°F (43°C).
Total responses: 43

FIGURE B34 Survey response to Question 39: "Under which of these conditions is flexible pavement testing not allowed?" (Check all that apply.)

PART 7: FWD FIELD TESTING—RIGID PAVEMENTS

Question 40: What kind of rigid field testing manual does your agency use?



* Other responses: (6) no testing is done on rigid pavements, (1) combination of FHWA and agency developed, (1) AASHTO, (1) ASTM, (1) varies by project, (2) no comment.

FIGURE B35 Survey response to Question 40: "What kind of rigid field testing manual does your agency use?"

Question 41: How much time does a complete rigid pavement network-level FWD testing cycle take?

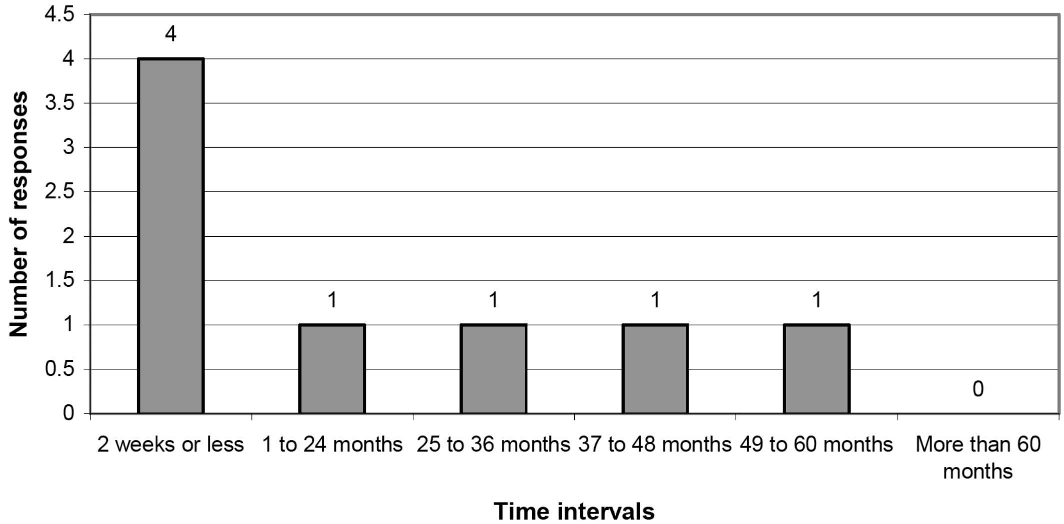


FIGURE B36 Survey response to Question 41: "How much time does a complete rigid pavement network level FWD testing cycle take?"

Question 42: For rigid pavement at the network level, are FWD tests done before the project starts, after the project is completed, or both?

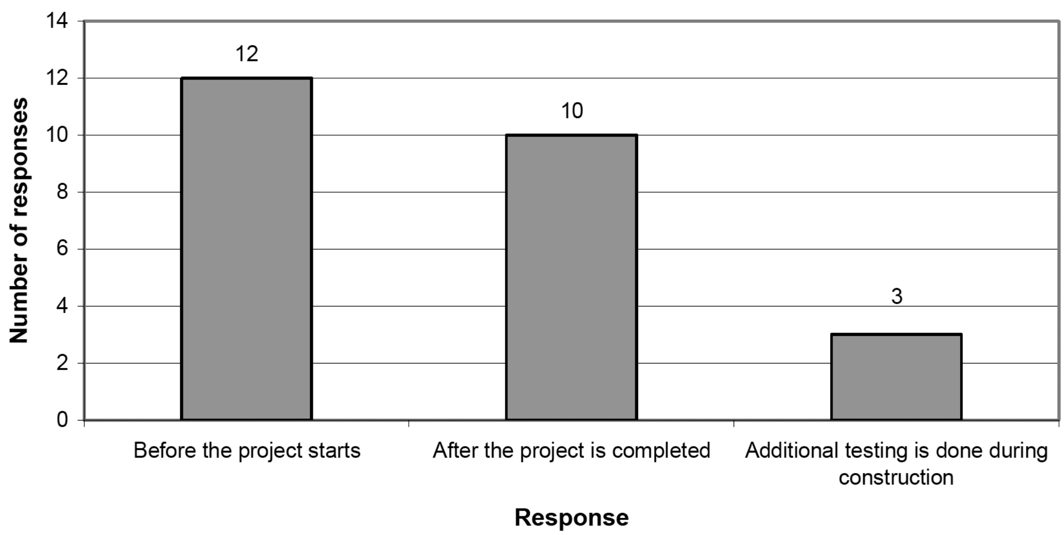
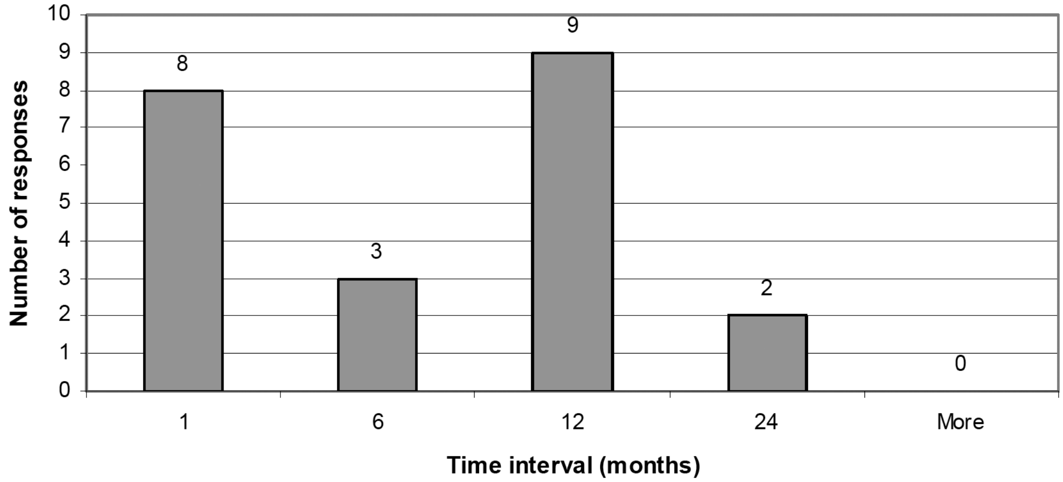


FIGURE B37 Survey response to Question 42: "For rigid pavement at the network level, are FWD tests done before the project starts, after the project is completed, or both?"

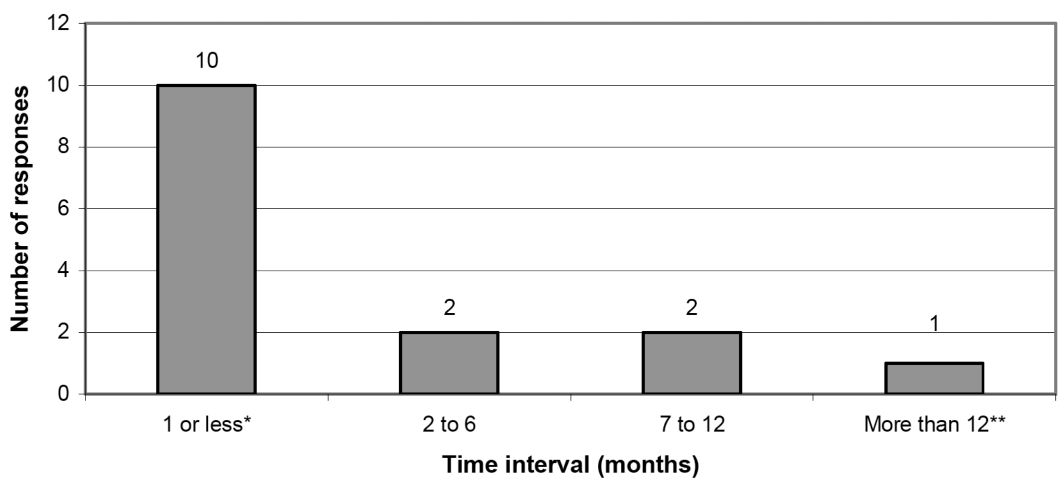
Question 43: For any given rigid pavement project, approximately how soon *before the project starts* does your agency perform FWD tests?



* Responses: (3) 1 day, (2) 2 weeks, (3) 1 month

FIGURE B38 Survey response to Question 43: "For any given rigid pavement project, approximately how soon *before the project starts* does your agency perform FWD tests?"

Question 44: For any given rigid pavement project, approximately how soon *after the project is completed* does your agency perform FWD tests?



* Responses: (3) 1 day, (1) 1 week, (2) 2 weeks, (4) 1 month
** Response: (1) 10 years

FIGURE B39 Survey response to Question 44: "For any given rigid pavement project, approximately how soon *after the project is completed* does your agency perform FWD tests?"

Question 45: Where on rigid pavements are data collected? (Check all that apply.)

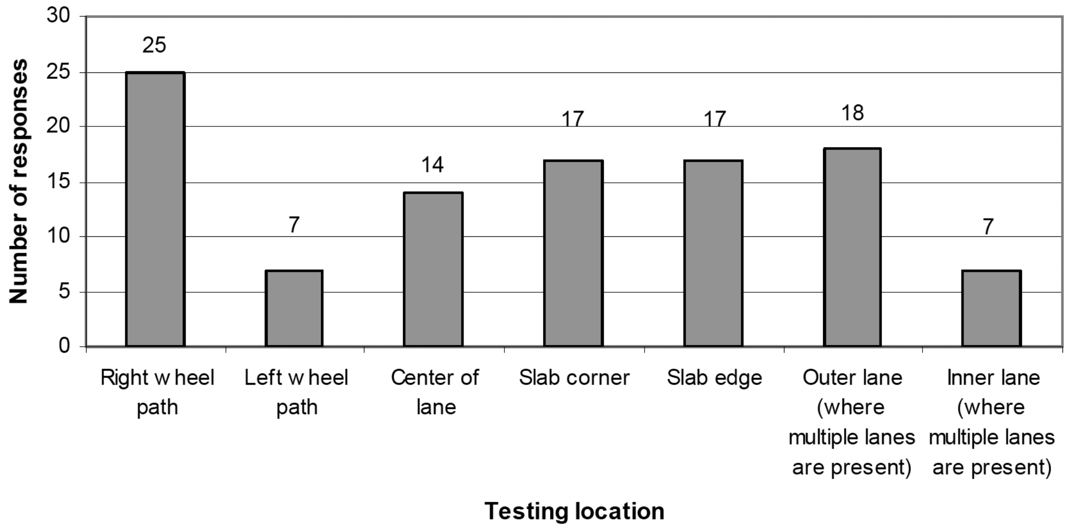
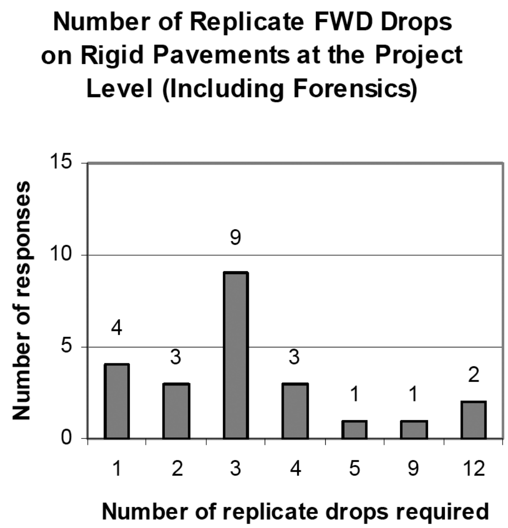
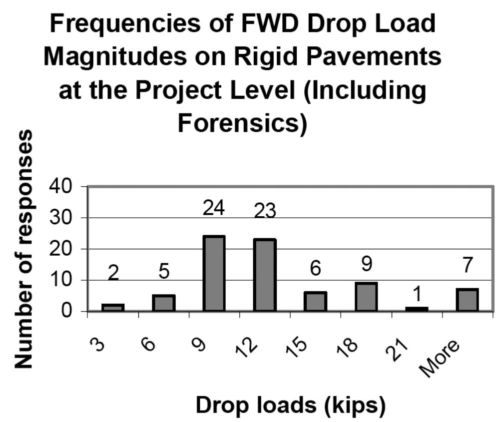


FIGURE B40 Survey response to Question 45: "Where on rigid pavements are data collected?" (Check all that apply.)

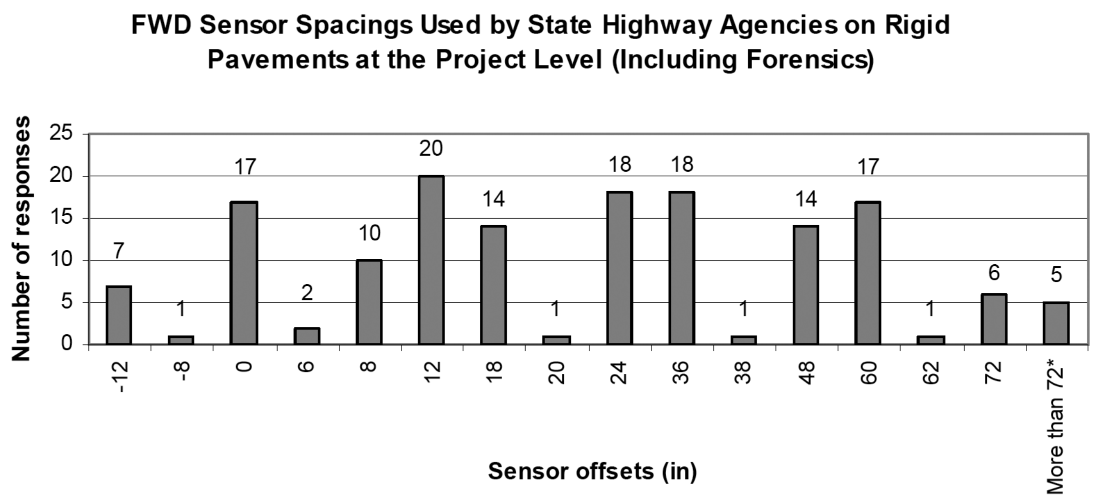
Questions 46–49: For each of the following levels, describe your rigid pavement measurement variables, where applicable.

Question 46: Project level (including forensics)





* Responses less than 3 kips: (1) 1.79 kips (8 kN), (1) 2.70 kips (12 kN)
** Responses greater than 21 kips: (2) 25 kips, (2) 33 kips, (2) 55 kips, (1) 160 kips



* Responses greater than 72 inches: (1) 78, (1) 98, (1) 146, (1) 206, (1) 278

FIGURE B41 Survey responses to Question 46, Project Level (Including Forensics): "For each of the following levels, describe your rigid pavement measurement variables, where applicable."

TABLE B12

SURVEY QUESTION 46: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR RIGID PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE" RIGID PAVEMENT TEMPERATURE GRADIENT HOLES AT THE PROJECT LEVEL (INCLUDING FORENSICS)

Responding State	No. of Temperature Gradient Holes	Temperature Gradient Hole Depth(s)	Temperature Gradient Hole Measurement Frequency
Idaho	1	Pavement mid-depth	20 min
Louisiana	1	1 in.	1 min
Montana	1	1 in.	1 min
Wisconsin	1	Bottom of slab	—
Michigan	4	1, 3, 5, and 8 in.	15 min

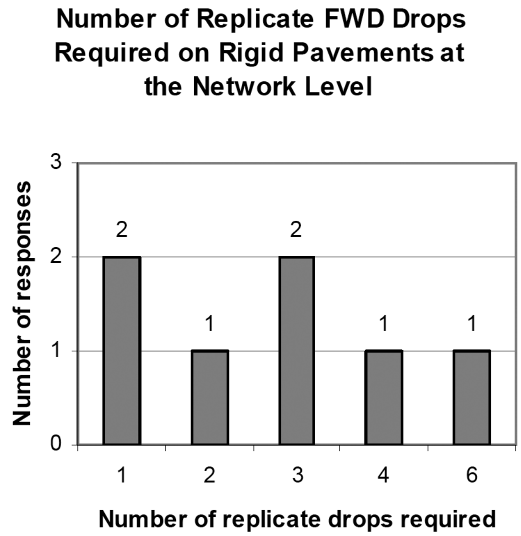
Note: — = no response given.

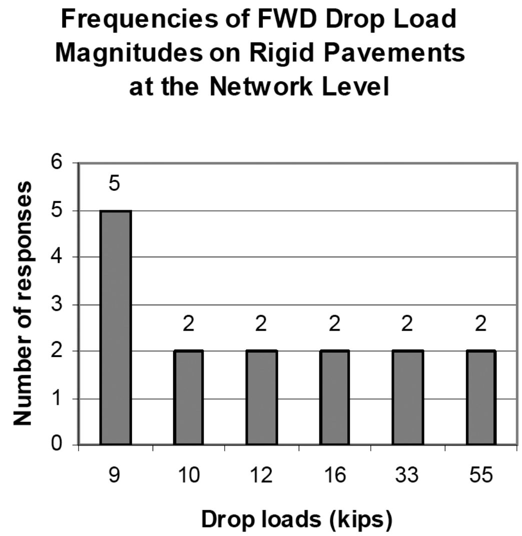
TABLE B13

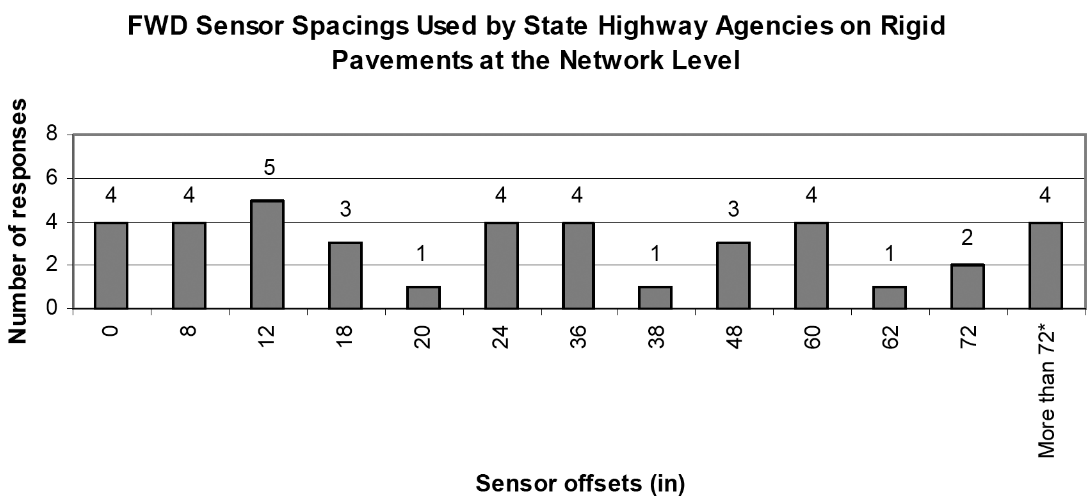
SURVEY QUESTION 46: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR RIGID PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE." OTHER RIGID PAVEMENT TESTING VARIABLES AT THE PROJECT LEVEL (INCLUDING FORENSICS)

Responding State	Other Testing Variables
Alabama	All projects more than 1 mile in length are tested every two-tenths of a mile; projects less then 1 mile are tested every tenth of a mile.
Alaska	No temperature gradient holes are done. Air and surface temperatures are measured. Testing is done at centerline of slab and across joints.
California	For temperature, we record ambient and pavement surface temperatures.
Colorado	We follow LTPP test sequence in center of slab.
Idaho	Temperature is taken at mid-depth of pavement at a minimum of one per hour.
Indiana	Surface temperature only.
Iowa	Surface temperatures are obtained with temperature sensor at test time.
Kansas	Varies.
Maryland	Varies depending on project.
Michigan	Time history testing.
Nevada	We use infrared surface temperatures for gathering temperature data. This measurement is taken at every test location.
New Jersey	We employ various LTPP setups and loads to 16,000 lb.
North Carolina	Asphalt surface temperature is taken at every drop location.
Pennsylvania	We do not drill any holes for taking temperatures.

Question 47: Network level







* Responses greater than 72 inches: (1) 98, (1) 146, (1) 206, (1) 278

FIGURE B42 Survey responses to Question 47, Network Level: “For each of the following levels, describe your rigid pavement measurement variables, where applicable.”

TABLE B14

SURVEY QUESTION 47: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR RIGID PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE" RIGID PAVEMENT TEMPERATURE GRADIENT HOLES AT THE NETWORK LEVEL

Responding State	No. of Temperature Gradient Holes	Temperature Gradient Hole Depth(s)	Temperature Gradient Hole Measurement Frequency
Michigan	4	1, 3, 5, and 9 in.	15 min
Montana	1	1 in.	1 min

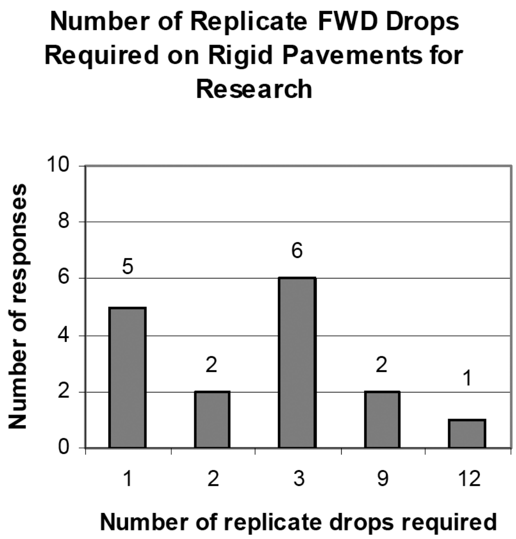
Note: — = no response given.

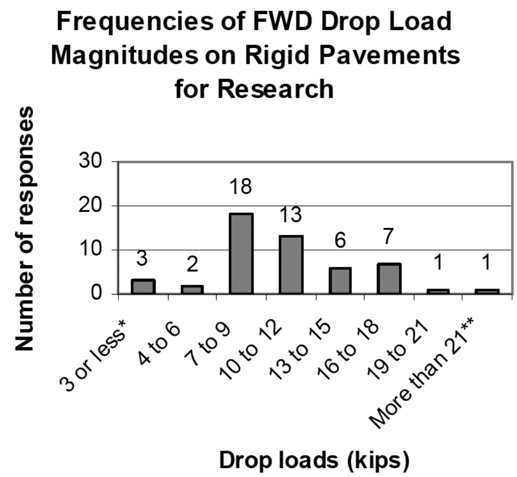
TABLE B15

SURVEY QUESTION 47: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR RIGID PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE" OTHER RIGID PAVEMENT TESTING VARIABLES AT THE NETWORK LEVEL

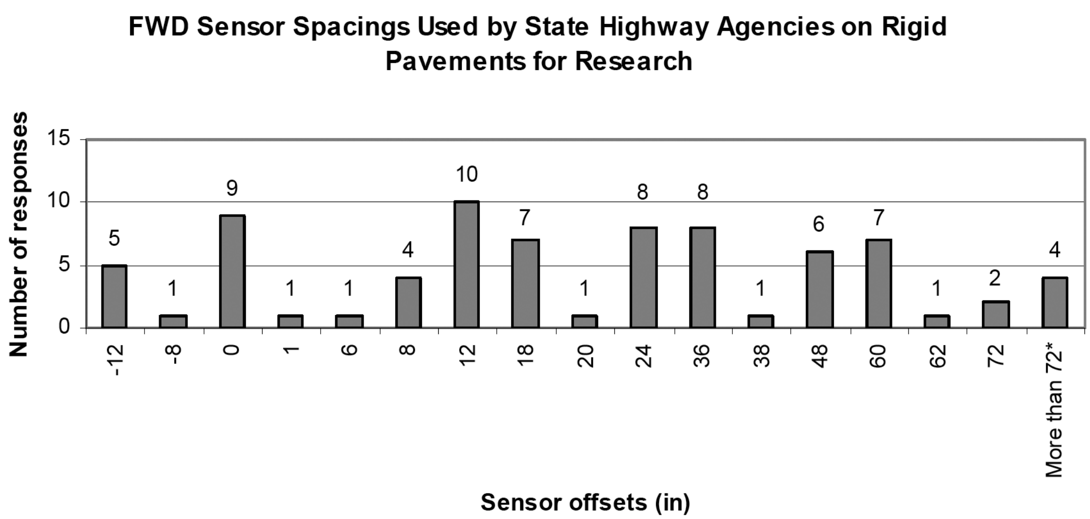
Responding State	Other Testing Variables
Alaska	No temperature gradient holes are done. Air and surface temps are measured. Testing is done at centerline of slab and across joints.
Indiana	Surface temperature only.
Iowa	Surface temperature obtained with temperature sensor at test time.
Utah	Only tests for load transfer are done at network level.

Question 48: Research level





* Responses less than 3 kips: (1) 0.9 kips, (1) 1.80 kips (8 kN), (1) 2.70 kips (12 kN)



* Sensor offsets greater than 72 inches: (1) 98 in, (1) 146 in, (1) 206 in, (1) 278 in

FIGURE B43 Survey responses to Question 48, Research: “For each of the following levels, describe your rigid pavement measurement variables, where applicable.”

TABLE B16

SURVEY QUESTION 48: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR RIGID PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE" RIGID PAVEMENT TEMPERATURE GRADIENT HOLES FOR RESEARCH

Responding State	No. of Temperature Gradient Holes	Temperature Gradient Hole Depth(s)	Temperature Gradient Hole Measurement Frequency
Idaho	1	Pavement mid-depth	20 min
Illinois	1	5 in.	—
Louisiana	1	1 in.	1 min
Montana	1	1 in.	1 min
Wisconsin	1	Slab bottom	—

Note: — = no response given.

TABLE B17

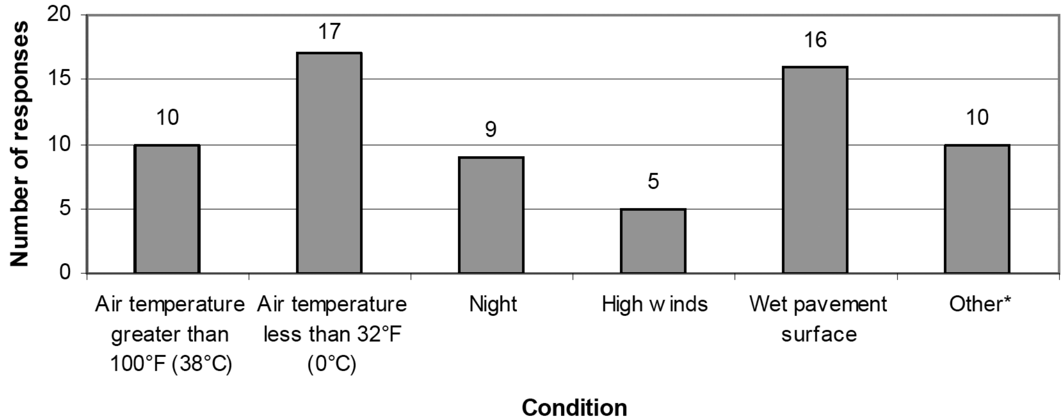
SURVEY QUESTION 48: "FOR EACH OF THE FOLLOWING LEVELS, DESCRIBE YOUR RIGID PAVEMENT MEASUREMENT VARIABLES, WHERE APPLICABLE" OTHER RIGID PAVEMENT TESTING VARIABLES FOR RESEARCH

Responding State	Other Testing Variables
California	Recorded data for temperature is ambient and pavement surface.
Colorado	We test when requested and researchers let us know what they want.
Florida	Load transfer and corner slab analysis with a.m. and p.m. testing, center slab analysis.
Idaho	Temperature taken at mid-depth of pavement at a minimum of once per hour.
Indiana	Surface temperature only.
Iowa	Varies by project request.
Kansas	Varies by research request.
Maryland	Varies widely.
Michigan	Depending on research requests, everything can vary.
Nevada	We use infrared surface temperatures for gathering temperature data. This measurement is taken at every test location.
New Jersey	We employ various LTPP setups with loads to 16,000 lb.
North Carolina	Asphalt surface temperature is taken at every drop location.
Virginia	Number of drops, drop heights, load and location will be as per the request.

Question 49: Other levels

No responses were given to this question.

Question 50: Under which of these conditions is rigid pavement testing not allowed? (Check all that apply.)



* Other responses: (2) pavement temperature greater than 80°F (27°C), (1) limited visibility, (1) subgrade temperature less than 32°F (0°C), (1) air temperature less than 45°F (7°C), (2) temperature greater than 70°F (21°C), (1) pavement temperature greater than 100°F (38°C), (1) safety factors.
Total responses: 30

FIGURE B44 Survey responses to Question 50: “Under which of these conditions is rigid pavement testing not allowed?” (Check all that apply.)

PART 8: FWD COMPUTERS

Question 51: What type of field data collection computers are most commonly used?

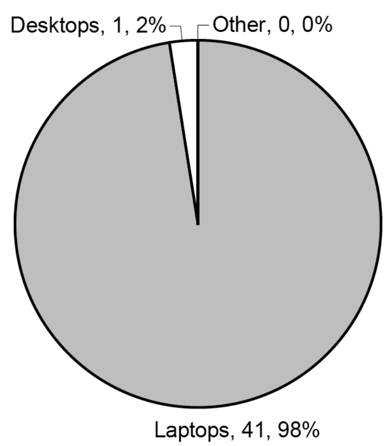
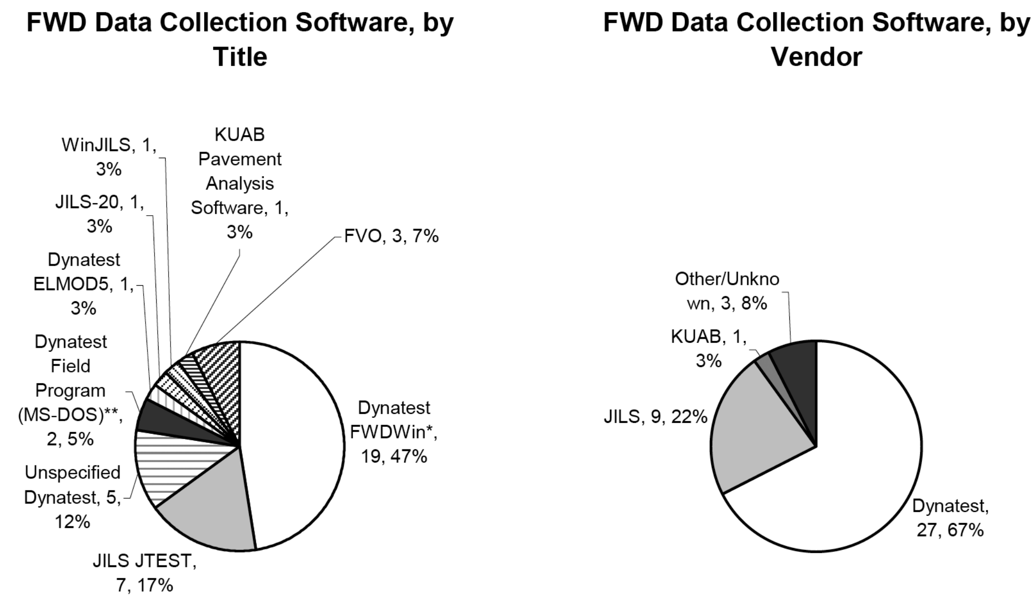


FIGURE B45 Survey response to Question 51: “What type of field data collection computers are most commonly used?”

Question 52: What is the name of the FWD data collection software used in the field? (Separate multiple names and versions with commas.)



* FWDWin versions reported: (1) 1.14, (1) 1.24, (1) 1.7, (1) 1.7.1, (1) 1.7.5, (1) 1.8, (1) 1.8.6, (1) 1.9.7, (1) 1.95, (1) 2, (2) 2.2.1, (1) 20, (1) F25, (4) did not specify

** Dynatest Field Program versions reported: (1) 20, (1) 25

FIGURE B46 Survey responses to Question 52, by title and by vendor: “What is the name of the FWD data collection software used in the field?” (Separate multiple names and versions with commas.)

Question 53: In which format does your FWD equipment give its output? (Check all that apply.)

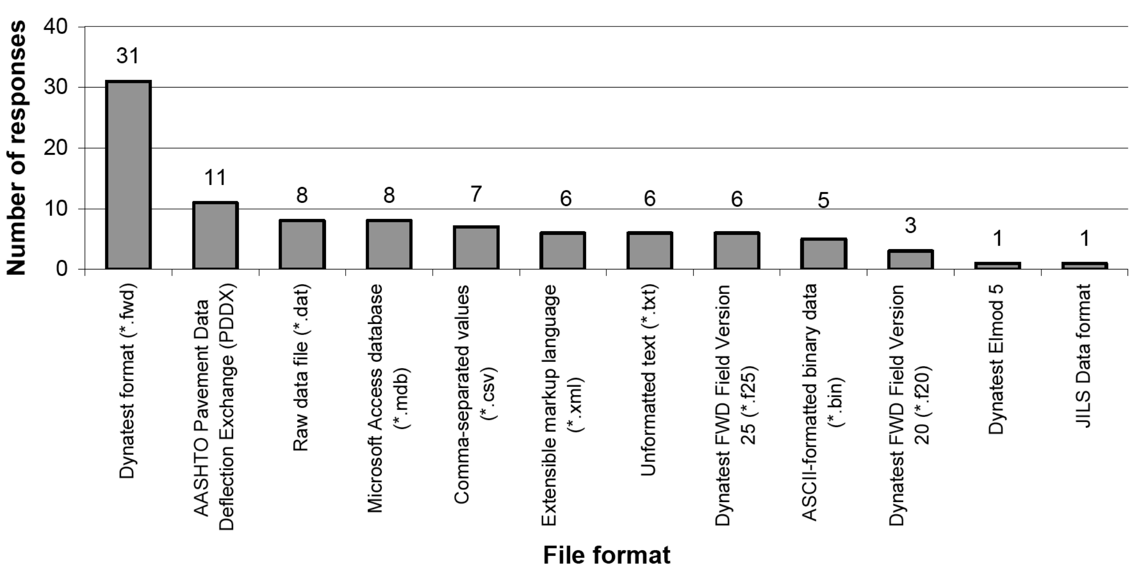
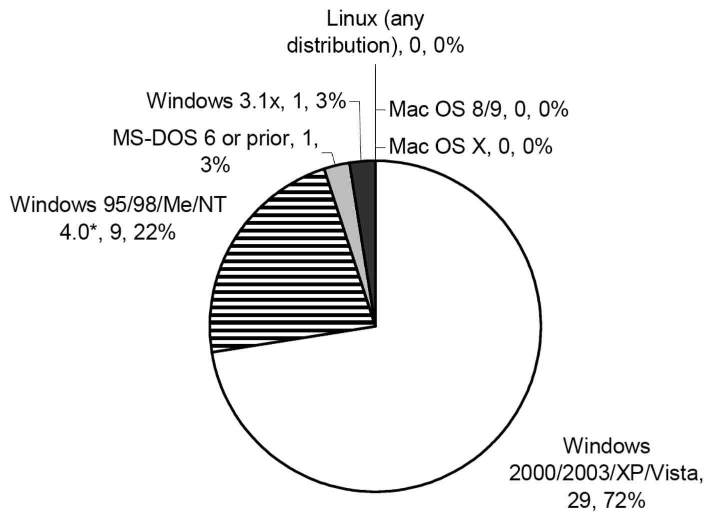


FIGURE B47 Survey response to Question 53: “In which format does your FWD equipment give its output?” (Check all that apply.)

Question 54: What operating system does your FWD unit(s) use?



* One respondent answered both Windows 95/98/Me/NT 4.0 and Windows 2000/2003/XP/Vista.

FIGURE B48 Survey response to Question 54: “What operating system does your FWD unit(s) use?”

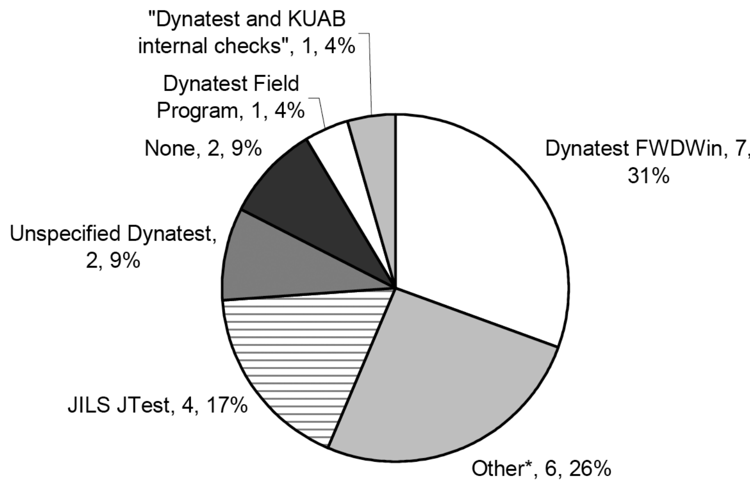
PART 9: DATA ANALYSIS

Question 55: Which of the following data checks are performed by FWD operators? (Check all that apply.)

* Includes respondents who specified that none of these checks are performed, and those respondents who have an FWD program and did not check any possible response.

FIGURE B49 Survey response to Question 55: “Which of the following data checks are performed by FWD operators?” (Check all that apply.)

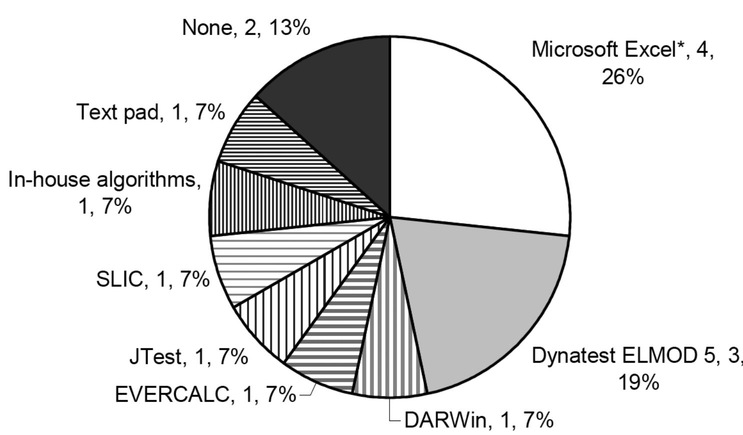
Question 56: What software is used to perform data quality checks in the field? (Separate multiple names and versions with commas.)



* Other responses: (2) "Dynatest" with no specific software title, (2) FVO, (1) text pad, (1) FHWA

FIGURE B50 Survey response to Question 56: "What software is used to perform data quality checks in the field?" (Separate multiple names and versions with commas.)

Question 57: What software is used to perform data quality checks in the office? (Separate multiple names and versions with commas.)



* One respondent noted both Microsoft Excel and Microsoft Acces.

FIGURE B51 Survey response to Question 57: "What software is used to perform data quality checks in the office?" (Separate multiple names and versions with commas.)

Question 58: Does your agency use FWD data to estimate pavement layer moduli?

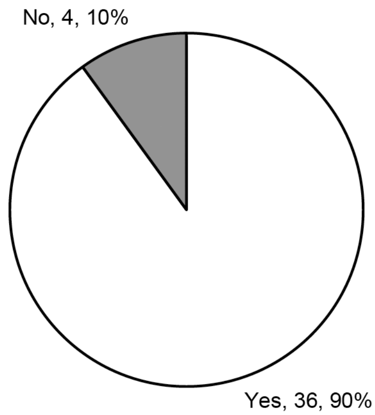


FIGURE B52 Survey response to Question 58: "Does your agency use FWD data to estimate pavement layer moduli?"

Question 59: What software is used to perform layer modulus calculations using FWD data? (Separate multiple names and versions with commas.)

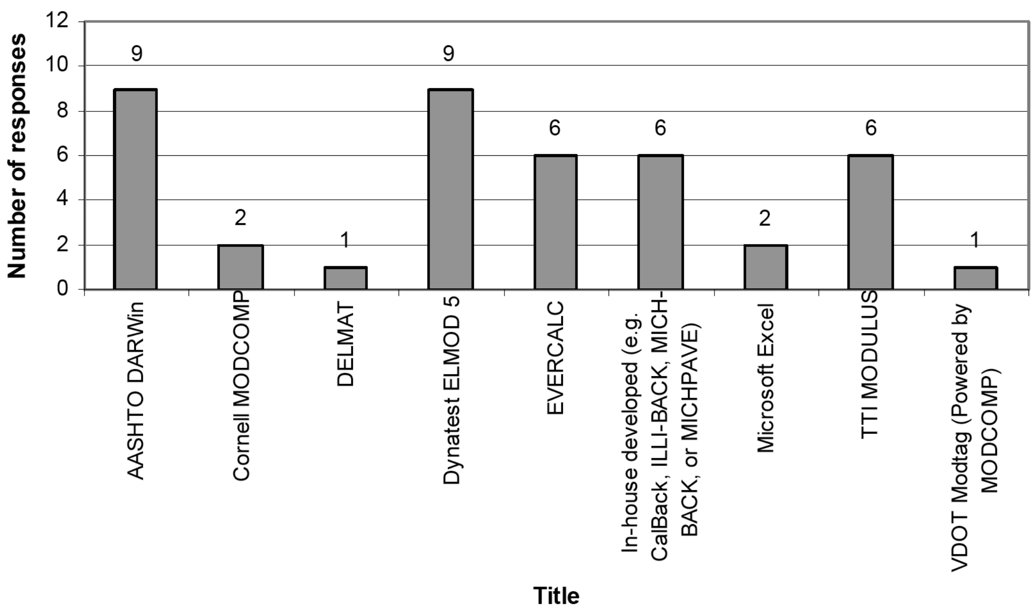


FIGURE B53 Survey response to Question 59: "What software is used to perform layer modulus calculations using FWD data?" (Separate multiple names and versions with commas.)

Question 60: Does your agency use a seasonal and/or temperature adjustment factor(s) in determining layer moduli using FWD data?

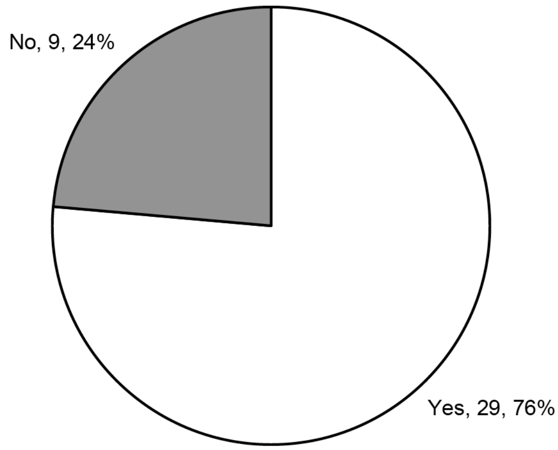


FIGURE B54 Survey response to Question 60: "Does your agency use a seasonal and/or temperature adjustment factor(s) in determining layer moduli using FWD data?"

PART 10: DATA MANAGEMENT AND STORAGE

Question 61: Are FWD program and configuration backups stored in the FWD vehicle?

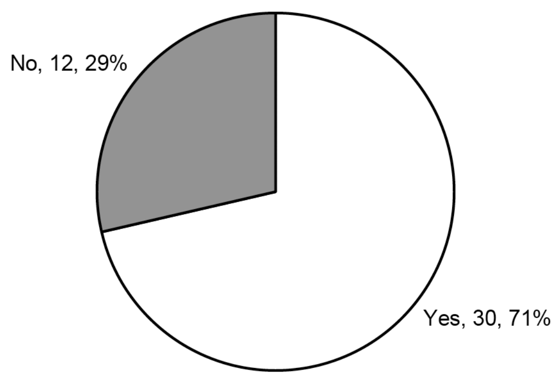


FIGURE B55 Survey response to Question 61: "Are FWD program and configuration backups stored in the FWD vehicle?"

Question 62: Does the FWD Operator back up FWD data files to any external media (e.g., floppy disks, CD-ROM, USB flash drive, etc.) prior to leaving the test site?

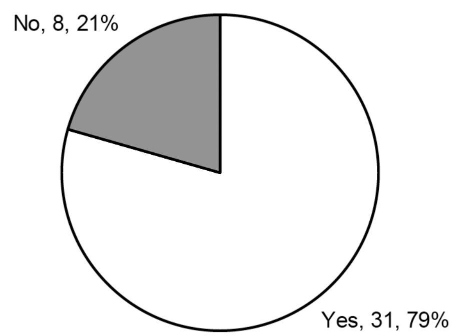


FIGURE B56 Survey response to Question 62: "Does the FWD Operator back up FWD data files to any external media (e.g., floppy disks, CD-ROM, USB flash drive, etc.) prior to leaving the test site?"

Question 63: How long are raw FWD field data stored?

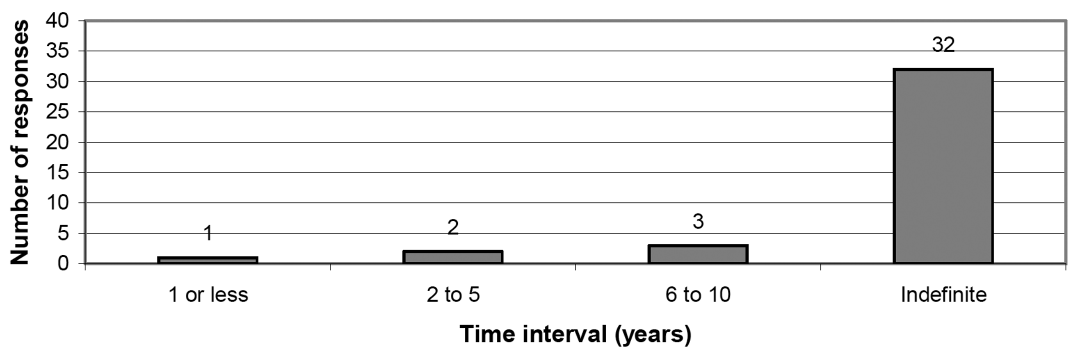


FIGURE B57 Survey response to Question 63: "How long are raw FWD field data stored?"

PART 11: PERSONNEL TRAINING

Question 64: How many months of training is required for new FWD operators?

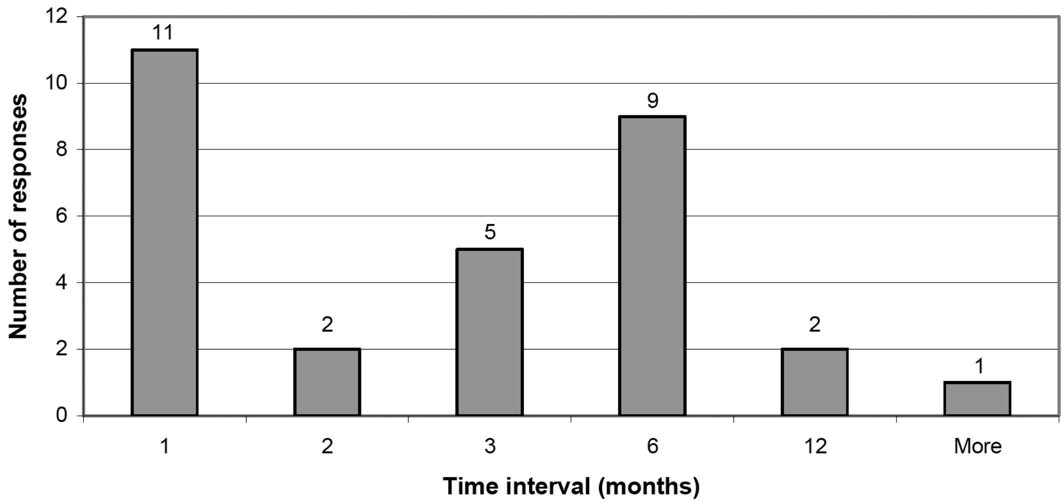


FIGURE B58 Survey response to Question 64: "How many months of training is required for new FWD operators?"

Question 65: How many months of training is required for new FWD data analysts?

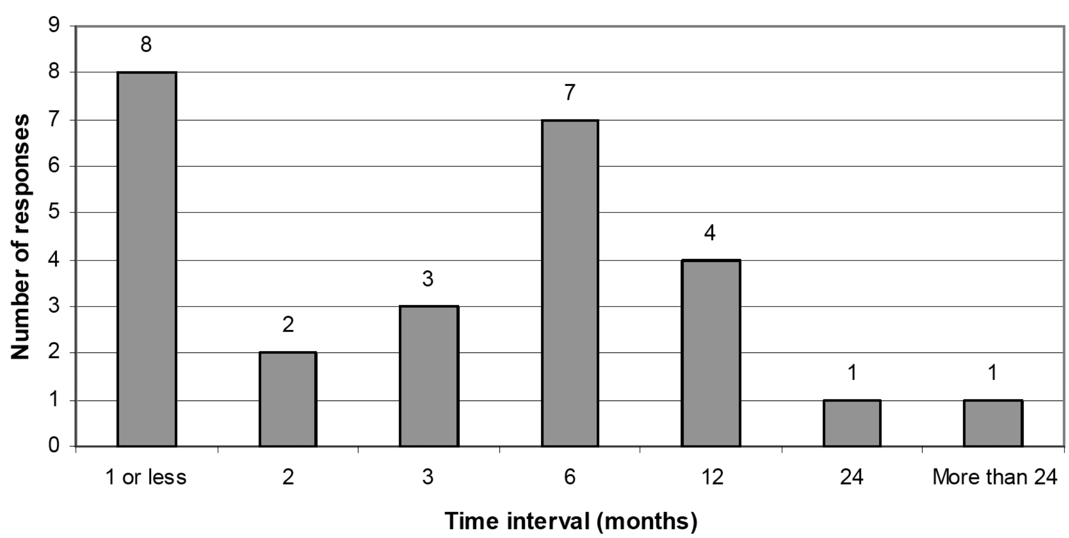


FIGURE B59 Survey response to Question 65: "How many months of training is required for new FWD data analysts?"

Question 66: Does your agency provide training to FWD operators?

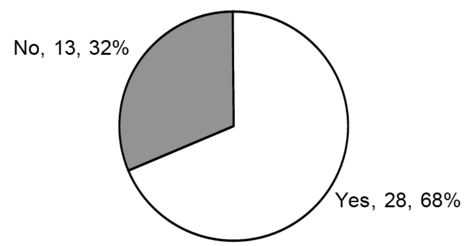


FIGURE B60 Survey response to Question 66: "Does your agency provide training to FWD operators?"

Question 67: If yes, please describe.

TABLE B18

SURVEY QUESTION 67: "DOES YOUR AGENCY PROVIDE TRAINING TO FWD OPERATORS? IF YES, PLEASE DESCRIBE"

Responding State	FWD Operator Training Description
Alabama	Alabama provides in-house training for our FWD operator; the junior operator is paired with a senior operator for 6 months to get a feel for different testing situation.
Alaska	Our two operators were trained years ago.
Arizona	Provided by trained operator.
California	On-the-job training.
Colorado	In-house training by supervisor.
Florida	In-house training on safety, equipment operation, and trouble shooting.
Hawaii	Hands-on with an experienced FWD operator.
Idaho	On-the-job training.
Illinois	In-house, on-the-job training.
Indiana	On-the-field training.
Kansas	New trainees go out with an experienced operator for several months.
Louisiana	On-the-job training. We receive training from Dynatest as well.
Maine	On-the-job training.
Maryland	In-house with current operator.
Michigan	On-the-job training, supplemented with manufacturer's training when funding is available.
Minnesota	On-the-job training with experienced operator.
Montana	The NDT supervisor instructs the new operators.
Nebraska	Previous operator trains the new operator.

continued

TABLE B18 (*continued*)

Responding State	FWD Operator Training Description
Nevada	The operator must review and demonstrate the operations plan on at least three projects before they are allowed to go to the field by themselves. They must understand where to find the troubleshooting information in the vendor-supplied manuals. They must be able to understand and try to fix any problem before calling the office or the vendor for assistance.
New Jersey	Vendor training.
New Mexico	On-the-job training only.
North Carolina	New operators must complete in-house training requirements with an experienced FWD operator until trainee meets proficiency in all operational aspects.
Oregon	In-house crew training by crew leader.
Pennsylvania	The FWD operation and trouble shooting procedures from the FWD manufacturer. ASTM data collection procedures.
South Carolina	Must ride with certified operator for a period of time to show proficiency and pass test to operate.
Texas	Typically a 2-day class for new operators.
Utah	On-the-job training.
Vermont	No new operators for the last 13 years.
West Virginia	Present operator does the training.
Wisconsin	Training provided by past FWD operator.

Question 68: Does your agency provide training to FWD data analysts?

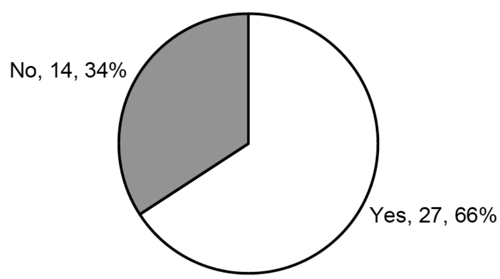


FIGURE B61 Survey response to Question 68: “Does your agency provide training to FWD data analysts?”

Question 69: If yes, please describe.

TABLE B19

SURVEY QUESTION 69: "DOES YOUR AGENCY PROVIDE TRAINING TO FWD DATA ANALYSTS? IF YES, PLEASE DESCRIBE"

Responding State	FWD Operator Training Description
Alabama	On-the-job training.
Alaska	We have brought Dynatest Consultants here for training.
Arizona	Provided by trained operator.
Arkansas	Case-by-case personal training.
Colorado	In-house training by supervisor.
Florida	We provide in-house and district training for data analysis for project engineers or FWD technicians.
Idaho	On-the-job training
Illinois	In-house training.
Indiana	In-house training based on experience.
Kansas	People with experience show the new people how to use the data.
Louisiana	On-the-job training. We attend Dynatest training sessions as well.
Maine	On-the-job training.
Maryland	In-house user support.
Michigan	On-the-job training, with informal training by University of Michigan and Michigan State University professors.
Minnesota	Occasional NHI course.
Montana	The NDT supervisor and his lead operator do this training.
Nebraska	Previous operator trains the new operator.
Nevada	(FWD data analysts) must understand the basics of the FWD data and how it relates to the pavement. With this in mind, they learn to correct deflection values for temperature and the thickness of the asphalt. They must be able to use Excel. The analysts in our office have all spent time operating the FWD.
New Jersey	Vendor-provided software training.
New York	We provide hands-on training on regular basis.
North Carolina	New analysts train under an experienced analyst/engineer until proficiency is met in all operational/analytical aspects.
North Dakota	The vendor has given a class.
Ohio	FWD data analysts have taken the NHI course.
Oregon	Part of the agency pavement designer's responsibility.
South Dakota	In-house training.
West Virginia	Present operator performs the training.
Wisconsin	Self-taught with constant contact with industry professionals, and leaders in FWD data analysis field.

Question 70: Does your agency have a certification program for FWD operators?

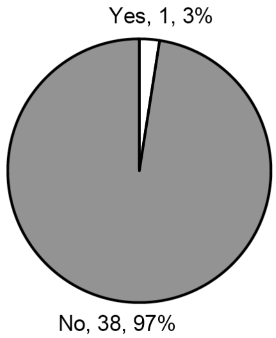


FIGURE B62 Survey response to Question 70: "Does your agency have a certification program for FWD operators?"

Question 71: If yes, please describe.

TABLE B20

SURVEY QUESTION 71: "DOES YOUR AGENCY HAVE A CERTIFICATION PROGRAM FOR FWD OPERATORS? IF YES, PLEASE DESCRIBE"

Responding State	FWD Operator Training Description
South Carolina	Must ride with certified operator for a period of time to show proficiency and pass test to operate.

Question 72: Does your agency have a certification program for FWD data analysts?

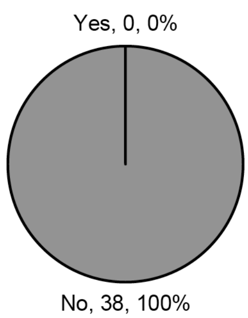


FIGURE B63 Survey response to Question 72: "Does your agency have a certification program for FWD data analysts?"

Question 73: If yes, please describe.

No responses were given to this question.

Question 74: Does your agency send representatives to the annual FWD User's Group meeting?

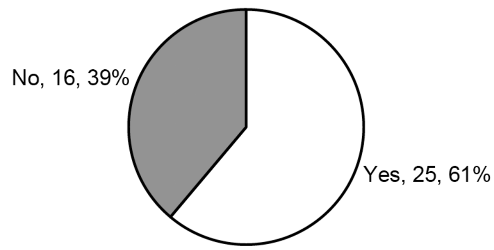


FIGURE B64 Survey response to Question 74: "Does your agency send representatives to the annual FWD User's Group meeting?"

Question 75: Would your agency support a National Highway Institute (NHI) course on FWD usage?

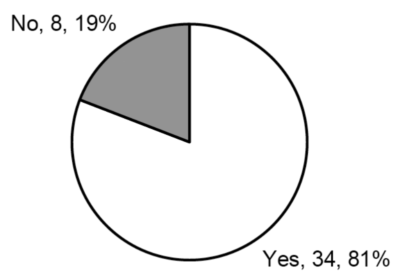
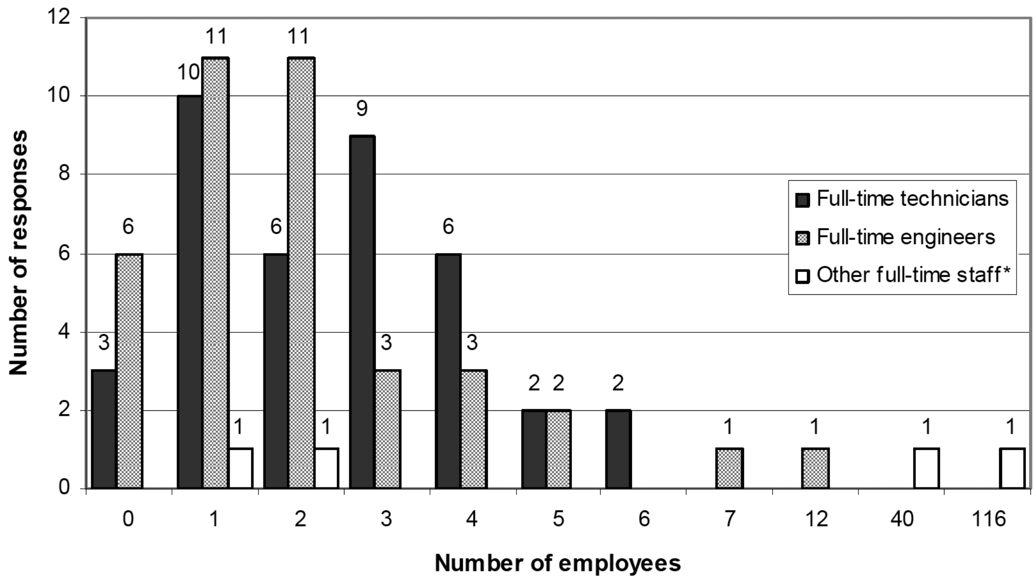


FIGURE B65 Survey response to Question 75: "Would your agency support a National Highway Institute (NHI) course on FWD usage?"

PART 12: FWD PROGRAM ADMINISTRATION—PART 1 OF 2

Questions 76 and 77: How many full-time staff are involved with your FWD program? If you answered others, please describe.



* Other full-time staff responses: (1) system analyst, (1) 2 engineering specialists, (1) 40 part-time operators and data analysts, (1) 116 district engineers and district technicians.

FIGURE B66 Survey response to Questions 76 and 77: "How many full-time staff are involved with your FWD program? If you answered others, please describe."

Question 78: Have there been any FWD-related accidents within the past 5 years?

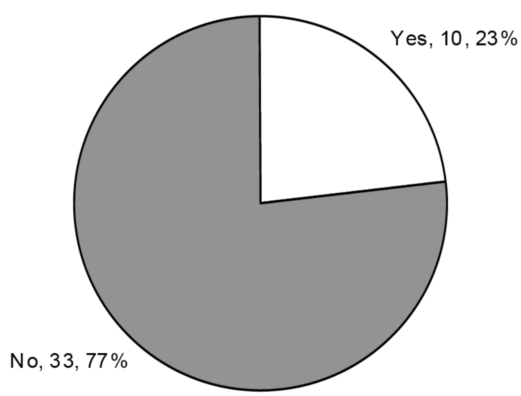


FIGURE B67 Survey response to Question 78: "Have there been any FWD-related accidents within the past 5 years?"

Question 79: If yes, how many?

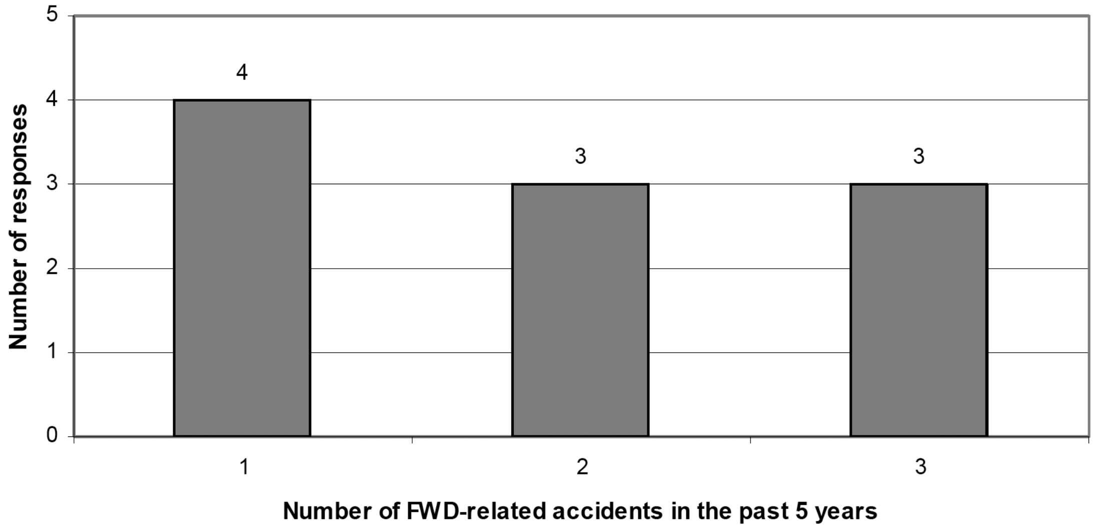
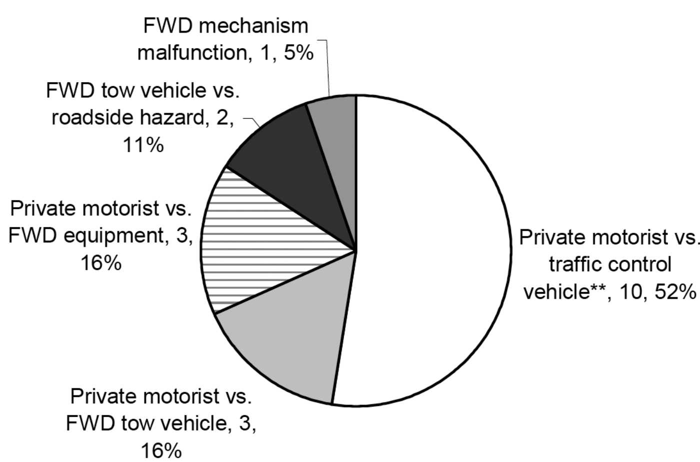


FIGURE B68 Survey response to Question 79: "If yes, how many?"

Question 80: Please describe the type(s) and severity of FWD-related accidents within the past 5 years.



* Across all accidents, 1 fatality and 2 injuries were reported. FWD crew members were not injured or killed during any of the accidents reported.
** All accidents in this category involved private motorists colliding with an attenuator.

FIGURE B69 Survey response to Question 80: "Please describe the type(s) and severity* of FWD-related accidents within the past 5 years."

PART 13: FWD PROGRAM ADMINISTRATION—PART 2 OF 2

Question 81: Does your agency have an FWD Quality Control and/or Quality Assurance plan(s) in effect for your entire FWD program (e.g., data collection, data analysis, data storage, maintenance, etc.)?

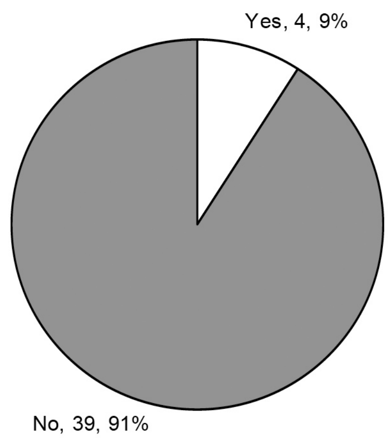


FIGURE B70 Survey response to Question 81: 'Does your agency have an FWD Quality Control and/or Quality Assurance plan(s) in effect for your entire FWD program (e.g., data collection, data analysis, data storage, maintenance, etc.)?"

Question 82: What is the average annual operating budget—including labor, materials, travel, etc.—for your FWD testing program?

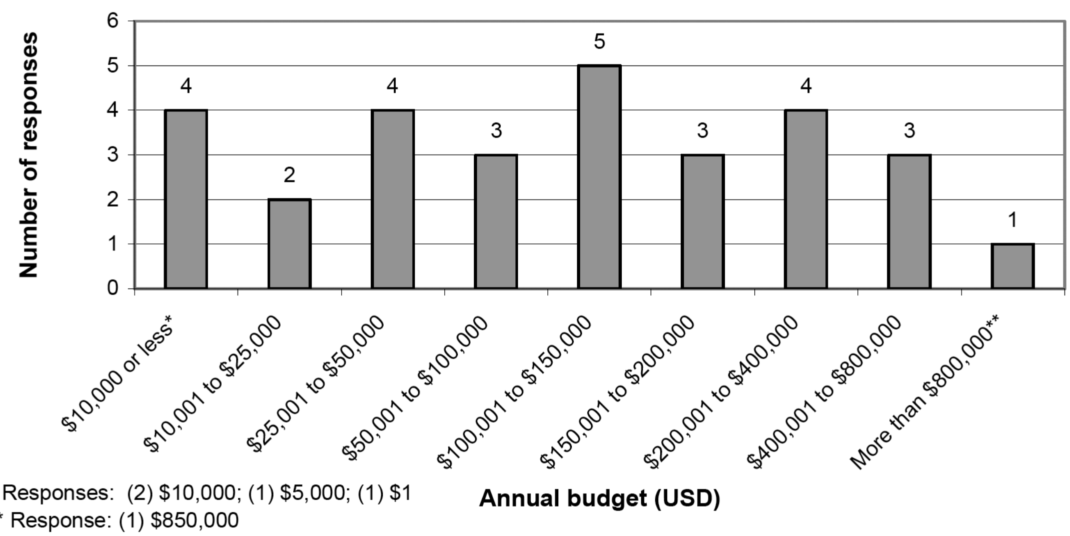


FIGURE B71 Survey response to Question 82: "What is the average annual operating budget—including labor, materials, travel, etc.—for your FWD testing program?"

Question 83: What fraction of your FWD program budget is applied to in-house activities? To outsourced activities?

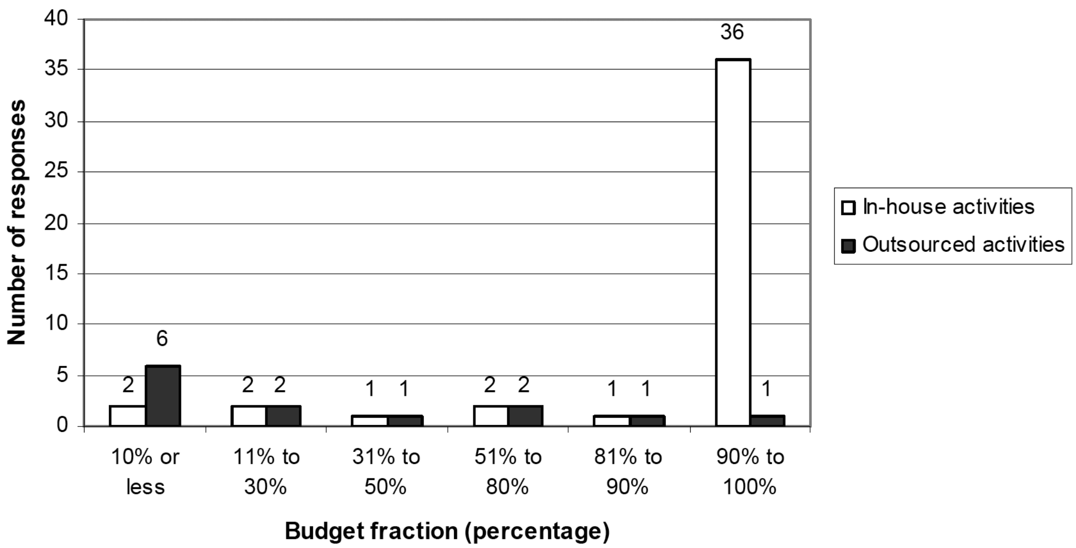


FIGURE B72 Survey response to Question 83: "What fraction of your FWD program budget is applied to in-house activities? To outsourced activities?"

Question 84: If outsourced, what are the contract requirements for personnel training, equipment calibration, data quality, and other deliverables?

TABLE B21

SURVEY QUESTION 84: "IF OUTSOURCED, WHAT ARE THE CONTRACT REQUIREMENTS FOR PERSONNEL TRAINING, EQUIPMENT CALIBRATION, DATA QUALITY, AND OTHER DELIVERABLES?"

Responding State	Contract Requirements
Alaska	Outsourced activities involve using the state's FWDs and personnel to collect data off state property (e.g., for the U.S. Army Corps of Engineers).
California	Current outsourced services are for manufacturer maintenance, parts, repairs, and calibration.
Florida	Follow FDOT procedures including training, equipment used, calibration, data quality checks, and deliverables as described in FDOT handbook.
Nebraska	The repairs and calibration is outsourced to KUAB.
Oregon	Proof of yearly calibration, deliverable of hard and electronic copy of the data in FWD format.
Texas	Calibration certification by LTPP contractor.

Question 85: What percentage of your FWD program budget is dedicated to each of the following levels?

TABLE B22

SURVEY QUESTION 85: "WHAT PERCENTAGE OF YOUR FWD PROGRAM BUDGET IS DEDICATED TO EACH OF THE FOLLOWING LEVELS?"

Level	Average (%)	Median (%)	Mode (%)
Project Level (including forensics)	63.7	79.5	90.0
Network Level	11.3	0	0
Research Level	22.4	10.0	10.0
Other (detailed in Question 86)	2.6	0	0

Question 86: If you answered other above, please describe.

TABLE B23

SURVEY QUESTION 86: "WHAT PERCENTAGE OF YOUR FWD PROGRAM BUDGET IS DEDICATED TO EACH OF THE FOLLOWING LEVELS?" "IF YOU ANSWERED OTHER ABOVE, PLEASE DESCRIBE"

Responding State	Description of Other Activities
California	Most work is done for project-level testing. Research work involves pavement performance data collection.
North Dakota	FWD deflections and calculated moduli are used to help determine when to remove spring load restrictions.

Question 87: Approximately what lane-distance does your FWD program test annually?

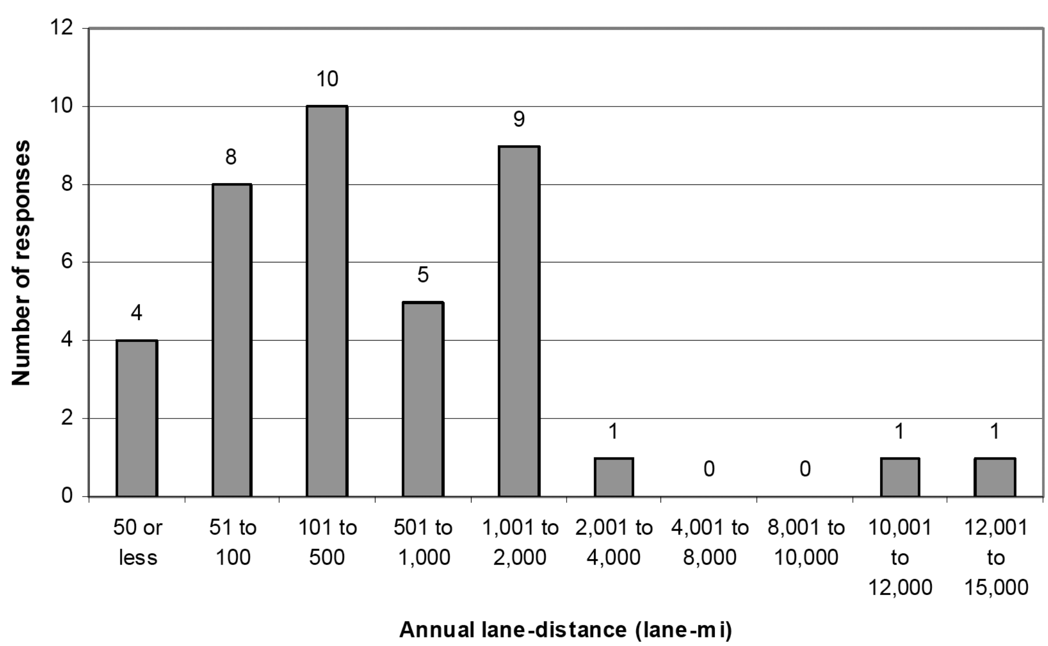


FIGURE B73 Survey response to Question 87: "Approximately what lane-distance does your FWD program test annually?"

Question 88: Please provide any additional comments on the advantages of FWD use in your agency.

TABLE B24

SURVEY QUESTION 88: "PLEASE PROVIDE ANY ADDITIONAL COMMENTS ON THE ADVANTAGES OF FWD USE IN YOUR AGENCY"

Responding State	FWD Program Comments
California	Versatility in the testing, both loading and in sensor configuration, has been the biggest advantage of the FWD. Additional FWD features have also been added for future data analysis.
Connecticut	We have not yet implemented an FWD program.
Florida	FWD complements our other nondestructive equipment (e.g., GPR, ADCP, Plate Bearing).
Illinois	Used primarily for structural monitoring of in-service pavements and research test sites. Not regularly used as a design tool.
Indiana	A decision-making tool that can save a lot of money.
Iowa	We are actually just getting into a network-level testing process. We are awaiting the arrival of a second testing unit to start this process. Currently, we are only doing FWD testing by request and for research purposes. We are also participants in the ongoing federal calibration protocol/calibration center pooled-fund study. Our in-house analysis is primarily a cooperative effort with Iowa State University and the algorithms are developed in a research effort.
Louisiana	It is a valuable tool for pavement assessment and we rely on it and the Dynaflect to make decisions about pavement performance.
Missouri	Network- and new project-level questions were not answered here since we routinely test neither with the FWD. Our FWD usage is sporadic; it is almost entirely reactive to district requests for existing pavement evaluations and early pavement failures.
Montana	We believe that this equipment is a tool that aids us in the design of our rehabilitation strategies, which in turn saves tax payer money.
Nevada	The FWD takes the guesswork out of the "how thick of an overlay is warranted" question. It shows us the benefit of the before-and-after repair strategy.
New York	FWD is essential equipment in determining subbase, subgrade moduli, and PCC load transfer efficiencies.
Ohio	FWD is currently used to test research sections. We plan to use the FWD to provide data for overlay design on four-lane and Interstate pavements in the near future.
Oregon	Used to establish equipment pattern for rubblization during construction by taking deflections after various energy adjustments to rubblization device.
Rhode Island	Our FWD is used almost exclusively for an ongoing research project. We have not yet implemented a pavement evaluation program utilizing the FWD.
South Carolina	Used for the project level only.
Texas	We have the same manufacturer for all of the FWDs, so we don't need to maintain parts for different manufacturers. Also, repairing them is the same.
Utah	Network-level testing program currently under review for usefulness of data.
Wisconsin	FWD usage is limited in our state. With mechanistic-empirical design, may see increased usage.

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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