Falling Weight Deflectometer (FWD) Testing and Analysis Guidelines Volume II: Supporting Documentation

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U.S. Department of Transportation
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Federal Lands Highway
Commitment to Excellence

Federal Lands Highway Division
400 7th Street, Southwest, Room 6311
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FOREWORD

The Federal Lands Highway (FLH) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The objective of this study was to produce a guide for project development and design personnel that clearly defined Falling Weight Deflectometer (FWD) testing requirements, data analysis approach and reporting requirements.

The study included a review of backcalculation computer programs, a review of prominent State DOT data collection and analysis procedures, as well as a review of the current FLH FWD testing and analysis approach. Based on the information collected and through consultation with a FLH technical working group (TWG), recommendations for a best practice FWD testing and analysis procedure were made. The guidelines developed will better assure that FLH collects quality FWD data and that the data is appropriately analyzed.

The contributions and cooperation of the CFLHD personnel is gratefully acknowledged.

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Notice

Quality Assurance Statement

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16. Abstract

This report contains supporting documentation for the *Falling Weight Deflectometer (FWD) Testing and Analysis Guidelines Volume I*. This report includes a review of previous FWD data collection on eight FLH development projects. The FWD data collection and analysis practices of nine state DOTs is also summarized. The methodology and capability of nine backcalculation programs is discussed.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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List of Acronyms and Symbols

AASHTO	-	American Association of State Highway and Transportation Officials
AC	-	asphalt concrete
AGDPS	-	AASHTO Guide for the Design of Pavement Structures, 1993 edition
C	-	subgrade resilient modulus correction factor
DOT	-	department of transportation
FAA	-	Federal Aviation Administration
FHWA	-	Federal Highway Administration
FEM	-	finite element model
FLH	-	Federal Lands Highway
FWD	-	falling weight deflectometer
HWD	-	heavy weight deflectometer
LTE	-	load transfer efficiency
LTPP	-	Long Term Pavement Performance Program
MEPDG	-	mechanistic-empirical pavement design guide
MET	-	method of equivalent thickness
M_r	-	Resilient Modulus
OWP	-	outer wheel path
PCC	-	portland cement concrete
PDDX	-	pavement deflection data exchange
RMSE	-	root mean squared error
SN_{eff}	-	effective structural number

1 INTRODUCTION

This report is Volume II of the guidelines for the collection and analysis of Falling Weight Deflectometer (FWD) data for use on Federal Highway Administration (FHWA) Federal Lands Highway (FLH) projects. It contains supporting documentation gathered during the development of the guidelines.

2 FWD DATA COLLECTION AND ANALYSIS ON FLH PROJECTS

This section summarizes our findings of the FWD testing and analysis procedures used on eight projects performed by or on behalf of FLH. This investigation was performed to augment the information on current FLH procedures and project types gathered during the initial project meeting and teleconference.

2.1 Project Summaries

We obtained eight reports involving FWD testing performed on behalf of Federal Lands Highway Offices. These reports are summarized in Table 1.

Table 1: Projects Reviewed

FLH Region	Project	Test Date	Extent (miles)	Prime Contractor	FWD Contractor
Central	General's Highway (CA)	9/19/05-9/21/05	15.9[1]	Stantec	Stantec
	Forest Highway 120 (CA)	11/19/03	9.25	Kleinfelder	Dynatest
	Trail Ridge Road (CO)	7/17/03	6.9	CFLHD	Ground Engineering
Eastern	Newfound Gap Road (NC)	5/07/02 – 5/14/02	15	EFLHD	EFLHD
	Natchez Trace Parkway (MS)	3/?/04[2]	34	ELFHD	ELFHD
Western	Cascade-Warm Lake Road (ID)	6/18/01 – 6/19/01[3]	26.8	Terracon	Terracon
	North Umpqua Highway (OR)	9/14/04	14.4	NTL Engineering & Geosciences	Pavement Services, Inc.
	McKenzie Highway (OR)	9/22/04	14.7	Terracon	Terrracon

Notes: 1: Includes five spur roads
2: Report states field work performed in March 2004
3: Dates determined from FWD data files; report is dated 4/2/2004

In Table 1, the term "Prime Contractor" is used for the organization that produced the pavement analysis report, and "FWD Contractor" is used for the organization that performed the FWD testing. In all cases the organization that performed the FWD testing also performed the FWD data analysis.

The report for Forest Highway 120 notes that "freezing conditions were encountered during the work." FLH staff involved in the project noted that although there was some snow on the ground, freezing conditions below grade were unlikely. The reported modulus of the base layer ranged from 27 to 59 ksi, and the reported subgrade modulus ranged from 8.6 to 15.3 ksi. These moduli ranges are typical, and do not indicate that either layer was frozen at the time of testing.

All of the pavement sections in these projects were flexible. The reported layer thicknesses and general pavement condition are summarized in Table 2.

Table 2: Pavement Sections

Project	**Thickness**		**Condition Notes**
	AC	**Aggregate Base**	
General's Highway	2.5 – 7.8	8[1]	
Forest Highway 120	2.5 – 4.5	6 - 10.25	Good to fair with isolated fatigue, transverse and block cracking
Trail Ridge Road	3 – 16[2]	?[3]	Chip seal may be masking pavement distress in lower layers. Frost heaves in areas. Stripping in many cores. Shallow depth to bedrock in areas.
Newfound Gap Road	3.75 – 8.5	8	Low to medium severity longitudinal cracking, isolated heaves and high severity cracking
Natchez Trace Parkway	5 – 7	5-8	Low to medium transverse, block and fatigue cracking. Isolated potholes and high severity cracking
Cascade-Warm Lake Road	2.25 – 5.75	0 – 9	Mostly poor condition, some portions fair. Areas with frost heaves
North Umpqua Highway	5.5 – 9.5	9.1 – 24.1	
McKenzie Highway	3.5 – 6	0 - 22	Little cracking. Asphalt cores mostly show heavy stripping.

Notes: 1: Base thickness was assumed, boring results were unsatisfactory
2: Includes material recycled with foamed-asphalt in some areas
3: Aggregate base layer could not be determined through coring; a base layer was used in data analysis, but information on the thickness used is not included in the report.

The thickness values presented in Table 2 are those used in backcalculation where possible. In cases where the report does not state the layer structures used in backcalcualtion, the data is determined from the boring logs or core reports. The base thickness also includes a subbase, where one was noted. The Trail Ridge Road report does not include any information on the base layer thickness, although a base layer was included in backcalcualtion. FLH project personnel have stated that the base layer could not be differentiated from the subgrade based on coring.

Determination of the thickness of the base and subbase layers was a problem on several projects. The large range of base layer thicknesses reported for these projects is in part due to difficulty in differentiating between the base and subgrade materials, although construction variability may also play a part. As many FLH projects are located in mountainous regions the subgrade may be naturally granular, or may consist of granular fill which contributes to the difficulty of differentiating the base material from the subgrade material.

2.2 FWD Equipment

The types of FWD equipment used on the projects reviewed along with their test setups are summarized in Table 3.

Table 3: FWD Equipment and Setup

Project	FWD Type	Seating Drops (kips)	Recorded Drops (kips)	Sensor Spacing (in.)
General's Highway	Dynatest FWD	9	6,9,12	0,8,12,18,24,36,48,60,-12
Forest Highway 120	Dynatest FWD	None	6,9,16	0,8,12,18,24,36,60
Trail Ridge Road	JILS Trailer	?[2]	6,9,12 -15[1]	0,8,12,18,24,36,60
Newfound Gap Road	KUAB 2m	12,12,12	6,6,6,6,9,9,9, 9,12,12,12,12, 16,16,16,16	0,-12,8,12,18,24,36
Natchez Trace Parkway	Dynatest FWD	5,7	9,9,9	0,8,12,18,24,36,48
Cascade-Warm Lake Road	Dynatest HWD	None	9,9	0,8,12,18,24,36,60
North Umpqua Highway	KUAB 2m	?,?[3]	9,9	0,8,12,18,24,36,48,60
McKenzie Highway	Dynatest HWD	None	6,9,12	0,11.8,24,36,48,60,72

Notes: 1: 12 kip nominal load was increased to 15 kips during testing due to low deflections at outer sensors.
2: One seating drop was used; the load level was not reported
3: Two seating drops were used; the load levels were not reported

Four different types of FWD equipment were used on the eight projects reviewed. A different test setup was used on each project. Only half used seating drops. The recorded load levels also varied, although all included at least one 9 kip load.

All FWDs tested with deflection sensors located at 0, 8, 12, 18, 24 and 36 inches. On seven of the eight projects the FWD also mounted a sensor at 60 inches. Two of the FWDs tested with a sensor mounted in the -12 inch position, which is generally used only for load transfer testing on PCC pavements.

The drop sequence used in testing on Newfound Gap Road includes 19 drops at each test location, and is a definite outlier. This drop sequence is that used by the Long Term Pavement Performance Program (LTPP) for research-grade testing on test sections up to 1,000 feet in length, and is not normally used for project-level testing.

2.3 FWD Test Points

Test point locations are summarized in Table 4. The total number of test points was calculated by dividing the project length (from Table 1) by the spacing and multiplying by two. This may not exactly match the actual number of tests performed. Likewise, the number of drops was calculated by multiplying the number of drops at each location (including seating drops) by the number of test points.

Table 4: Test Point Summary

Project	Spacing (ft)	Lane Position	Test Points	Drops	Testing Days
General's Highway	328[1] (100 m)	ML	435	1740	3
Forest Highway 120	328[1] (100 m)	OWP	298	894	1
Trail Ridge Road	328[2] (100 m)	OWP	223	892	1
Newfound Gap Road	2,000	OWP	80	1520	4
Natchez Trace Parkway	2,640 (0.5 miles)	OWP	136	680	3
Cascade-Warm Lake Road	1,000[1]	OWP	284	568	2
North Umpqua Highway	600[1]	?	247	988	1
McKenzie Highway	1,056[1] (0.2 miles)	?	147	441	1

Notes:
1: Report specifies that test points in opposing lanes were staggered
2: Additional data points collected in areas with high deflections

The test point spacing varied by almost an order of magnitude, from 328 feet to 2640 feet. The transverse position of the FWD was only specified in three reports; two specified outer wheel path (OWP). The printed text of the General's Highway report states that the OWP was tested, however that is crossed in the version supplied to MACTEC and the statement "No, between wheel lines" is written in by hand. According to FLH staff, the shoulder was too narrow to allow the FWD to be positioned in the OWP.

The report on the Trail Ridge Road project states that the test point spacing was reduced from 100 meters to 25 or 50 meters in areas with high deflections or variable test results. The results from these weak or variable areas were averaged along with the data collected at fixed spacings. None of the remaining project reports indicate that testing was targeted in specific areas.

2.4 Data Analysis

Table 5 summarizes the data analysis methods used on the selected projects.

Table 5: Data Analysis Methodologies

Highway	Software	M_r Correction factor	No. Layers	AC Temp. Correction	Mid-depth Temperature Source
General's Highway	AGDPS[1]	0.33	2	No	Measure
Forest Highway 120	ELMOD	?	3	Yes	BELLS
Trail Ridge Road	DAPS 1.5.1	0.33	3	Yes	Measure, ~ 1.5 mile interval
Newfound Gap Road	DarWin	0.33	2	Yes	Measure, each test point
Natchez Trace Parkway	DarWin	0.33	2	Yes	Measure
Cascade-Warm Lake Road	Evercalc 5.0	?	3	Yes	?
North Umpqua Highway	PAVBACK	1.0	3	Yes	?
McKenzie Highway	DarWin	0.33	2	?	?

Notes:
1: Report does not specify software, only that AASHTO 1993 method was followed.

DARWin was used for data analysis on three of the projects. The report for a fourth project, General's Highway, states that the "AASHTO 1993 Design Guide backcalculation analysis" method was used. While this does not rule out use of DARWin, from the plots included in the report it seems likely that the analysis was performed in a spreadsheet.

Of the remaining four projects, two were analyzed using layer-elastic backcalculation programs (DAPS, EVERCALC), and two were analyzed using Odemark-Boussinesq equivalent layer backcalculation programs (PAVBACK, ELMOD). In each case, the pavement was modeled as a three layer system, comprised of an AC surface layer, an aggregate base layer and a subgrade layer. None of the reports listed the seed modulus values used in the analysis. The report for the Forest Highway 120 project did not include root mean squared errors (RMSEs) or any other criteria for evaluating the quality of the analysis.

The three reports based on DARWin all state that a subgrade resilient modulus correction factor of 0.33 was used. The report based on PAVBACK states that "because the program accounts for the potential of non-linear, finite subgrade depth, direct calculation of the subgrade moduli can be performed without the need for a correction factor recommended by the procedure outlined in the 1993 AASHTO Guide." Of the remaining projects, it appears that only Trail Ridge Road used a correction factor. None of the analyses addressed seasonal variation of subgrade modulus.

The four reports that are not based on the AGDPS all include a temperature correction for the asphalt concrete layer. For the Forest Highway 120 project, the asphalt mid-depth temperature was estimated using the BELLS equations. For the Trail Ridge Road project the mid-depth temperature appears to be measured based on comments in the FWD data file, however the methodology used is unspecified. For the Cascade-Warm Lake Road and North Umpqua Highway projects, a temperature correction was applied to the AC layer; however the source of the pavement temperature data is unspecified.

None of the reports documented any quality control checks or processes performed on raw FWD data.

Two of the projects included FWD analyses that were highly problematic. On the Cascade-Warm Lake Road project, very high RMSEs were reported. The minimum RMSE was 3.3%, and the maximum was 96.46%. Typically, an RMSE of 2% is considered high. The report describes this situation as follows:

> "When reviewing the Evercalc data, the RMS error (how well the collected deflection match the predicted deflections) is higher than normal. In many cases, there is very little perceivable difference between the deflections of the sixth and seventh sensors. Stiffness and thickness of the pavement layers affect the shape of the stress bowl and the magnitude of the stress in each individual layer. Because the pavement section is relatively thin and not stiff, Evercalc might be modeling the subgrade resilient modulus using the last sensor which may be too far away from the load plate to give a result with low errors. Modeling the pavement as a two-layer system or analyzing a narrower bowl (5- or 6- sensor analysis) will tend to improve the error."

Without having analyzed this data ourselves, it is difficult to speculate on the source of the error. Certainly removing the outer sensor from the analysis is a reasonable approach.

As the pavement structure at this section is very thin, perhaps two or three outer sensors should be removed. A review of the surface modulus plot would be helpful in determining the validity of data from the outer sensors. Combining the base layer and the subgrade layer also seems reasonable, especially in light of the difficulty in differentiating the base layer from the subgrade layer on this project. Also, it appears that the minimum values for the seed moduli were set too low for both the AC layer and the base layer, which limits the ability of Evercalc to find a good fit.

On the Trail Ridge Road project the reported base and subgrade moduli are unreasonable for the section "From Entrance to Moraine Park Museum, North on Bear Lake Road". In this area, the average moduli for the AC, granular base layer and subgrade are 499 ksi, 25 ksi and 999 ksi respectively. The base layer is highly variable, with a low of 1 ksi and a high of 487 ksi. The subgrade is also highly variable, with a low of 32 ksi and a high of 7,817 ksi. Extreme high values of the subgrade modulus are associated with extreme low values of the base modulus, and vice versa. Interestingly, the RMSEs were not extreme for this section, averaging 0.92%, with a high of 1.94% and a low of 0.41%. The report addresses high subgrade modulus values as follows:

> "The average resilient modulus of the base material was often lower than that of the subgrade. Many times, the modulus of the subgrade exceeded one million psi. This is likely due to rock cuts and dense cobbles/rock fragments which compose the subgrade throughout many of the roadway alignments. In addition, it may be the result of the gradual contamination of the base course with fine material that has propagated upward."

Again, without having analyzed this data ourselves, it is difficult to speculate on the source of the error. One technique often used in this situation is creating a bedrock layer with a fixed stiffness, usually 1,000 ksi. This may yield more reasonable base layer moduli. However, it is likely that the problem is highly variable sub-surface conditions as the report stated. FWD testing is not capable of determining individual layer moduli unless the layer structure is reasonably well known for each FWD test point.

2.5 Summary

The variation of FWD testing and analysis procedures in the eight projects reviewed reinforces the need for standardization. In addition, many of the reports failed to adequately document the testing and analysis procedures used. Basic information such as deflection sensor spacing and drop sequences varied widely across projects and could only be found by reviewing the included raw data in many cases, and could not be determined at all in a few cases.

Three different analysis techniques were utilized: AASHTO 1993 (4 projects), Odemark-Boussinesq equivalent layer theory (2 projects) and layered elastic theory (2 projects). Those analyses performed using DARWin were well documented because that program intrinsically reports its input parameters. The remaining analyses were less well documented, and in general could not be repeated based on the information included in the reports. Temperature correction of AC modulus was addressed in the four analyses that were not based on the AGDPS. None of the analyses addressed seasonal variation of subgrade modulus.

The pavement conditions varied from good to poor. The pavement sections were highly variable, but generally consisted of a thin layer of AC over an aggregate base. Shallow depth to bedrock was noted in one report. Frost heaves and areas of high distress were noted in five of eight reports. Unreasonable analysis results were noted in two projects. In one of these projects the poor results were attributed to weakness of the pavement structure, in the other they were attributed to shallow depth to bedrock.

2.6 Recommendations

Above and beyond the general need for standardization, several needs were noted.

- Clear and consistent reporting of equipment setup, including deflection sensor spacing and drop sequence (including seating drops).

- Clear and consistent reporting of analysis parameters, including layer thicknesses, seed moduli, resilient modulus correction factors and AC modulus temperature correction methodology.

- Quality control of raw data, including deflections, loads and temperature measurements.

- Quality control of analysis results. Reports should include a factor such as RMSE which indicates the goodness of fit between computed and measured deflections. Reasonableness ranges of reported moduli should be established. Procedures should be established for cases where the RMSE or reported moduli are outside acceptable ranges.

- Guidelines on combining layers. On several projects, the base and subgrade layers were difficult to differentiate, not only through analysis of FWD data but also with other techniques such as coring and ground penetrating radar. The guidelines should address situations when combining layers leads to better analysis results.

3 FWD ANALYSIS AND DATA COLLECTION PROCEDURES USED BY SELECTED STATE DOTS

This section summarizes the FWD data collection and analysis practices of nine selected state DOTs. A wide range of practices were found. The analysis procedures in use by the state DOTs investigated are described first, as these procedures in large part determine the operational procedures used.

3.1 Analysis Procedures

Table 6 lists the theoretical basis of the analysis procedures used by the state DOTs investigated, as well as the computer software utilized to carry out those procedures.

Table 6: Analysis Theories and Software Used

State DOT	Analysis Theory	Software
California	Deflection	N/A
Colorado	AGDPS	DARWin
Maryland	AGDPS	MODTAG
Minnesota	Deflection	"FWD DATA ANALYSIS"
Nevada	AGDPS/Layer Elastic	DARWin/MODULUS
Oregon	AGDPS/Deflection	DARWin
Texas	Layer Elastic	MODULUS
Virginia	AGDPS	MODTAG
Washington	Layer Elastic	AREA/EVERCALC

3.1.1.1 Surface Deflection Based Methods

Two of the state DOTs, California and Minnesota, use surface-deflection based analysis procedures. Oregon also uses the California method for some overlay projects. These methods use only the deflection recorded in the center of the load plate, and are derived from methods originally developed for the analysis of Benkleman Beam data.

California uses a surface-deflection based FWD analysis procedure, which uses only the deflections measured at the center of the load plate. The mean and 80th percentile deflections are calculated for the test section. These deflections are then converted to equivalent "California Deflectometer" measurements using an empirical calibration curve. Tolerable surface deflections are determined for the section based on the pavement thickness and traffic volume using a compiled chart. If the measured 80th percentile deflection is more than the tolerable surface deflection, rehabilitation is required. The percentage by which the deflection needs to be reduced is calculated, and the required structural enhancement, expressed as feet of "gravel equivalence", is determined from a table. This thickness of gravel equivalence can then be converted to thickness of various types of overlay materials using further conversion factors.

Minnesota DOT uses an approach originally developed for Benkelman Beam data. Center deflections are normalized to 9,000 pounds, and then converted to an equivalent Benkelman beam defection using a regression equation. Structural sufficiency of an in-service pavement is determined by allowable deflection – a table has been compiled with allowable deflections for different traffic volumes and pavement thicknesses. An equation is provided to estimate the reduction in deflection based on the thickness of an asphalt concrete overlay.

3.1.1.2 AGDPS Based Methods

Colorado DOT, Maryland DOT, and Virginia DOT all use the deflection analysis procedures described in the AGDPS for all analysis. Nevada and Oregon use this procedure for new construction only. Washington uses this procedure, with some modifications, on the majority of projects. Maryland and Virginia use the MODTAG computer program to carry out this analysis. The remaining states use DARWin.

3.1.1.3 Linear Elastic Based Methods

Nevada, Texas and Washington perform analysis of FWD data with backcalculation using linear-elastic theory. Nevada uses this method for the analysis of overlays on flexible pavements only. Texas and Washington use this method for the analysis of all FWD data. Nevada and Texas use the MODULUS computer program for backcalculation. Washington uses the EVERCALC program for backcalculation and AREA as a screening tool to identify areas in need of specific attention.

None of these states have strictly-defined procedures for performing backcalculation. In Nevada and Washington, backcalculation is performed by a limited number of individuals in a centralized materials office. In Texas, backcalculation is performed by individuals in the regional offices and Texas DOT has developed a series of training courses to educate these individuals in backcalculation techniques.

Nevada uses the seed values shown in Table 7 for backcalculation.

Table 7: Seed values used by Nevada DOT

Material Type	**Modulus (ksi)**	
	Lower bound	**Upper bound**
Asphalt Concrete	100	1,000
Stabilized Base	100	400
Granular Base	30	200
Subgrade	8	

Texas uses the parameters shown in Table 8 for backcalculation.

Table 8: Parameters used by Texas DOT

Material Type	Modulus (ksi)		Poisson's Ratio
	Lower bound	Upper bound	
Portland Cement Concrete	2000	7000	0.20
Asphalt Concrete	500	850	0.35
Asphalt Stabilized Base	250	400	0.35
Cement Treated Base	80	150	0.25
Granular Base	40	70	0.35
Lime Stabilized Subgrade	30	45	0.30
Good Subgrade	16	20	0.40
Normal Subgrade	8	12	0.40
Poor Subgrade	2	4	0.40

Washington has an in-depth method for determining seed moduli for various material types. The seed modulus of asphalt concrete is determined using Equation 1.

$$E = 10^{\left(6.4721 - 0.000147362 \times T^2\right)}$$

Figure 1. Equation 1.

where: E = asphalt concrete modulus, psi
T = mid-depth asphalt concrete temperature, Fahrenheit

Washington DOT's guidelines note that the modulus of fatigued asphalt concrete is typically between 100 ksi and 200 ksi. The Poisson's ratio of asphalt concrete is assumed to be 0.35.

Seed moduli and Poisson's ratios for base, subbase and stabilized materials are as shown in Table 9.

Table 9: Base, Subbase and Stabilized Materials Parameters Used by Washington DOT

Material Type	Seed Modulus, ksi	Poisson's Ratios
Granular Base	35	0.35
Granular Subbase	30	0.35
Sand Base	20	0.35
Sand Subbase	15	0.35
Cement Stabilized Material	1000	0.25-0.35
Lime Treated Subgrade	50	0.25-0.35

The seed moduli for subgrade materials are determined based on material type and climate, as shown in Table 10.

Table 10: Subgrade Parameters by Climate Type Used by Washington DOT

Material	Seed Modulus, ksi				Poisson's Ratio
	Dry	Wet - No Freeze	Wet-Freeze		
			Unfrozen	Frozen	
Clay	15	6	6	50	0.45
Silt	15	10	5	50	0.45
Silty or Clayey Sand	20	10	5	50	0.35-0.40
Sand	25	25	25	50	0.35-0.40
Silty or Clayey Gravel	40	30	20	50	0.35-0.40
Gravel	50	50	40	50	0.35-0.40

3.1.1.4 Correction Factors

Beyond the basic analysis methodology, we also investigated the use of correction factors. These correction factors include laboratory/field resilient modulus correlation factor, asphalt concrete temperature correction and seasonal correction of results. Table 11 shows the usage of these factors by the state DOTs investigated.

Table 11: Correction Factors

State DOT	Subgrade Modulus Correction	AC Temperature Correction	Seasonal Correction
California	NA	No	No
Colorado	No policy (typically 0.33)	No policy	No
Maryland	0.33	Yes	No
Minnesota	NA	Yes	Yes
Nevada	0.33[1]/No[2]	Yes	No
Oregon	0.33[1]/NA[3]	Yes[1]/No[3]	No
Texas	No	Yes	No
Virginia	0.33	Yes	No
Washington	0.33[1]/No[4]	Yes	No

Notes 1: For AGDPS analysis
2: For MODULUS analysis
3: For Surface deflection based analysis
4: For Evercalc analysis

All of the state DOTs use a subgrade resilient modulus correction factor of 0.33 when using the AGDPS analysis procedure. None of the state DOTs use a resilient modulus correction factor when using a surface deflection or linear-elastic analysis procedure. As surface deflection based analysis procedures do not directly calculate the subgrade resilient modulus, such a correction is not applicable. None of the three states that use linear-elastic methodologies for backcalculating layer moduli use those moduli in the AASHTO 1993 pavement design procedure. Therefore although they do not use a correction factor, this is not relevant to the use of a subgrade resilient modulus backcalculated using a layered elastic program in AGDPS procedure.

All of the states investigated performed temperature correction of FWD results, with the exception of California. Minnesota, which uses a similar procedure, applies a temperature correction directly to measured deflections. The remaining states with the exception of Nevada use the temperature correction procedures provided by the analysis software used. Nevada uses an external spreadsheet to perform temperature correction of asphalt concrete.

Only Minnesota DOT applies a seasonal adjustment as part of the FWD data analysis procedure. Tables of seasonal adjustment factors have been compiled by Minnesota DOT for various test calendar dates, pavement thicknesses and subgrade types. The measured surface deflections are multiplied by the appropriate seasonal correction factor to determine the equivalent "spring deflection".

3.2 Data Collection

Our investigation of state DOT FWD operational procedures focused on equipment setup and test point spacing.

3.2.1.1 Equipment and Setup

The types of FWD equipment used by the nine states investigated along with information on how that equipment is configured are presented in Table 12.

Table 12: Equipment Type and Setup

State	FWD Types	Number Owned	Load Levels, kips		Sensor Spacing, inches
			Seating	Recorded	
California	KUAB/JILS	2/2	9	9,9,9	0
Colorado	JILS	1	None	9,9,9	0,8,12,18,24,36,60
Nevada	Dynatest	2	9	9	0,12,24,36,48,60,72
Maryland	Dynatest	1	Varies, see Table 13		
Minnesota	Dynatest	4	None	9,9,12,12,15,15	0,8,12,18,24,36,48,60,72
Oregon	Dynatest	1	None	6,9,12	0,8,12,18,24,36,60
Texas	Dynatest	15	None	9	0,12,24,36,48,60,72
Virginia	Dynatest	1	12,12	6,6,6,9,9,9, 12,12,12,15,15,15	0,8,12,18,24,36,48,60,72 (0,8,12,18,24,36,60 acceptable)
Washington	Dynatest	1	9,9	16,12,9,6	-12,0,8,12,24,36,48

Of the states investigated, only California owns FWDs built by more than one manufacturer. At this time however, the KUAB FWDs are not in active use.

Five of the nine state DOTs investigated include at least one seating drop in their drop sequence. Every state except Maryland includes at least one recorded drop at the 9 kip load level. Maryland includes a 9 kip drop in most, but not all test setups.

Maryland is unique in tailoring the drop sequence and sensor spacing to the specific project. Drop sequences are selected using the following table, where 1,2,3,4 are recorded drops at 6,8,12,16 kips, respectively, and A,B,C,D are seating drops at those load levels. Sensor spacings other than those in this table are allowed at the discretion of the engineer. Table 13 presents the test setups used by Maryland DOT.

Table 13: Test setups used by Maryland DOT

Pavement Type	HMA Thickness, inches	Test Type	Sensor Spacing, inches	Drop Sequence
Flexible	<4	Basin	0,8,12,24,26,48,60	BA1B2
Flexible	4 – 8	Basin	0,8,12,24,26,48,60	BB2C3
Flexible	> 8	Basin	0,8,12,24,26,48,60	BB2D4
Rigid	N/A	Basin	0,8,12,24,26,48,60	BC3D4
Rigid	N/A	Joint	-12,0,12,24,26,48,60	BB2C3D4
Composite	N/A	Basin	0,8,12,24,26,48,60	BC3D4
Composite	N/A	Joint	-12,0,12,24,26,48,60	BB2C3D4
Composite	N/A	Joint/Basin	0,12,18,24,26,48,60	BB2C3D4
Subgrade	N/A	Basin	0,8,12,24,26,48,60	AA1B2

3.2.1.2 Test Point Spacing

The test point spacings used by the nine DOTs investigated are presented in Table 14. These test point spacings are on a lane basis, however all of the DOTs perform testing only in the outer lane on highways with more than one lane per direction except in special circumstances.

Table 14: Test Point Spacings

State DOT	Test Point Spacing, feet	Lane Pos.
California	262 (80 m, minimum 21/project)	OWP
Colorado	528 (0.1 mile)	OWP
Nevada	1056 (0.2 mile)	OWP
Maryland	Varies	OWP
Minnesota	528 (0.1 mile, minimum 5/section)	OWP
Oregon	250	OWP
Texas	528 (0.1 mile, minimum 30/project)	OWP
Virginia	Varies, see Table 8	OWP
Washington	250	OWP

All of the state DOTs test in the outer wheel path (OWP).

California tests at 80 meter interval, with a minimum of 21 tests in a project. Alternatively, one 300 meter section tested at a 15 meter interval may be selected out of every 1600 meters.

Maryland leaves the test point spacing up to the pavement engineer, based on the expectation of 150 test points to be performed in a day. A minimum of thirty test points per direction should be collected. Two days of testing are recommended for projects over 3 centerline miles. For a two lane, five mile section this would equate to a test point spacing of 176 feet, which would be rounded up to 200 feet in practice.

Virginia varies the test point spacing according to the project length, as shown in Table 15.

Table 15: Test Point Spacings Used by Virginia DOT

Project Length, miles	Test point spacing, feet
0 – 0.5	25
0.5-2	50
2-4	100
4-8	150
> 8	200

4 REVIEW OF BACKCALCULATION PROGRAMS

This section summarizes our investigation of FWD backcalculation programs with regards to their suitability FLH usage.

4.1 Software Investigated

We investigated nine FWD backcalculation programs. In addition, DARWin has been included in the analysis as a reference, although it is not under consideration for future FLH usage. Summary information on these programs in contained in Table 16.

Table 16: Software Investigated

Program	Latest Version	Developer	Environment	Availability
BAKFAA	1/3/2006	FAA	Windows	Free, source code available
Bousdef	2.01 (1/2/2001)	Haiping Zhou	Windows	Free
DAPS	1.5.1	Abatech	Windows	$600
ELMOD	5 (12/8/2005)	Dynatest	Windows	$5000 site license, additional license $575
Evercalc	5.0 (3/2001)	Washington DOT	Windows	Free
MICHBACK	1.0 (1995)	Michigan State University	DOS	Free
MODCOMP	6 (9/26/2004)	Cornell University	DOS	Free
MODULUS	6.01 (2/3/2003)	Texas Transportation Institute	Windows	Free
MODTAG	3.1.68 (10/12/2005)	Virginia DOT/Cornell University	Windows	Free
DARwin	3.1	AASHTO	Windows	$2000

Of these nine programs, seven are available for free. The other two, DAPS and ELMOD have substantial licensing fees, however they are commercially supported. The others are nominally supported by their authors in the cases of errors and bugs, however prompt support for installation and other user-associated problems is not likely.

Seven of these programs have a MS Windows-based graphical user interface. The remaining two, MICHBACK and MODCOMP are DOS programs which can run under DOS or in a DOS shell under MS Windows. All of these programs will run on MS Windows 98, 2000 and XP.

BAKFAA is unique among the programs investigated in that its source code is freely available. This would allow an interested user to add or modify its functionality, especially with regards to adding support for new FWD file formats.

DARWin was included in this investigation as a reference point only, as DARWin is not capable of backcalculating individual layer moduli.

4.2 File Formats and Units

Table 17 summarizes the file formats and units used in the nine backcalculation programs.

Table 17: File Formats and Units

Program	File Formats	Program Units
BAKFAA	F20, PDDX	US
Bousdef	User input, program specific format	US
DAPS	F20	SI
ELMOD	F9, F10, F20, F25, FWDWin	US or SI
Evercalc	F20, F25	US or SI
MICHBACK	KUAB, program specific format	US or SI
MODCOMP	User input, program specific format	US or SI
MODULUS	F9, F10, F20, program specific format	US
MODTAG	F20, F25, PDDX	US (SI support under development)
DARWin	F20, KUAB, PDDX	US or SI

Of the nine backcalculation programs, only two accept data from more than one brand of FWD equipment. These are MODTAG and BAKFAA, both of which accept data in the Pavement Deflection Data Exchange (PDDX) format. PDDX is a file format specified by the AASHTO publication "Pavement Deflection Data Exchange Technical Data Guide, Version 1.0" dated April 1998. All four FWD manufacturers have recently added support for this format in their data collection software, however it is often not supported by older equipment.

The F9, F10, F20, F25 and FWDWin formats were created by Dynatest. Support for these formats by equipment made by other manufacturers is rare. The KUAB format was created by KUAB, although some FWDs manufactured by JILS can also export data in that format. Two of the programs, BOUSDEF and MODCOMP can not directly import data from any standard FWD data format.

Four programs have dual-unit capability, while four use the US Customary system only, and one uses the SI system only. SI support for MODTAG is currently under development.

4.3 Theory and Modeling

The basic theories and methodologies used by the backcalculation programs in modeling the pavement system are presented in Table 18.

Table 18: Theory and Modeling

Program	Theory	Forward Engine	Max. Sensors	Max. Layers
BAKFAA	layer-elastic	LEAF	7	10
Bousdef	MET	internal	9	5
DAPS	layer-elastic	ELSYS	9	4[1]
ELMOD	MET[2]	internal	15	5[1]
Evercalc	layer-elastic	Weslea	10	5
MICHBACK	layer-elastic	Chevlay2	10	4[1]
MODCOMP	layer-elastic	Chevlay2	9	12
MODULUS	layer-elastic	Weslea	7	4[1]
MODTAG	layer-elastic	Chevlay2 (via MODCOMP)	9	7
DARWin	MET/DL	internal	9	2

Notes: 1 Program can additionally include a stiff layer (e.g. bedrock)
2 ELMOD can also use Weslea or a finite element model through add-in modules

4.3.1 Pavement Response Models

There are two different models commonly used for calculating surface deflections in flexible pavement systems: Layer-elastic theory and the Method of Equivalent Thickness (MET). Seven of the programs use the former, and two use the latter. The two programs based on MET both have internal forward-calculation engines that are specific to them. Of the linear-elastic based programs, three use Chevlay2 as a forward calculation engine, which is an enhanced version of the CHEVRON program originally developed by the Chevron Corporation. Two use the Weslea program, which was developed by the Army Corps of Engineers Waterways Experiment Station. One uses the layered-analysis program LEAF which was recently developed by the Federal Aviation Administration. The remaining program uses ELSYS, the origin of which is not known to us, but it may be related to ELSYM5 which was originally developed at the University of California Berkley and modified by FHWA.

Layered-elastic theory was first developed by Burmister in 1945.[1] This theory is mathematically derived from the theory of elasticity, and it is correct for materials that are linear-elastic, isotropic, homogenous and of infinite extent in the horizontal directions. It is, however, computationally-intensive. The first computer program capable of solving arbitrary problems using this theory was CHEVRON in 1962. These programs were not ported to personal computers until the mid-1980s.

In the interim, the method of equivalent thickness, which is not theoretically correct but is capable of being solved by hand, was developed by Odemark in 1949.[2] Odemark's basic assumption is that the influence of a layer on the layers below it is dependent on the stiffness of that layer only. Therefore a layer with a given elastic modulus and thickness can be equivalent to another layer with a different elastic modulus and thickness but the same overall stiffness for the purpose of determining stresses, strains and deflections in the layer below it. If all the layers in the system are transformed into equivalent layers with the same elastic modulus as the subgrade, the problem is now a semi-infinite half-space and the deflection of the subgrade is now solvable using Boussinesq theory. Deflections in the layers above the subgrade are calculated as the difference in deflection at the top of the layer and the bottom of the layer in a transformed system with the modulus equal to the modulus of that layer.

For most problems layered-elastic theory and the method of equivalent thickness do not yield exactly the same answers. For problems where the layer moduli decrease with depth, and the thickness of each layer is greater than the load plate radius both methods tend to give similar answers. For these situations a simple calibration factor of 0.8 or 0.9 is typically applied to moduli backcalculated using the method of equivalent thickness. For other situations more complicated calibration equations must be used.

Thin layers are a problem for all backcalculation methods and programs. This problem is inherent in the nature of backcalculation. Because there are no closed-form solutions for calculating layer moduli based on surface deflections, backcalculation involves iterative methods of varying layer moduli to match the measured surface deflections. Thin layers contribute little to the surface deflections regardless of their layer moduli. Therefore the thin layer may have a wide range of moduli without a significant effect on surface deflections. Solutions to the thin layer problem would require collecting data other than surface deflections, such as sub-surface stresses or strains.

4.3.1.1 Rigid Pavement Models

DARWin performs backcalculation of flexible and rigid pavements in different ways. Flexible pavements are analyzed using the method of equivalent thickness, however only two layers are considered. These layers are the subgrade and pavement layer (including all bound and unbound pavement layers). Rigid pavements are analyzed using Westergaard's theory for the interior loading of a plate on a dense liquid (DL) foundation.[3] The plate is assumed to be infinite in the horizontal directions. The subgrade is modeled as a dense liquid with no shear strength. Both these assumptions greatly simplify the calculations.

None of the nine computer programs investigated are specific to rigid pavements, although such programs exist. These programs use either slab on dense liquid, slab on elastic sold or finite element models. Some of these programs, such as ILLI-SLAB, can correct for slab size. These corrections are complicated, as the load transfer between adjacent slabs and the shoulder must be known.

Historically, there has been little consensus in the pavement engineering community as to whether special-purpose rigid pavement backcalculation programs yield better results than general purpose programs such as those investigated here. The Long Term Pavement Performance Program (LTPP) avoided this issue by performing backcalculation on rigid pavements using the layered-elastic model, the slab on dense liquid model and the slab on elastic solid model.

However, two recent and important rigid pavement design methodologies use layered elastic theory. LEDFAA, which was developed by the Federal Aviation Administration for airfield pavement design, uses the computer program LEAF to calculate stresses and strains in both flexible and rigid pavements. LEAF is based on layered elastic theory, and is also used in the BAKFAA backcalculation program.

The mechanistic-empirical design guide being developed under NCHRP 1-37A (commonly known as the "MEPDG") uses JULEA, which is a layered elastic program, for computing the effective dynamic modulus of subgrade reaction (effective k-value) for rigid pavements with multiple subgrade layers. This reduces the problem to three layers (slab, base and subgrade), which is further analyzed using ISLAB2000, which is based on plate theory.

4.4 Program Limitations

Two programs, MODULUS and BAKFAA are limited to a maximum of seven deflection sensors. Many FWDs currently mount more then seven deflection sensors, with nine being a typical number. Some new FWDs are capable of mounting up to 15 deflection sensors, but such a configuration is rare.

MODULUS, MICHBACK and DAPS have a pavement model that is limited to a maximum of four layers. This is typically sufficient for project-level pavement analysis. These four layers are typically interpreted as a bound surface layer, unbound base layer, unbound subbase layer and subgrade. These three programs can also include a stiff layer (e.g. bedrock) which is treated separately from the four explicit layers. For programs that do not include a separate stiff layer, the lowest layer can be explicitly modeled as bedrock.

MODTAG uses MODCOMP as its backcalculation engine. Its theory of operation is therefore identical to that of MODCOMP, subject to an additional limitation on the number of layers. Alternatively, MODTAG can export data to MODULUS. MODTAG is unique among the investigated backcalculation programs in that deflection basins at the same location and target load are averaged prior to analysis.

4.5 Additional Features

The additional features of the backcalculation programs investigated are summarized in Table 19.

Table 19: Additional Features

Program	Non-Linear Materials	Depth-to-bedrock Estimation	AC Temperature Correction	AC Temperature Estimation	Raw Data QC Tools	Load Transfer Efficiency	Void Detection	Segmentation Tools
BAKFAA								
Bousdef								
DAPS		●						
ELMOD	●	●	●	●	●	●	●	●
Evercalc	●	●	●	●				
MICHBACK		●			●			
MODCOMP	●	●						
MODULUS		●						●
MODTAG	●	●	●	●	●	●	●	●
DARWin			●			●		

4.5.1 Non-Linear Materials

ELMOD, EVERCALC, MODCOMP and MODTAG are capable of analysis of the non-linear elastic properties of pavement layers. MODCOMP includes nine stress-dependency models, the most of any program investigated. Every stress-dependency model included in the other programs is also included in MODCOMP.

LTPP used MODCOMP for backcalculating FWD data and all nine stress-dependency models were utilized. It was found that none of the models consistently converged on an acceptable solution for all of the pavements in the study, and that the root-mean-squared errors were more often unacceptably high for nonlinear models than for the linear model.[4] These results indicate that non-linear analysis requires detailed knowledge and experience to apply correctly, and that rigid guidelines for their application are inappropriate.

4.5.1.1 MODCOMP

MODCOMP allows the user to choose one of nine different stress-dependency models for backcalculated moduli. Depending on which model is chosen, the user must also enter the unit-weight of each pavement layer, the lateral earth pressure ratio, or the percentage passing the #200 sieve. Data for at least four different load levels at each test point is required.

4.5.1.2 MODTAG

MODTAG uses MODCOMP as its backcalculation engine, but currently limits the user to one stress-dependency model. The model used is the Uzan Model of the form shown in Equation 2.

$$E = k_1 \theta^{k_2} \tau_{oct}^{k_3}$$

Figure 2. Equation 2.

where:	E	= elastic modulus, psi
	θ	= bulk stress, psi
	τ_{oct}	= octahedral shear stress, psi
	k_1, k_2, k_3	= regression constants

The developers of MODTAG plan on including all of the non-linear models currently in MODCOMP in the future.

4.5.1.3 ELMOD

ELMOD accounts for non-linearity in the subgrade material based on the shape of the outer portion of the deflection basin. This is not a formal stress-dependency model, and it does not yield coefficients that can be entered into any stress-dependency model. Rather, it is an empirical method that is used to estimate the subgrade modulus directly underneath the load plate at the test load. Typical linear backcalculation yields the subgrade modulus at some distance from the load plate, at a point where the stress is generally lower than that directly underneath the load plate. ELMOD uses this method by default, but it can be disabled. An advantage of this method is that it does not require drops at more than one drop height.

Alternatively, through the use of the FEM/MET/LET add-in module (which must be purchased separately) ELMOD can use a formal stress-dependency model. The model used is the principal stress model of the form shown in Equation 3.

$$E = k_1 \sigma_1^{k_2}$$

Figure 3. Equation 3.

where: E = elastic modulus, psi
σ_1 = major principal stress, psi
k_1,k_2 = regression constants

ELMOD does not include the overburden stress in the major principal stress calculation, so unit weight of the pavement material is not required. As the overburden stress in the subgrade is typically larger than the load-related stress, the neglection of overburden stress magnifies the perceived non-linearity of the subgrade response.

4.5.1.4 Evercalc

Evercalc uses two stress-dependency models, one for coarse-grained materials and one for fine-grained materials. For coarse-grained materials a bulk stress model is used, as shown in Equation 4.

$$M_r = k_1 \theta^{k_2}$$

Figure 4. Equation 4.

where: M_r = resilient modulus, psi
θ = bulk stress (the sum of the principal stresses), psi
k_1,k_2 = regression parameters.

EVERCALC uses a deviator stress model for fine-grained materials, as shown in Equation 5.

$$M_r = k_1 \sigma_d^{k_2}$$

Figure 5. Equation 5.

where: M_r = resilient modulus, psi
σ_d = deviator stress, psi
k_1,k_2 = regression parameters.

As with ELMOD, overburden stress is not included and material unit weights are not required inputs. At least two different load levels are required to perform non-linear analysis with EVERCALC.

4.5.2 Depth to Bedrock

Six of the nine backcalculation programs investigated will estimate the depth to bedrock. ELMOD, Evercalc, MODULUS and MODTAG use a technique originally developed by Per Ullidtz of Dynatest. This technique first plots measured deflection versus the inverse of deflection sensor offset (1/r). This plot typically has a linear section followed by a non-linear concave-down section at high values of 1/r. Sometimes there is also a non-linear concave-up section to the plot at low values of 1/r. The linear portion of the plot is extrapolated down to the X-axis, and the inverse of this intercept is taken as an estimate of the depth to bedrock. MODULUS and Evercalc further refine this estimate using empirical regression equations developed by Rhode and Scullion.[5]

DAPS and MICHBACK will also estimate the depth to bedrock, however the methodology is not explained in the accompanying documentation.

4.5.3 Asphalt Concrete Temperature Correction

Three of the nine backcalculation programs investigated will correct the modulus of asphalt concrete layers for temperature effects.

4.5.3.1 ELMOD

ELMOD includes a "Temperature Table", which includes ratios of E_t / E_{ref} for each whole degree Celsius between -45 at 59. This table is populated by default with a reference temperature of 25º C, but it is user-modifiable.

4.5.3.2 Evercalc

Evercalc performs temperature correction using a regression equation developed by Washington DOT, as show in Equation 5.

$$E_{ref} = E_t \times 100.000147362\left(T^2 - T_{ref}^2\right)$$

Figure 6. Equation 6.

where:
- E_{ref} = elastic modulus at reference temperature, psi
- E_t = elastic modulus at test temperature, psi
- T_{ref} = reference temperature, degrees Fahrenheit
- T = test temperature, degrees Fahrenheit

This equation is not modifiable, however the reference temperature is. By default, the reference temperature is set to 77º F.

4.5.3.3 MODTAG

MODTAG performs temperature correction using Equation 6.

$$E_{ref} = E_{calc} \times 10^{k(T_{ref} - T_{calc})}$$

Figure 7. Equation 7.

where: E_{ref} = Modulus at the reference temperature
E_{calc} = Backcalculated modulus
k = -0.0195 for testing in the wheel path, -0.021 for mid-lane
T_{ref} = Reference temperature, ºC
T_{calc} = Mid-depth temperature at the time of testing, ºC

This equation is not modifiable. The reference temperature is set by the user, and there is no default value.

4.5.4 Asphalt Concrete Mid-depth Temperature Prediction

The asphalt concrete modulus correction methodologies described above require the mid-depth pavement temperature at the time of testing as an input. Measuring the mid-depth pavement temperature is tedious, and typically takes longer then the actual FWD test. For this reason several equations have been developed to estimate the mid-depth pavement temperature based on more readily available data such as the pavement surface temperature at the time of testing, and the previous day's average air temperature. ELMOD, Evercalc and MODTAG all include such predictive equations.

4.5.4.1 ELMOD and MODTAG

ELMOD and MODTAG both use the BELLS3 predictive equation. This equation requires the pavement surface temperature at the time of testing and the previous day's average air temperature as inputs.

4.5.4.2 Evercalc

Evercalc uses the Southgate predictive equation. This equation requires the pavement surface temperature at the time of testing and the average air temperature over the previous five days as inputs.

4.5.5 Raw Data QC Tools

Raw data quality control (QC) tools assist the user in evaluating the quality of the raw data. They may also enable the user to eliminate erroneous or suspicious data points. Three of the nine backcalculation programs include raw data QC tools.

4.5.5.1 MICHBACK

MICHBACK provides some basic raw data QC tools. It will provide an automatic warning when the load data varies from the target load by more then 10%. It also plots the raw deflection data and allows the user to eliminate entire test points or individual sensor data at a test point which appear anomalous.

4.5.5.2 ELMOD

ELMOD also provides some raw data QC tools. It provides the ability to plot the raw deflections and composite modulus. Anomalous test points can be removed, but individual sensor data can not be removed. During backcalculation, the user can choose to review the composite modulus plot for each deflection basin and remove individual sensor data from further analysis.

4.5.5.3 MODTAG

MODTAG provides a wide array of raw data QC tools. It includes a series of checks that it calls "Pre-analysis". These checks include: non-decreasing deflections, zeros in data, overflow, non-linearity, and erroneous sensor position.

- "Non-decreasing deflections" is a situation where the reported deflections do not decrease with increasing distance from the load plate.
- "Zeros in Data" is triggered when one or more deflection value is reported as zero.
- "Overflow" triggers when a deflection sensor reports more than 2032 microns (80 mils) of deflection, which is the maximum deflection that most Dynatest FWDs can measure.
- "Linearity test failed" triggers when a linear regression line drawn through the maximum deflection vs. load level data at a test point does not intercept the y axis close to zero. This is not necessarily an indication of problems with the raw data, however it does indicate that non-linear backcalculation of the data is warranted.
- "SLIC warning" triggers when the reported deflection data does not agree with the reported deflection sensor position.

Deflection basins that that fail these checks may be deleted.

MODTAG also allows the user to review the composite modulus plots for each deflection basin, and either delete the entire basin or remove specific sensors from the analysis.

4.5.6 Load Transfer Efficiency

Among the nine backcalculation programs reviewed, only ELMOD and MODTAG will compute load transfer efficiency (LTE). Both programs compute LTE according to Equation 7 for joint approach testing, and Equation 8 for joint leave testing.

$$LTE_a = \frac{d_{12}}{d_0} \times 100$$

Figure 8. Equation 8.

$$LTE_l = \frac{d_{-12}}{d_0} \times 100$$

Figure 9. Equation 9.

where: LTE_a = load transfer efficiency from joint approach testing, %
LTE_l = load transfer efficiency from joint leave testing, %
d_0 = deflection at center of load plate, mils
d_{12} = deflection at 12 inches in front of center of load plate, mils
d_{-12} = deflection at 12 inches behind center of load plate, mils

The major difference between these two programs is how joints are identified in the FWD data file.

4.5.6.1 ELMOD

ELMOD identifies joints based on specific codes imbedded in the Dynatest F25 and FWDWin file formats. During testing the FWD operator is presented with a graphical representation of a PCC slab and can select his position on the slab. These positions are saved in the data file as codes. ELMOD reads these codes out of the data file, and automatically computes LTE for codes that indicate load transfer testing. These codes can be manually edited in ELMOD prior to analysis. In addition to joint approach and joint leave testing, ELMOD will also compute LTE across transverse joints for appropriate test locations.

4.5.6.2 MODTAG

MODTAG requires that load transfer tests be labeled “JA” (i.e. joint approach) or “JL” (i.e. joint leave). It can automatically determine the test type from the FWD data file if it is properly commented in the field, or the user can manually input the test type in MODTAG. MODTAG does not have the capability of calculating load transfer across transverse joints or cracks.

4.5.7 Void Detection

Among the nine backcalculation programs reviewed, only ELMOD and MODTAG will perform void detection. The methodology used in these programs is similar. Both programs a linear regression line through the center deflection vs. load data collected at a given location. The y-intercept of this line is taken as an indication of the presence of a void at that location.

ELMOD will perform void detection at all test locations, regardless of the position of the FWD or number of drop heights.

MODTAG will perform void detection only at test locations that are labeled "C" (i.e. corner testing). Void detection will only be performed if data at three or more load levels is collected.

4.5.8 Segmentation Tools

Segmentation tools assist a user in breaking up FWD data into logical segments for further analysis. Segmentation may be performed in order to allow for different structural properties such as layer thickness or as a way of presenting analysis results. Three of the nine backcalculation programs investigated allow for segmentation of FWD data.

4.5.8.1 ELMOD

ELMOD allows an analysis project to consist of one or more FWD data file. Prior to backcalculation, plots of raw deflection data or composite modulus vs. station may be reviewed. Based on these plots the user may choose to break the project up into two or more segments with different structural properties. No automated assistance is provided to the user in making that determination. Subsequent to backcalculation the user may further segment the project for the purpose of reporting statistics.

4.5.8.2 MODULUS

MODULUS allows an analysis project to consist of only one FWD data file. Prior to backcalculation raw deflection data vs. station can be plotted for deflection sensors 1, 2 and 7. MODULUS does not directly allow segmentation based on structural properties prior to backcalculation; however it does allow test locations to be excluded from analysis. So, MODULUS could be run twice on the same FWD data file with two different sets of layer thicknesses, and then all but the appropriate test locations could be excluded from analysis.

After backcalculation, MODULUS can automatically segment the project based on the analysis results. The methodology used in automatic segmentation is not explained in the documentation which accompanies the software. Alternatively, the user may manually create segments. The mean and standard deviation of the analysis results are reported for each segment.

4.5.8.3 MODTAG

MODTAG allows an analysis project to consist of one or more FWD data file. Prior to analysis, several plots may be reviewed to assist the user in making segmentation determinations. The cumulative differences of deflections plot is provided expressly for segmentation purposes. Depth to stiff layer and composite modulus vs. station may also be used for segmentation. Based on these plots the user may choose to break the project up into two or more segments with different structural properties. No automated assistance is provided to the user in making that determination. There is no way to perform segmentation based on backcalculation results, except to re-segment the project and perform backcalculation again.

4.6 Recommendations

We recommend that the following programs be excluded from further consideration because of the listed drawbacks and lack of redeeming features.

- BAKFAA – Maximum of seven sensors
- Bousdef – No FWD file import capability
- DAPS – Cost
- MICHBACK – DOS program, limited to KUAB files
- MODCOMP – DOS program, no FWD file import capability

The remaining four programs are Evercalc, ELMOD, MODULUS and MODTAG.

4.6.1.1 Evercalc

Evercalc was developed by Washington DOT for their own usage, although it is freely available to others. The last major update was in 2001.

Pros

- Depth to bedrock estimation
- Temperature correction of AC moduli
- Estimation of mid-depth AC temperatures

Cons

- File import is limited to Dynatest F20 and F25 formats
- Lack of segmentation capability
- Lack of data quality control checks

4.6.1.2 ELMOD

ELMOD was developed by Dynatest as a revenue-generating product. The latest version was issued in December of 2005.

Pros

- User interface – the most polished of the programs reviewed
- Customer support
- Full range of additional features

Cons

- Cost ($5000 for a site license)
- Data import is limited to Dynatest formats.

4.6.1.3 MODULUS

Modulus was developed by the Texas Transportation Institute (TTI) under contract to Texas DOT. The last major update was in February of 2003.

Pros

- Simplicity of operation – the most straight-forward and easy to understand of the programs reviewed
- Depth to bedrock estimation

Cons

- Relative lack of features
- Data import is limited to Dynatest F20 format

4.6.1.4 MODTAG

MODTAG was developed by Virginia DOT and Cornell University. It is currently in use by Maryland DOT and Virginia DOT, although they do not use its backcalculation features. Development is ongoing, and the latest public release was in October 2005.

Pros

- Ability to import data in non-manufacturer specific PDDX format
- Full range of features
- Most comprehensive data QC tools among programs reviewed
- Ability to perform data analysis using the methodology included in the AASHTO 1993 Pavement Design Guide

Cons

- Program is currently in a usable, but not finished state
- Users may find the number of options overwhelming

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