Backcalculation of Layer Moduli of LTPP General Pavement Study (GPS) Sites

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LTPP

FOREWORD

A key challenge faced by engineers using the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO Guide) is the selection of appropriate design values for the subgrade soil and for the pavement materials. Until now, the information available to help engineers choose appropriate values has been incomplete. This report documents one aspect of the analysis of the Long-Term Pavement Performance (LTPP) data conducted to develop more complete information on the backcalculation of pavement layer moduli from the LTPP deflection data. The specific guidelines and procedures developed through this analysis are presented in a series of three design pamphlets addressing: (1) the selection of appropriate design values to characterize the subgrade soil, (2) interpretation of pavement deflection data, and (3) characterization of the pavement materials. These pamphlets are *Design Pamphlet for the Determination of Design Subgrade Moduli in Support of the 1993 AASHTO Guide for the Design of Pavement Structures* (FHWA-RD-97-083), *Design Pamphlet for the Backcalculation of Pavement Layer Moduli in Support of the 1993 AASHTO Guide for the Design of Pavement Structures* (FHWA-RD-97-076), and *Design Pamphlet for the Determination of Layered Elastic Moduli for Flexible Pavement Design in Support of the 1993 AASHTO Guide for the Design of Pavement Structures* (FHWA-RD-97-077).

Application of the procedures and guidelines developed through this analysis will facilitate and improve application of the AASHTO Guide flexible pavement design procedures. Their use will provide: (1) improved designs, (2) more realistic estimates of pavement performance, and (3) more consistent use of the AASHTO design parameters. Furthermore, although the procedures are specifically developed for use with the 1993 AASHTO Guide, their use will give agencies a "leg up" on implementation of the design procedures being developed for inclusion in the 2002 AASHTO Guide for Design of New and Rehabilitated Pavement Structures.

This report is a valuable resource for those who use—or are considering using—pavement deflection data to evaluate the structural properties of pavement materials. It will also be of interest to those who wish to fully understand the technical basis for the referenced design pamphlets.

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NOTICE

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16. Abstract

This report details the activities and process by which the re-backcalculation of LTPP General Pavement Study (GPS) test sections were completed. These activities were completed under FHWA Contract DTFH61-95-C-00029 as part of Task B - "Backcalculate Resilient Modulus". This report details how the backcalculation program was selected, lists the GPS sections re-backcalculated, presents the results of the revised backcalculations and discusses the problem sections that were encountered. The report is also accompanied by a data base that contains results from the original SHRP backcalculation process and those sections that were re-backcalculated.

17. Key Words
MICHBACK, MODCOMP, MODULUS, and WESDEF, backcalculation, modulus, surface deflection, stress sensitivity

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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 milimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	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)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°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	35.71	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 ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°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 September 1993)

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BACKCALCULATION OF LAYER MODULI OF LTPP GENERAL PAVEMENT STUDY (GPS) SITES

1.0 INTRODUCTION

As part of the Strategic Highway Research Program's - Long Term Pavement Performance (SHRP-LTPP) program, every General Pavement Study (GPS) test section has been tested (and will continue to be for the life of LTPP) with a Falling Weight Deflectometer (FWD) to determine its load response characteristics. One of the more common analysis methods of the deflection data is to backcalculate material response properties for each structural layer within the pavement structure. The specific layer property determined from the peak deflection basin is Young's modulus, determined by an elastic layer based backcalculation program. The program selected by the SHRP-LTPP researchers was a modified version of MODULUS 4.0 as developed by the Texas Transportation Institute.[1] The LTPP researchers conducted a thorough comparison of industry leading backcalculation programs of the time and selected this program based on that comparison.[2]

The MODULUS program was modified by SHRP to run in a "batch mode" which allows automated data input from files generated by the FWD and the Information Management System (IMS) developed by LTPP for the GPS test sections.[3] To accomplish this batch mode processing, several data manipulation steps had to be accomplished prior to the data being input into the program.[4] This step, however important to the data processing, may have caused some backcalculation errors because several generalizations had to be made when combining layers. The MODULUS program is limited to backcalculating a maximum of four pavement layers. As a result, several substantial pavement layers (of similar materials) had to be combined so as not to exceed four layers. This was specifically important and limiting for structures with stabilized base materials, substantially different subgrade soils, and/or when subsurface water was encountered close to the surface.

Other rules used by LTPP may also have caused some backcalculation errors. These rules included:

1. letting the program determine the depth to bedrock (or rigid layer) based on measured deflections,

2. including an arbitrary 36 in (0.9 m) subgrade layer when analyzing a conventional three-layer asphalt concrete (AC) pavement and the total subgrade thickness was greater than 72 in (1.8 m) as determined by the program, and

3. joining the AC pavement layers into a single layer regardless of thickness or material type (or code).

Knowing the shortcomings of the previous procedure used by LTPP, it was the intention of the current analysis to try and overcome these shortcomings by individually reviewing certain results and re-backcalculating sections that warranted further study. The primary goals for this study were to select an appropriate backcalculation program that would provide more flexibility in the number of unknown layers that could be backcalculated, choose sections to re-backcalculate, and improve on the previous results. These improvements were to be combined with the previous results in a comprehensive data base that could be used for analysis purposes using LTPP data.

2.0 BACKCALCULATION PROGRAM SELECTION

In determining which backcalculation program to use in the re-backcalculation process, several existing programs were evaluated by the research team. These programs included:

1. MODULUS 4.2[4]
2. MODCOMP 3 Version 3.6[5]
3. WESDEF[6]
4. WESNET[7]
5. MICHBACK 1.0[8]
6. FWD-DYN[9]

These programs were evaluated on the basis of technical merit, useability or functionality and data processing compatibility. Similar evaluation studies have been conducted by other agencies to select a backcalculation program for pavement evaluation (i.e., the study completed by Kim, Ref. 11). The current evaluation was based upon backcalculation of 18 sections selected from the LTPP Southern Region. These sections included 12 sections that had poor results from the original LTPP backcalculation process and 6 with favorable results. Table 1 lists the GPS sections and experiment type that were used in the evaluation and selection process. These sections were selected based upon the following:

1) LTPP backcalculation quality checks

2) Modulus convexity check

3) Pavement structural cross-section

4) Material types included in the pavement cross-section

Table 1. GPS sections used for program evaluation.

GPS Section I.D.	Station	GPS Experiment Type	SHRP Backcalculation Results[a]
011019	5+60	GPS-1	Poor
015008	5+60	GPS-5	Good
053058	0-50	GPS-2	Good
053071	0-50 5+60	GPS-2 GPS-2	Poor Poor
123995	5+62	GPS-1	Poor
124100	5+60	GPS-2	Poor
137028	0-50	GPS-7A	Poor
351112	0-50	GPS-1	Poor
373011	5+60	GPS-3	Poor
401017	5+63	GPS-2	Good
404086	0-50 5+60	GPS-6B GPS-6B	Poor Poor
463052	0-50 5+60	GPS-3 GPS-3	Poor Poor
471023	0-50	GPS-2	Poor
473075	5+60	GPS-1	Good
481065	5+63	GPS-1	Good
481076	5+60	GPS-1	Good
481113	0-50 5+60	GPS-6B GPS-6B	Poor Poor
493010	0-50 5+60	GPS-3 GPS-3	Poor Poor

Note a: Results based upon SHRP LTPP quality and convexity test checks; Good means that the results of the backcalculation process passed both the quality and modulus anvexity checks with convergence errors less than 1.0 percent per sensor, while poor means that the solution did not pass one or both of the quality and convexity tests with convergence errors greater than 2.5 percent per error.

Table 2 lists the results for each of the backcalculation programs from the 18 sections that were initially reviewed. As can be seen from the table, MODULUS 4.2, MODCOMP 3.6, MICHBACK 1.0 and WESDEF all supplied error terms that were similar at the 9,000 lb. (40 kN) load level, with a few notable exceptions. The Dynamic Backcalculation Program (FWD. DYN) provided consistently low errors, but it was excluded from further evaluation because it was returning negative thicknesses as part of its moduli calculation routine. Also, the WESNET program is restricted to a three-layer conventional asphalt over granular base over subgrade cross-section, so it was also excluded from this evaluation. Figures 1 through 3 show a graphical comparison of the calculated layer moduli from MODULUS 4.0 results for the bound, unbound and subgrade materials, respectively, to those layer moduli determined from the other programs.

When evaluating which program should be used for re-backcalculation, it was felt that the MODULUS 4.2 Program should not be excluded from the evaluation, even though it was technically the same as the original LTPP batch backcalculation program (with only some minor changes in the convexity test routine). It was anticipated that the MODULUS 4.2 program may have the same difficulty with "problem" sections that the batch program did, but it was felt that this conclusion should be verified. Table 2 and figures 1 through 3 show that the results between MODULUS 4.0 and 4.2 are similar (with a few exceptions where the layer configuration was changed to match the layer configuration used with the other programs). Hence, a decision on which program to use for re-backcalculation was made between WESDEF, MICHBACK 1.0 and MODCOMP 3.6.

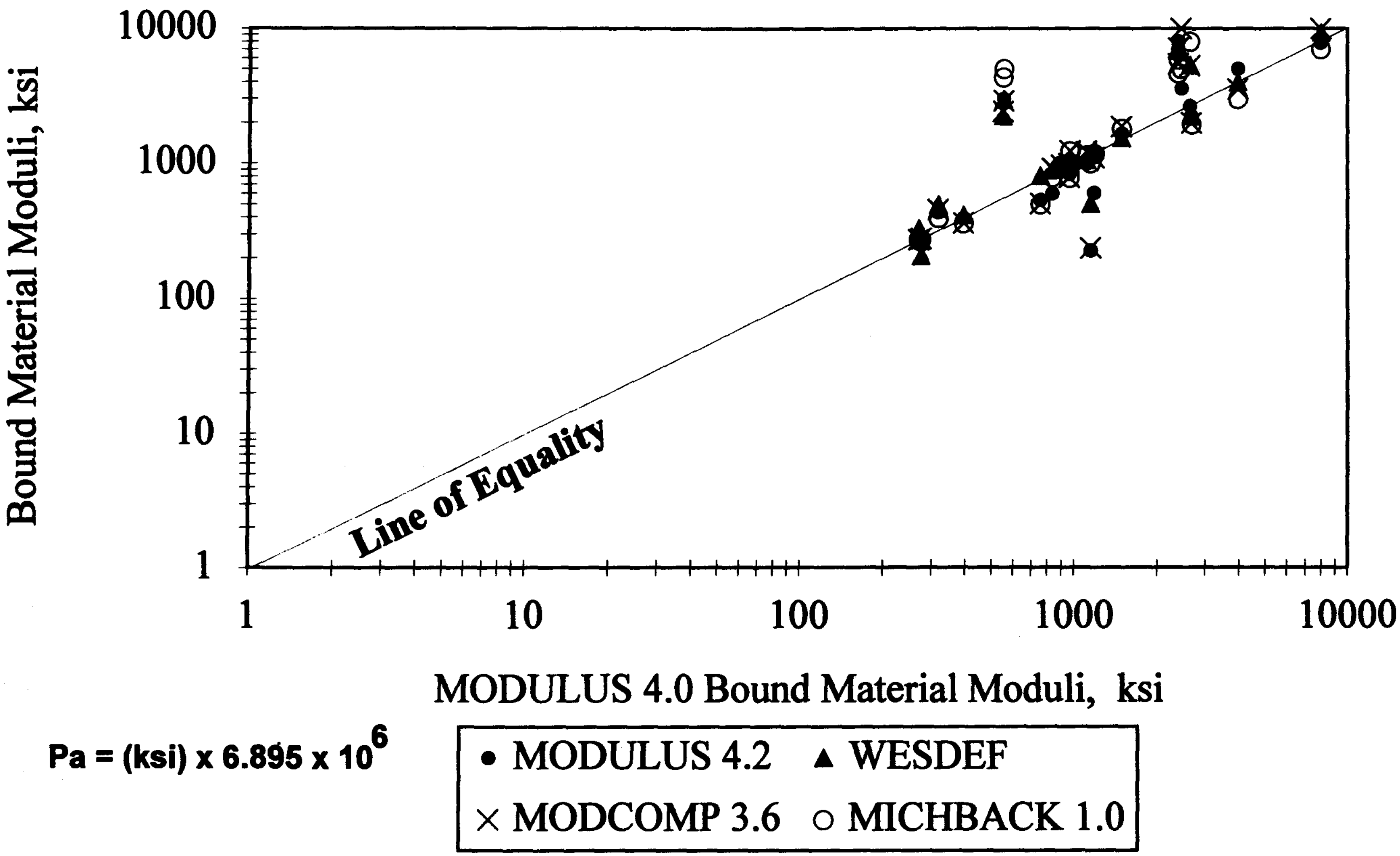
Table 2 shows that MICHBACK 1.0 provided the lowest overall error term when comparing to the other programs; however, MODCOMP 3.6 and MICHBACK 1.0 were found to provide subgrade moduli values that were consistently higher than the MODULUS program and possibly too high for the described material. Thus, these two programs were dropped from further analysis. Final program selection was based on the fact that the WESDEF program seemed to provide reasonable results for both the AC and portland cement concrete (PCC) pavement sections and has also been used extensively by the authors on several datasets.

The WESDEF Program utilizes an iterative procedure to minimize the error between a calculated deflection bowl (based on elastic layer theory) and the observed deflection bowl. WESDEF uses the WESLEA layered elastic program to generate the deflection basins and has been used successfully by the U.S. Army Corps of Engineers - Waterway Experiment Station and by others (including the research team) over the years to backcalculate pavement layer moduli. Therefore, the program met the subjective technical criteria put forth. The research team (as mentioned) is also very familiar with the WESDEF program and has used it successfully on several projects. Based on this past work, the team found the program to be very user friendly and functional, as well as allows the user to input FWD data in various ways.

Table 2. Results of backcalculation program comparison and evaluation.

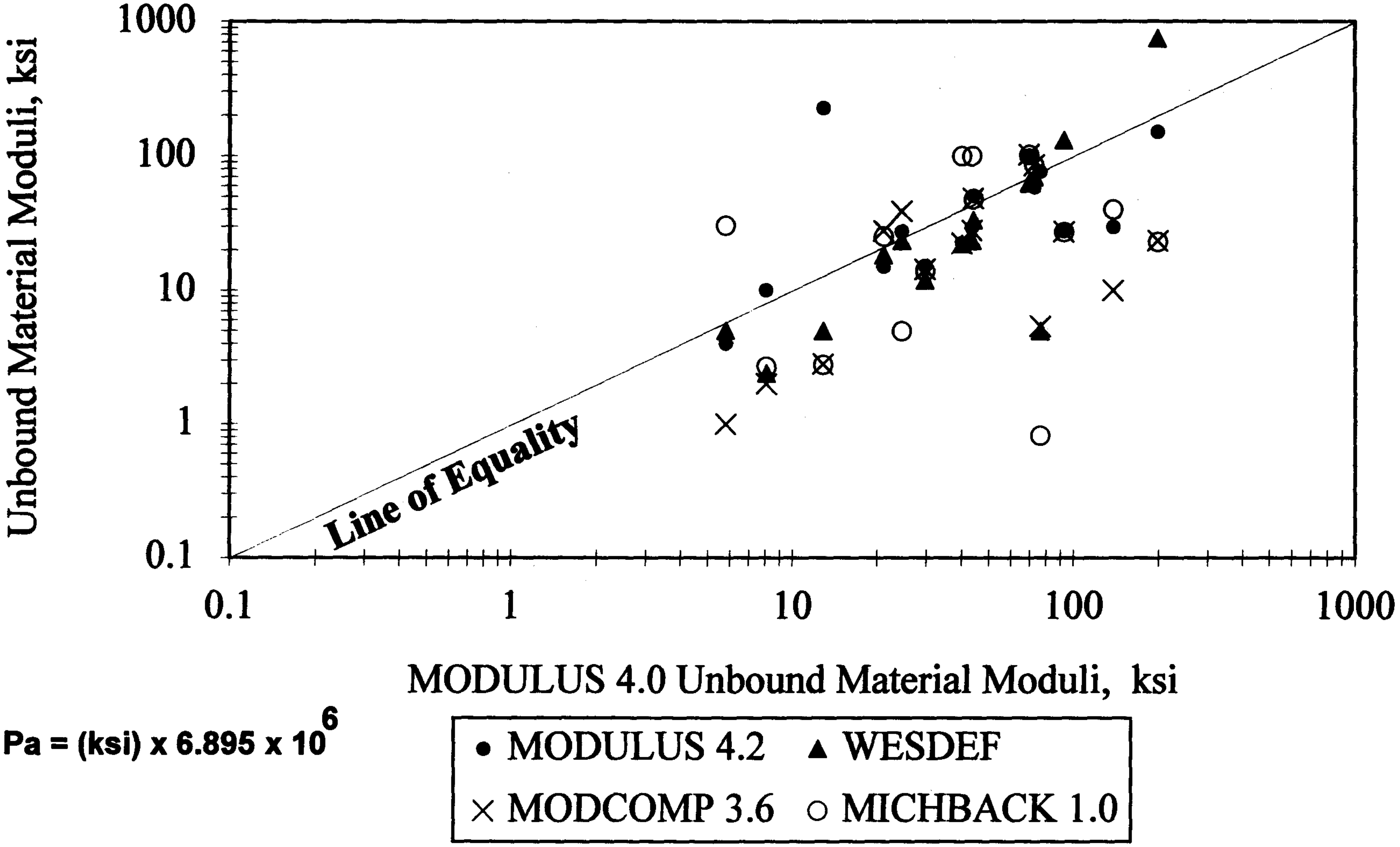
SHRP ID	STATION	% ERROR/SENSOR					
		MODULUS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11019	5+60	0.60	0.70	1.05	0.35	0.50	0.030
15008	5+60	0.30	0.52	0.61	0.79	0.62	
53058	0-50	0.30	1.04	0.60	0.24	0.30	0.010
53071	0-50	0.70	0.93	1.21	0.50	0.92	
53071	5+60	3.10	****	1.26	0.56	0.85	
123995	5+62	0.50	1.18	2.30	0.32	0.30	0.050
124100	5+60	0.80	0.53	0.49	1.09	0.40	0.002
137028	0-50	0.90	0.75	4.95	0.54	1.45	
351112	0-50	0.30	0.26	1.82	1.02	0.20	0.030
373011	5+60	0.90	2.80	3.13	0.43	0.93	
401017	5+63	2.00	1.76	13.35	9.81	5.80	0.080
404086	0-50	0.90	0.34	0.20	0.12	0.13	
404086	5+60	11.70	10.11	21.24	0.16	37.27	
463052	0-50	11.00	0.63	0.11	0.08	0.40	
463052	5+60	7.70	1.55	1.79	0.10	1.53	
471023	0-50	6.80	0.86	3.27	2.09	3.60	0.007
473075	5+60	0.60	6.10	0.53	0.33	0.50	0.010
481065	5+63	1.90	5.41	2.97	2.30	1.60	0.010
481076	5+60	0.60	2.08	0.96	0.59	1.40	0.040
481113	0-50	5.80	1.10	1.67	0.52	1.72	
481113	5+60	5.40	1.17	1.65	0.46	1.85	
493010	0-50	34.50	34.90	****	0.49	26.30	
493010	5+60	3.70	1.53	20.35	0.28	****	
	AVG	4.39	6.89	12.49	1.01	4.03	0.03
	STD	7.25	17.53	40.78	1.96	9.02	0.02
	MIN	0.30	0.26	0.11	0.08	0.13	0.00
	MAX	34.50	82.12	201.78	9.81	37.27	0.08

Note****denotes that program would not provide solution



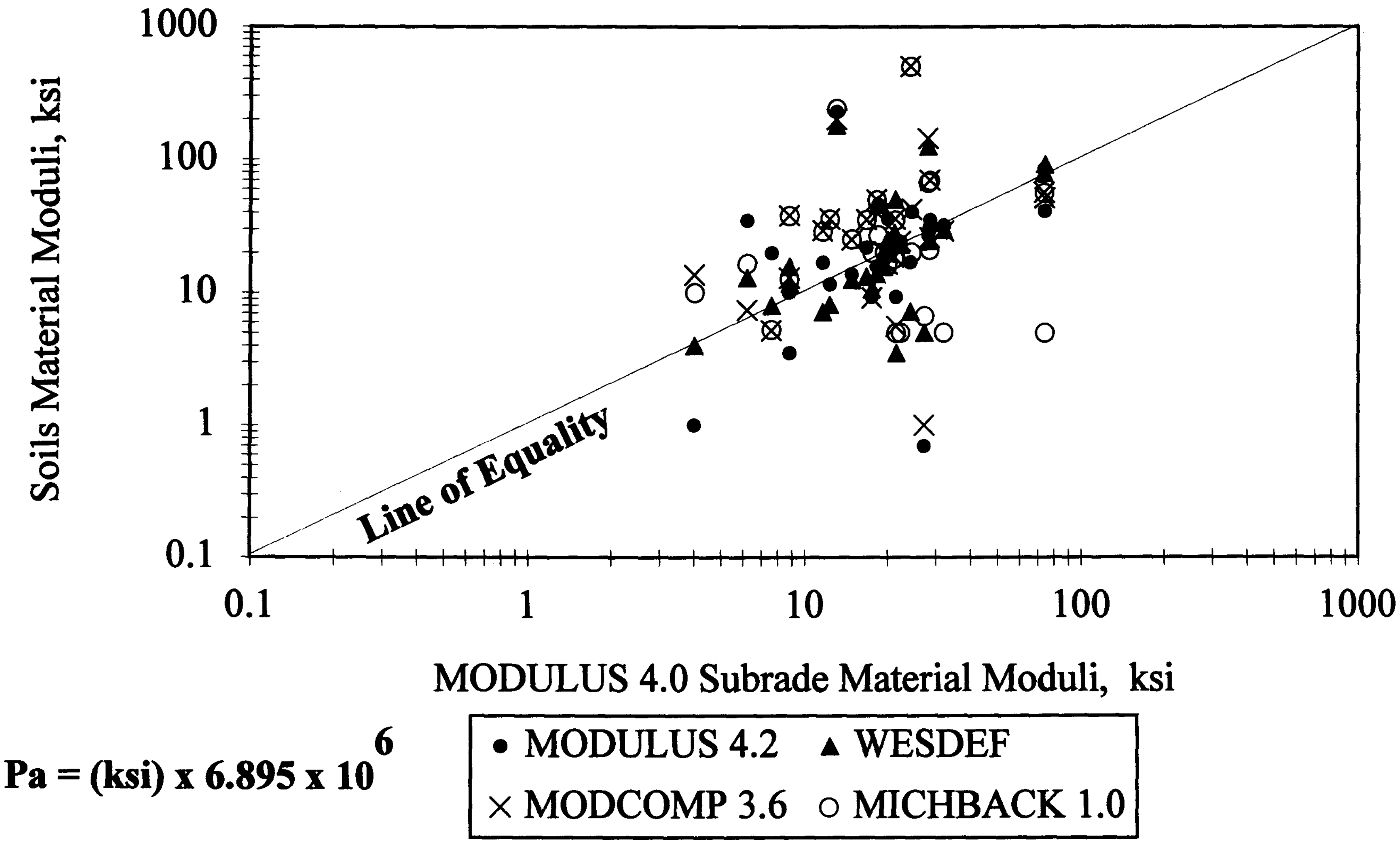
Pa = (ksi) x 6.895 x 10^6

Figure 1. Comparison of calculated layer moduli with different programs to the results from Modulus 4.0 for bound base and surface materials.



Pa = (ksi) x 6.895 x 10^6

Figure 2. Comparison of calculated layer moduli with different programs to the results from Modulus 4.0 for unbound base and subbase materials.



Pa = (ksi) x 6.895 x 10^6

Figure 3. Comparison of calculated layer moduli with different programs to the results from Modulus 4.0 for subgrade soils.

Three important observations were made during this evaluation. These observations are listed below:

1) Each of the backcalculation programs are based on static loads being applied to the pavement's surface and can be used to derive a set of layer moduli with a relatively low error term (observed deflection basin compared to the calculated deflection basin). Other agencies have also reported similar findings.

2) There is no unique solution for a particular deflection basin, and engineering judgement must be used in determining "reasonable" solutions or layer moduli. Other agencies have also reported this observation.

3) The layer moduli determined for a particular deflection basin can be significantly different between the programs used in this study. This observation has a significant impact on selecting a particular program to be used and prevents the random use of different programs to calculate/determine layer moduli for a specific deflection basin.

As a result of observation No. 3 and the fact that the WESDEF and MODULUS 4.0 Programs gave similar results, the WESDEF program was selected to complete the re-backcalculations on selected GPS sites.

It is realized that this type of analysis is very subjective and that any of the programs listed could have provided the best results (in terms of percent error or moduli values) for any given pavement section and deflection data set. However, for the sections initially reviewed, the WESDEF program seemed to have provided the best results and were similar to the initial LTPP results.

3.0 SELECTION CRITERIA FOR RE-BACKCALCULATION

Specific criteria needed to be set when determining which GPS section ends (i.e., bulk-sampling areas at Stations 0-50 or 5+60 on the 500-ft (152-m) GPS sections) to re-backcalculate. Review of the initial LTPP backcalculation quality check revealed that results were considered unreasonable by LTPP if the results had an average absolute arithmetic error in excess of 2 percent per sensor. This corresponds to a total sum of absolute error of 14 percent when all seven sensors are used in the backcalculation or 12 percent when six sensors are used, etc. Therefore, initial selection of GPS sites for re-backcalculation were based upon whether or not the percent error per sensor from the LTPP GPS backcalculation was greater than 2 percent.

Figure 4 is a histogram that shows the distribution of the percent error per sensor from the original LTPP backcalculation. As shown, slightly over 38 percent (450 basins) of the original backcalculation runs with the MODULUS 4.0 program exceeded the limit of 2.0 percent per sensor. These GPS deflection basins from either the approach and/or leave ends were identified as requiring additional study and review. As a general guideline, 10 percent or less of the backcalculated basins exceeding an error of 2 percent per sensor is considered good, 10 through 20 percent is considered adequate and greater than 30 percent or more is considered unacceptable.

The review process started with those deflection basins exhibiting the highest error terms. Table 3 summarizes the number or percentage of section ends by State that exceeded the allowable error initially set by LTPP, and figure 5 shows the distribution of those areas across the U.S. It is interesting to note that most of the areas with the larger percentage of section ends (greater than 50 percent) exceeding an error of 2 percent per sensor are western States. This observation was briefly investigated in an attempt to identify the reason(s) for this high percentage of section ends but came to no definite conclusions.

The second step of the re-backcalculation was to evaluate the reasonableness of the calculated moduli by material type. Section ends were selected for re-backcalculation if the predicted moduli hit a boundary, as set by the LTPP backcalculation program. This is also considered a guideline for checking the reasonableness of the results for the LTPP backcalculation procedure. Histograms showing the distribution of layer moduli by material type were originally prepared from the initial LTPP results. Examples of these histograms are given in figures 6 through 8 for PCC, granular base materials and subgrade soils, respectively.

Other section ends that did meet the above criteria but had predicted moduli values that seemed unreasonable for a specific material type were also reviewed and considered for re-backcalculation. As a result of this evaluation, over 450 section ends were considered for re-backcalculation. However, as will be described in the following sections, due to "problem" deflection basins, approximately 250 section ends were actually rebackcalculated (see table 4).

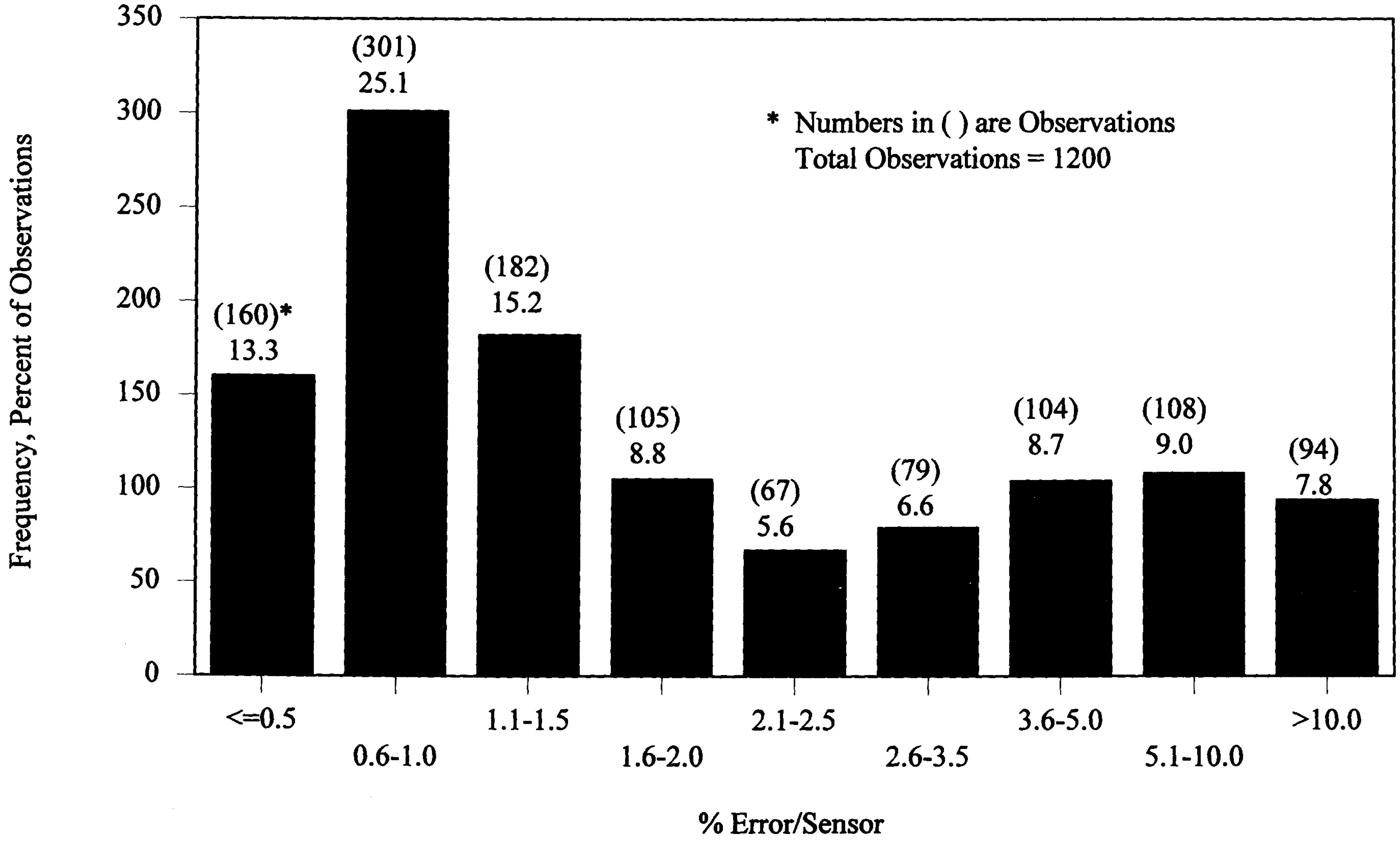


Figure 4. Histogram of the distribution of the percent error per sensor from the original LTPP backcalculation results.

Table 3. Summary of percentages of section ends exceeding the allowable error per sensor by area or State.

Code	State	Number of Section Ends Exceeding Allowable Error Term, %	
01	Alabama	8.7	2 of 23
02	Alaska	28.6	2 of 7
04*	Arizona	87.0	40 or 46
05	Arkansas	19.2	5 of 26
06*	California	48.4	15 of 31
08*	Colorado	94.7	18 of 19
09	Connecticut	12.5	1 of 8
10	Delaware	0.0	0 of 4
11	District of Columbia	50.0	1 of 2
12	Florida	24.1	14 of 58
13	Georgia	12.5	5 of 40
15*	Hawaii	100.0	2 of 2
16*	Idaho	100.0	19 of 19
17	Illinois	12.5	4 of 32
18	Indiana	33.3	7 of 21
19	Iowa	33.3	6 of 18
20	Kansas	27.6	8 of 29
21	Kentucky	28.6	4 of 14
22	Louisiana	0.0	0 of 4
23	Maine	6.7	1 of 15
24	Maryland	0.0	0 of 2
25	Massachusetts	0.0	0 of 4
26	Michigan	36.4	8 of 22
27	Minnesota	9.1	4 of 44

Table 3. Summary of percentage of section ends exceeding the allowable error per sensor by area or State (continued).

Code	State	Number of Section Ends Exceeding Allowable Error Term, %	
28	Mississippi	13.9	5 of 36
29	Missouri	30.0	9 of 30
30*	Montana	100.0	14 of 14
31*	Nebraska	55.6	5 of 9
32*	Nevada	75.0	9 of 12
33	New Hampshire	0.0	0 of 2
34	New Jersey	0.0	0 of 14
35	New Mexico	15.0	3 of 20
36	New York	12.5	1 of 8
37	North Carolina	22.5	9 of 40
38	North Dakota	50.0	4 of 8
39	Ohio	18.2	2 of 11
40	Oklahoma	33.3	12 of 36
41	Oregon	35.7	5 of 14
42	Pennsylvania	8.7	2 of 23
44	Rhode Island	0.0	0 of 0
45	South Carolina	27.8	5 of 18
46	South Dakota	18.2	4 of 22
47	Tennessee	17.9	5 of 28
48	Texas	31.8	47 of 148
49*	Utah	100.0	19 of 19
50	Vermont	50.0	2 of 4
51	Virginia	22.7	5 of 22
53*	Washington	72.7	16 of 22

Table 3. Summary of percentage of section ends exceeding the allowable error per sensor by area or State (continued).

Code	State	Number of Section Ends Exceeding Allowable Error Term, %	
54	West Virginia	44.4	4 of 9
55	Wisconsin	8.3	2 of 24
56*	Wyoming	72.2	13 of 18
72*	Puerto Rico	100.0	4 of 4
81	Alberta	0.0	0 of 4
82	British Columbia	0.0	0 of 6
83	Manitoba	16.7	2 of 12
87	Ontario	0.0	0 of 6
90	Saskatchewan	20.0	1 of 5
TOTALS		**33.0**	**375 of 1138**

*Denotes areas where a significant percentage of section ends exceeded the allowable error per sensor.

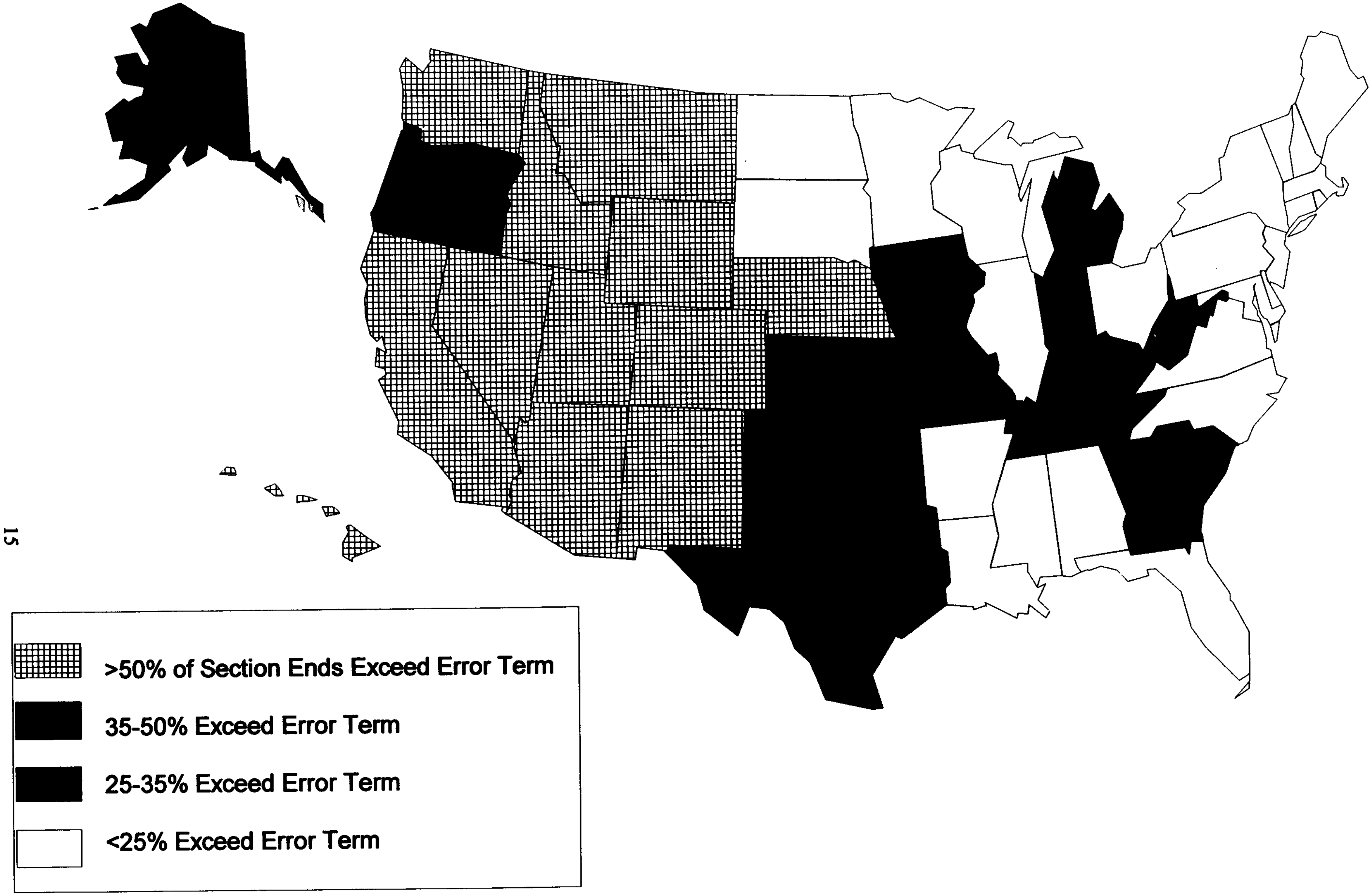
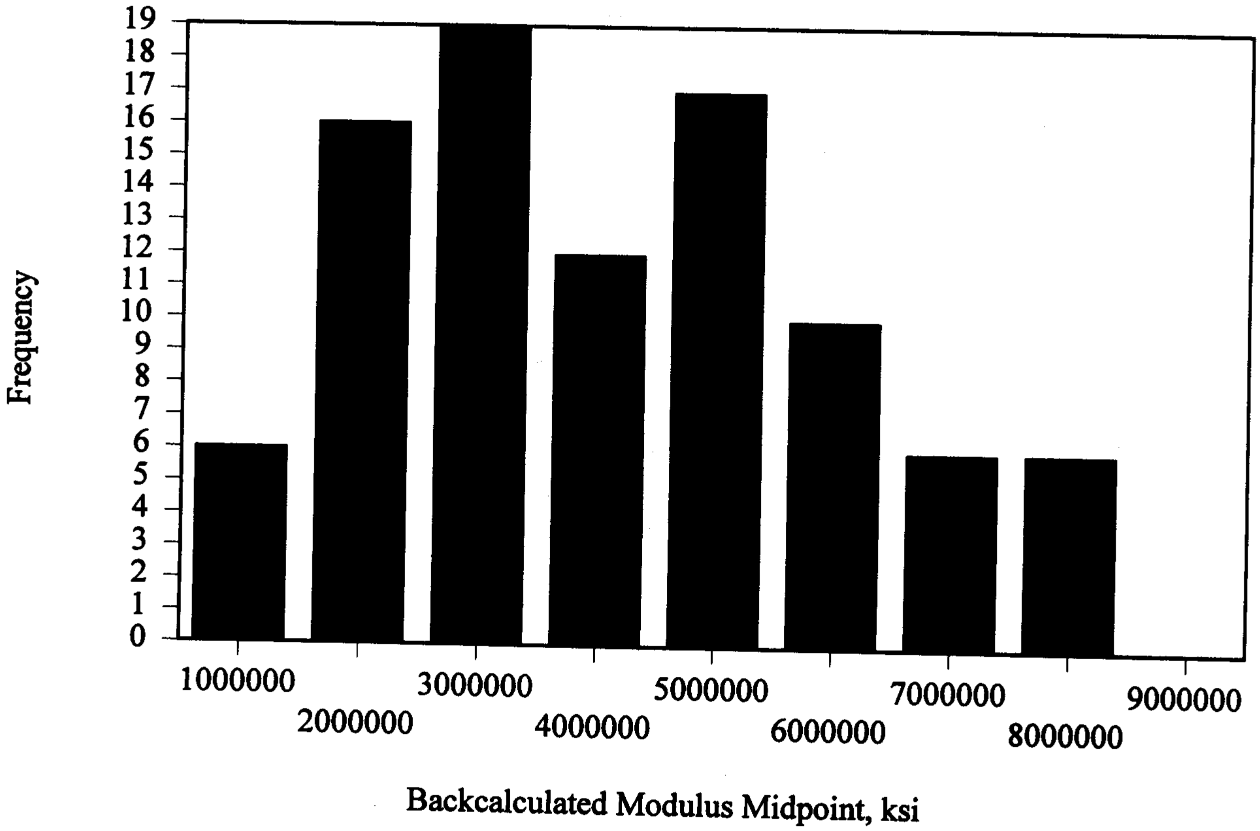
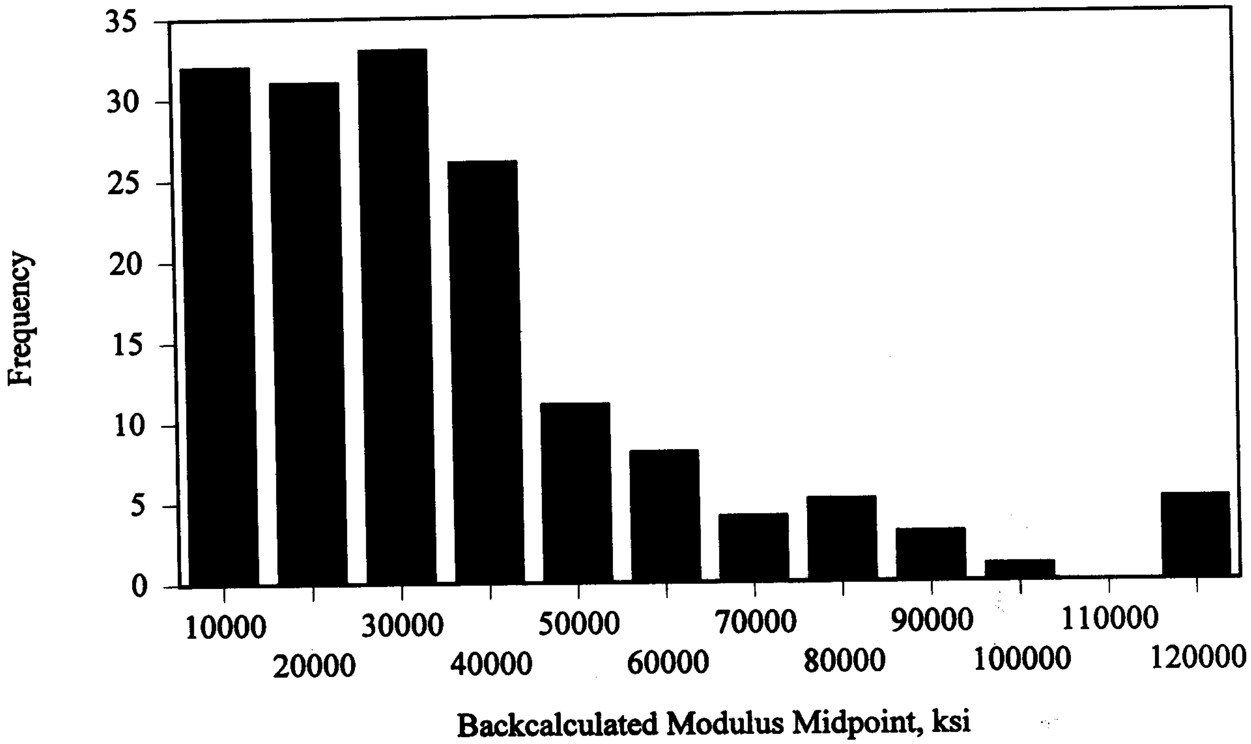


Figure 5. Identification of areas where a significant number of section ends failed to meet the allowable error per sensor.



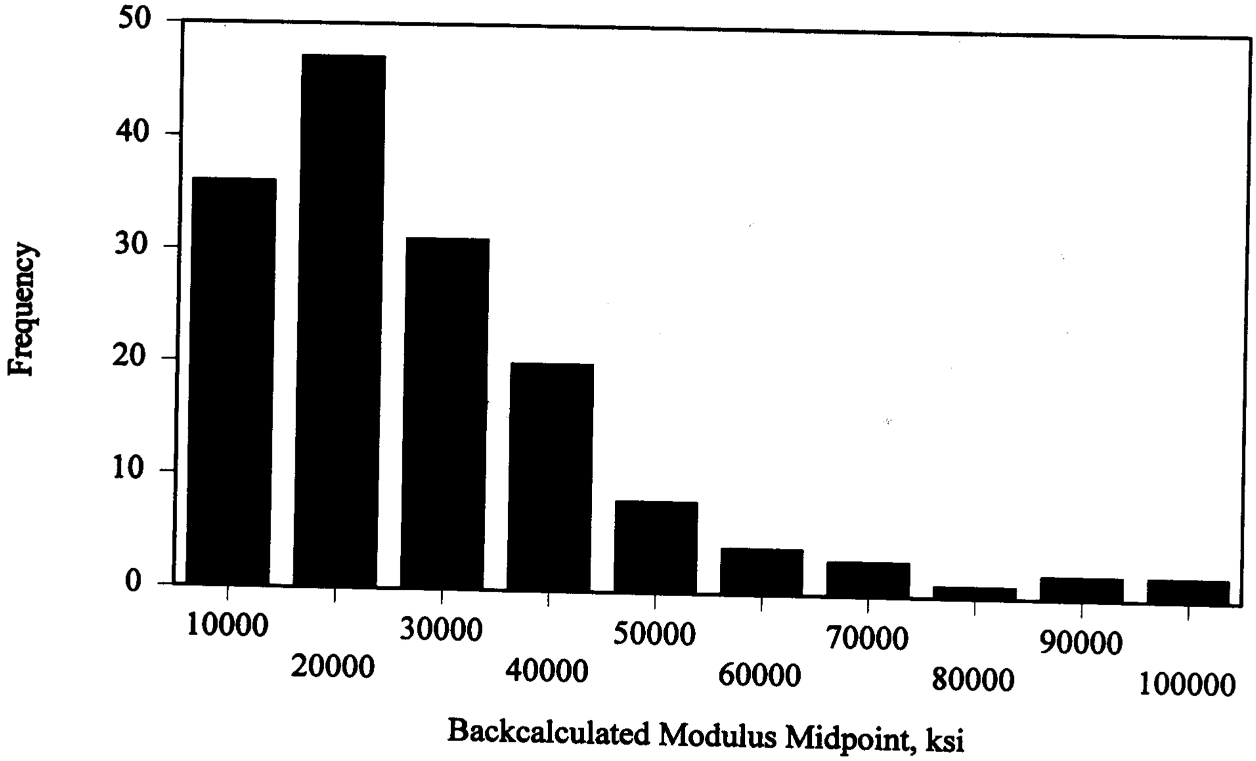
Pa = (ksi) x 6.895 x 10^{6}

Figure 6. Histogram of backcalculated PCC modulus (10).



Pa = (ksi) x 6.895 x 10^6

Figure 7. Histogram of backcalculated granular layer modulus (10).



$Pa = (ksi) \times 6.895 \times 10^6$

Figure 8. Histogram of subgrade layer moduli (10).

Table 4. GPS section ends rebackcalculated using WESDEF and/or Modulus 4.2.

GPS Section I.D.	Station	GPS Section I.D.	Station
011001	0-50	089019	5+60
011001	5+60	089020	0-50
011011	5+60	089020	5+60
011011	0-50	121370	5+60
011019	0-50	121370	0-50
011019	5+60	124057	5+60
011021	5+60	124057	0-50
011021	0-50	124102	0-50
013028	5+60	124102	5+60
013028	0-50	124103	0-50
014007	5+60	124103	5+60
014007	0-50	124105	5+60
014073	0-50	124105	0-50
014073	5+60	124135	5+60
014084	0-50	124135	0-50
014084	5+60	124136	5+60
014125	0-50	124136	0-50
014125	5+60	124138	5+60
014126	0-50	124138	0-50
014126	5+60	124153	0-50
021002	0-50	124153	5+60
021004	0-50	129054	0-50
021004	5+60	129054	5+60
026010	0-50	133011	5+60
026010	5+60	134092	0-50
029035	5+60	134092	5+60

Table 4. GPS section ends re-backcalculated using WESDEF and/or Modulus 4.2 (continued).

GPS Section I.D.	Station	GPS Section I.D.	Station
029035	0-50	137028	0-50
041001	5+60	137028	5+60
041001	0-50	161001	5+60
041002	5+60	161001	0-50
041002	0-50	161007	0-50
041003	5+60	161007	5+60
041003	0-50	161010	0-50
041006	5+60	161010	5+60
041006	0-50	161020	0-50
041007	5+60	169034	0-50
041007	0-50	184021	5+60
041015	5+60	184021	0-50
041015	0-50	201005	0-50
041016	0-50	283018	5+60
041016	5+60	283083	5+60
041017	5+60	283083	0-50
041017	0-50	294031	0-50
041018	5+60	294031	5+60
041018	0-50	294036	5+60
041021	0-50	294036	0-50
041021	5+60	295081	5+60
041022	5+60	295081	0-50
041022	0-50	301001	0-50
041024	5+60	301001	5+60
041024	0-50	307076	0-50
041025	5+60	307076	5+60
041025	0-50	308129	0-50
041034	0-50	308129	5+60

Table 4. GPS section ends re-backcalculated using WESDEF and/or Modulus 4.2 (continued).

GPS Section I.D.	Station	GPS Section I.D.	Station
041034	5+60	351002	0-50
041036	5+60	351002	5+60
041036	0-50	396019	5+60
041037	5+60	396019	0-50
041037	0-50	404086	5+60
041062	5+60	404086	0-50
041062	0-50	404160	0-50
041065	5+60	415022	5+60
041065	0-50	415022	0-50
046054	5+60	416012	0-50
046054	0-50	416012	5+60
046055	5+60	451024	0-50
046055	0-50	451024	5+60
046060	5+60	451025	5+60
046060	0-50	451025	0-50
047613	5+60	463013	5+60
047613	0-50	463013	0-50
047614	5+60	463052	5+60
047614	0-50	463052	0-50
052042	0-50	473104	0-50
052042	5+60	473104	5+60
053011	5+60	481113	0-50
053011	0-50	481113	5+60
053071	5+60	481122	5+60
053071	0-50	481122	0-50
054021	5+60	483679	5+60
054021	0-50	483689	5+60
055805	0-50	483689	0-50

Table 4. GPS section ends re-backcalculated using WESDEF and/or Modulus 4.2 (continued).

GPS Section I.D.	Station	GPS Section I.D.	Station
055805	5+60	483865	0-50
062041	5+60	483865	5+60
062041	0-50	485035	0-50
063024	5+60	485035	5+60
063024	0-50	491004	5+60
063030	0-50	491004	0-50
067452	0-50	491008	0-50
067452	5+60	491008	5+60
067452	0-50	491017	5+60
067456	0-50	491017	0-50
067456	5+60	493010	0-50
068534	0-50	493010	5+60
068534	5+60	531002	0-50
081029	5+60	531002	5+60
081029	0-50	531008	5+60
081047	0-50	531008	0-50
081047	5+60	533011	5+60
081053	5+60	533011	0-50
081053	0-50	533011	0-50
081057	5+60	533011	0-50
081057	0-50	553012	5+60
082008	0-50	553012	0-50
086002	0-50	553016	0-50
086002	5+60	553019	0-50
086013	0-50	553019	5+60
086013	5+60	566029	0-50
087035	5+60	566029	5+60
087035	0-50	566032	5+60

Table 4. GPS section ends re-backcalculated using WESDEF and/or Modulus 4.2 (continued).

GPS Section I.D.	Station	GPS Section I.D.	Station
087780	5+60	566032	0-50
087781	5+60	567775	5+60
087781	0-50	567775	0-50
087783	5+60	831801	0-50
089019	0-50		

4.0 BACKCALCULATION PROCESS

The backcalculation process for this analysis differed from the initial LTPP process in that the backcalculation was handled on a per site basis instead of a batch process, and individual deflection bowls (at a particular load level) were analyzed instead of the average load and deflections. For the re-backcalculation analysis, as with the original LTPP backcalculation, the FWD 9,000 lb. (40 kN) load level was selected for backcalculation. However, for re-backcalculation, the deflections were normalized to a 9,000 lb. (40 kN) load level and then were backcalculated on an individual drop basis, as mentioned above. The original LTPP backcalculation process did not normalize to a standard load, but took an average of the load and deflections from the individual drops and then backcalculated one bowl for each end of the GPS test sections. Deflections were normalized simply as a matter of convenience in comparing the deflection basins prior to backcalculating the layered elastic moduli.

The next step in this backcalculation process was to evaluate the combination of pavement layers into a single pavement layer that is part of the overall pavement structure. The LTPP backcalculation process combined specific layers based on material codes and similarities with material types through a batch process. For the re-backcalculation analysis, layers from the individual sections and their respective ends were combined based on a detailed review of the layer structure. Moduli ranges were set in various combinations to obtain the best fit or lowest error term in the backcalculation process. As an example, in some cases the asphalt base mixtures were considered a separate layer from the wearing surface to reduce the error term. This method generally provided better results and certainly allowed more flexibility in the backcalculation process.

More importantly, the 20-ft (6-m) shoulder boring, samples from the thin-walled shelby tubes, and test results on the subgrade soil samples were reviewed in selecting different subgrade layers and/or the depth to a rigid layer. When subsurface water was encountered and noted on the boring logs, two subgrade layers (one above and the other below the water table) were considered for use.

In general, ASTM D5858 (Standard Guide for Calculating Insitu Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory) was used as an initial guide for the problem sections. The following briefly summarizes the steps involved in the re-backcalculation process:

1) Review the measured deflection basins to ensure that the deflections decrease consistently with those sensors farther from the applied load.

2) Review the pavement structure used in the original backcalculation process and ensure that the layered structure is consistent with the test results and material definitions. Recombine and/or separate layers, if necessary, to decrease the error term.

3) Review the soils and conditions identified in the 20-ft (6-m) shoulder boring, as well as from the shelby tubes. Separate significantly different subgrade soils or subsurface conditions into different layers (i.e., above and below any water table and at a rigid layer or boundary condition).

4) Identify potential problem layers included in the structure. For example, weak soils above stiffer soils, sandwich sections (a soft layer or material between two strong materials), and thin and thick layers relative to the adjacent layers.

Based on the results obtained to reduce the error term, the resulting layer moduli and moduli ratios were reviewed for reasonableness. For those basins that consistently hit the upper limit set for a particular material, the structure was again reviewed in an attempt to reduce the error term, while maintaining reasonable values. Moduli ratios between two adjacent unbound layers were determined. Sections with high moduli ratios (values exceeding 4) were also identified. This was completed because large tensile stresses can occur at the bottom of the upper layer when moduli ratios of adjacent unbound layers exceed 3.5. These tensile stresses can result in decompaction of that layer reducing the modulus. As such, modulus ratios exceeding 4 are considered unrealistic, or suggest that the unbound material may in fact be acting as a bound material.

Section ends that hit the lower limit were considered less critical and the lower limit was further reduced. Very low moduli values can be found in pavement structures due to the possibility of contamination of underlying materials, the presence of cracks or internal damage (such as stripping), and the weakening of some unbound materials with an increase in moisture and/or decrease in density.

5.0 BACKCALCULATION RESULTS

Nearly 250 section ends were re-backcalculated using the previously mentioned process which resulted in much lower error terms. Figure 9 shows the revised distribution of the percent error per sensor using the re-backcalculation results. Although many of the higher error terms were significantly reduced from the initial results, there are still many section ends that have unacceptable errors. On the positive side, many of the section ends exceeding an error of 2.5 percent per sensor (as seen in figure 4) were reduced.

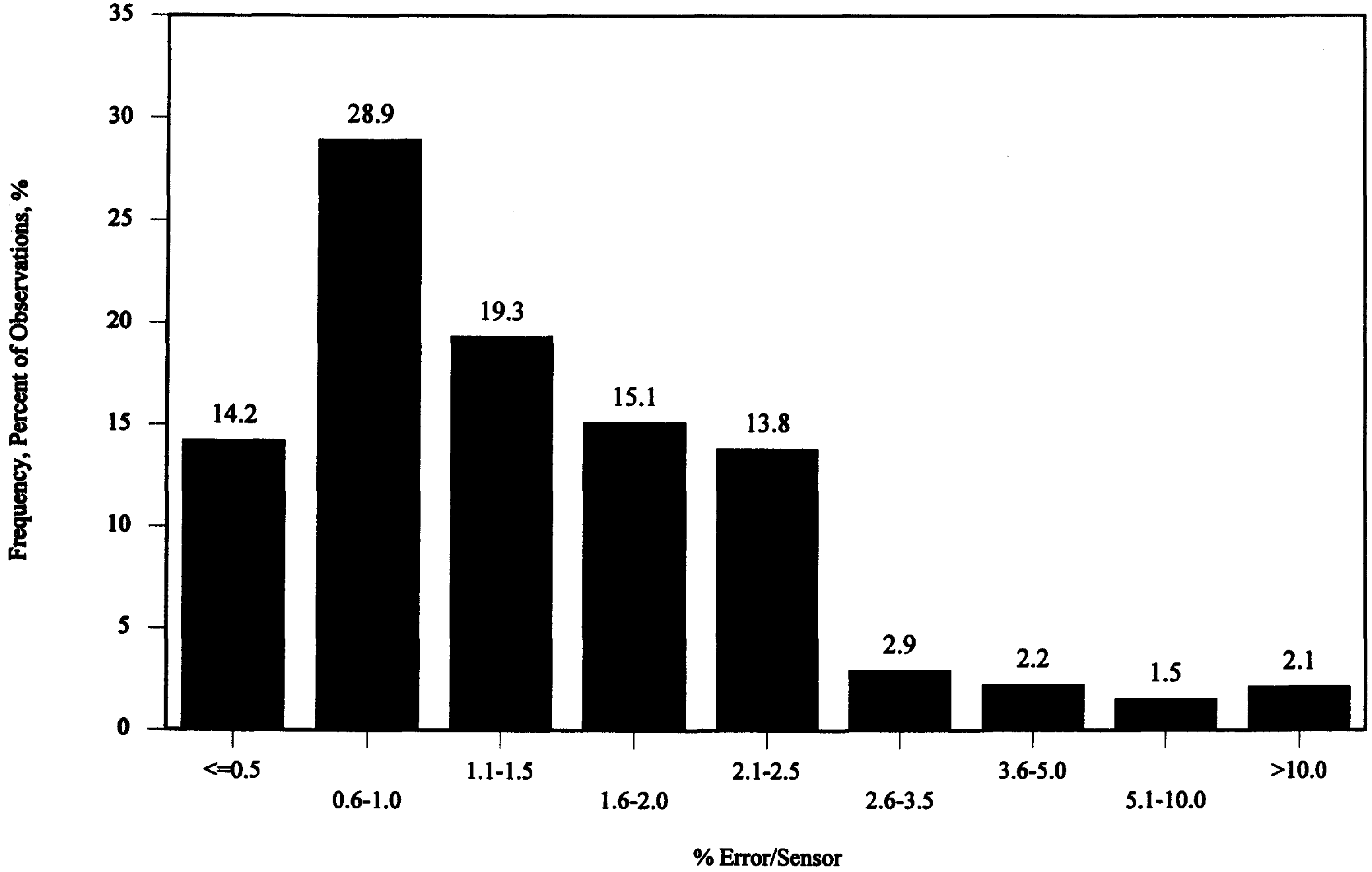


Figure 9. Histogram of the distribution of the percent error per sensor using the revised results from this study.

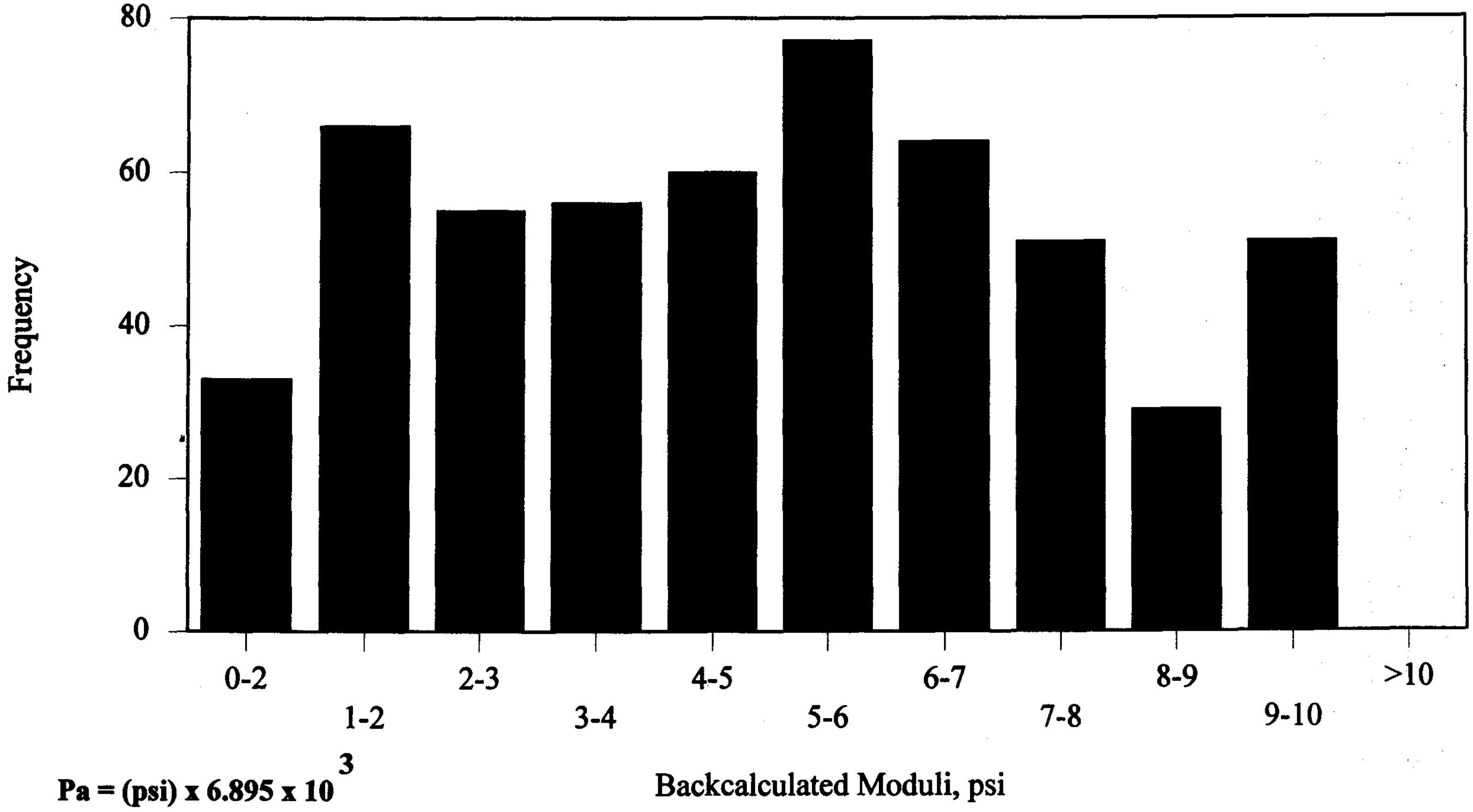
Several plots shown in reference 10 were regenerated so that a graphical comparison could be made between the original LTPP results and the new results. Figures 10 through 16 detail the new results for layer moduli of different pavement materials and subgrade soils. It should be noted that several of the AC sections re-backcalculated were sections that originally had a thin AC surface layer (less than 2 in [50 mm]) . However, for re-backcalculation, these thin surface layers were combined with lower AC layers to help improve the results or decrease the error term.

Figure 11 is a histogram of the AC layer moduli developed by combining the revised results with the original LTPP results. The histogram shows that there is a very wide range of moduli values (<200,000 psi to >2,000,000 psi) (<1,400 to > 14,000 mPa) for the AC layers. However, the AC modulus is highly dependent upon temperature so a better representation is shown in figure 17. It should be stated that the plots noted with "revised results" include all section ends (with improved WESDEF data) and plots from the original LTPP runs include only successful runs. This explains why there are so many sections above 2,000,000 psi (14,000 mPa) shown in the revised results plots.

In summary, none of the PCC thickness were altered when re-backcalculating with the WESDEF program, with the exception of possible errors in the thicknesses used in the original backcalculation, as compared to the laboratory core thickness measurements. The PCC moduli values, as shown in figure 10, show that the moduli ranges (1,000,000 psi to 10,000,000 psi) (6,900 to 69,000 mPa) was comparable between the two iterations. However, when looking at the error for the PCC sections, it can be seen that the error is generally very high indicating that neither backcalculation program handles PCC sections very well. More importantly, some of the layer moduli calculated for the unbound bases and subbases appear to have very high moduli. Section ends with layer moduli that do not appear to be reasonable for the type of material identified are listed in appendix B of reference 12. Some of these are discussed in more detail in the following section.

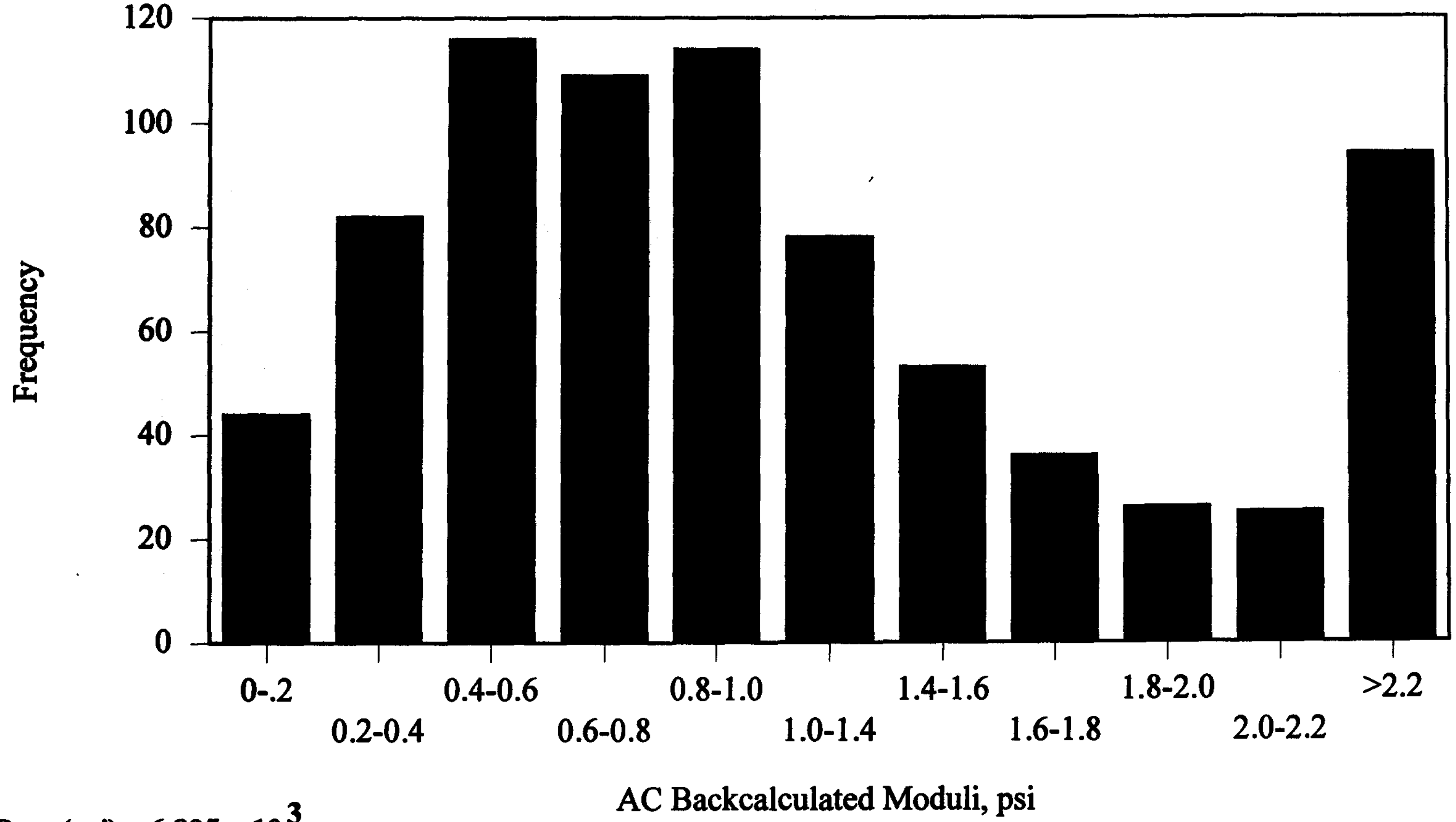
6.0 PROBLEM SECTIONS

In reviewing the deflection data and the pavement structures, some data discrepancies were identified. For example, several sections were found to have "problem" deflection bowls where increasing or identical deflection measurements were noted with increasing sensor number. As expected, these sections generally did not provide reasonable results in the backcalculation process, because no bowls could be fit with this type of basin measurement. Those GPS sections with irregular deflection basins are listed in table 5, and were not used in any detailed analysis. It



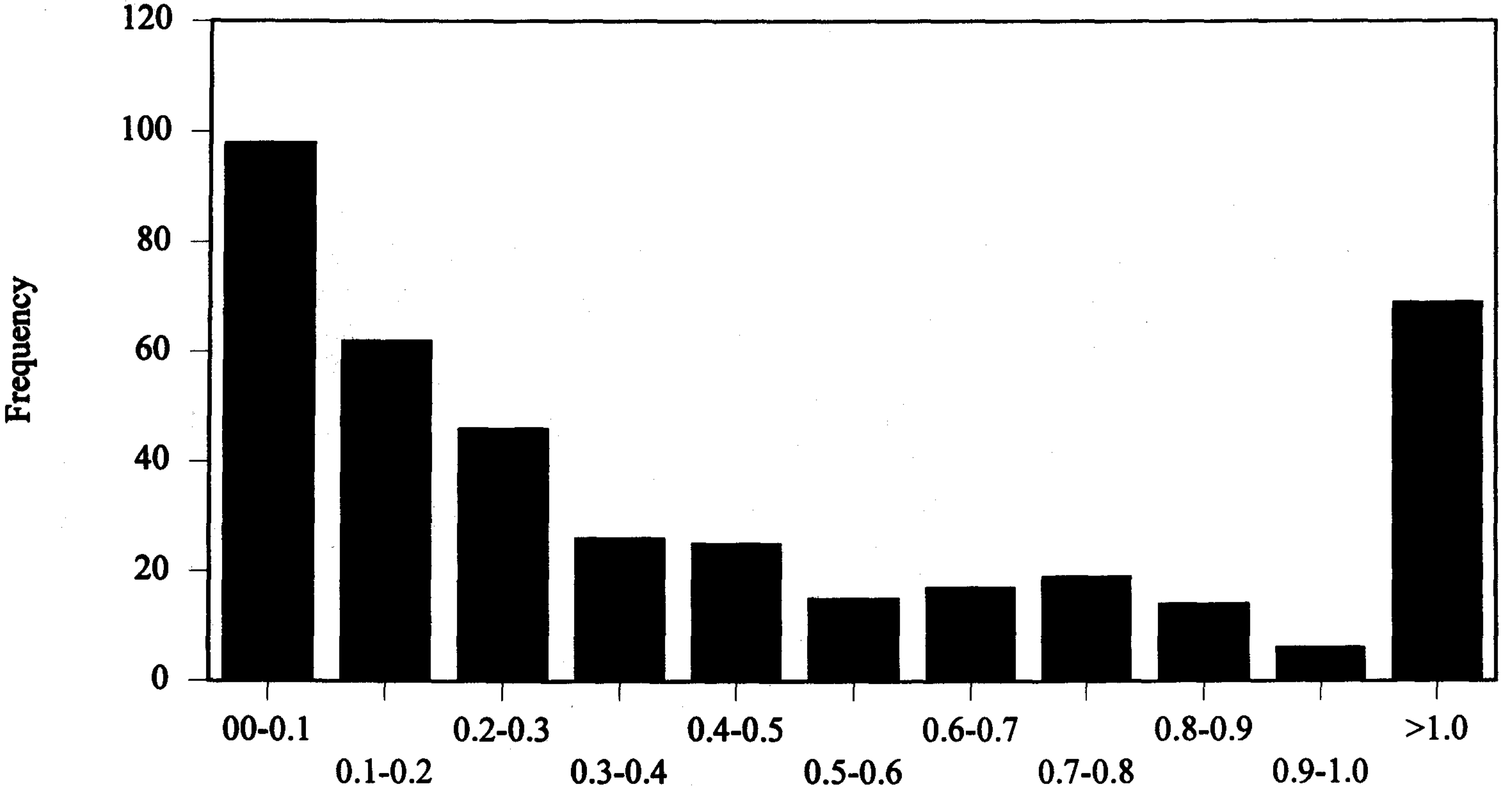
Pa = (psi) x 6.895 x 10^3

Figure 10. Histogram of backcalculated PCC layer moduli for the revised results.



Pa = (psi) x 6.895 x 10^3

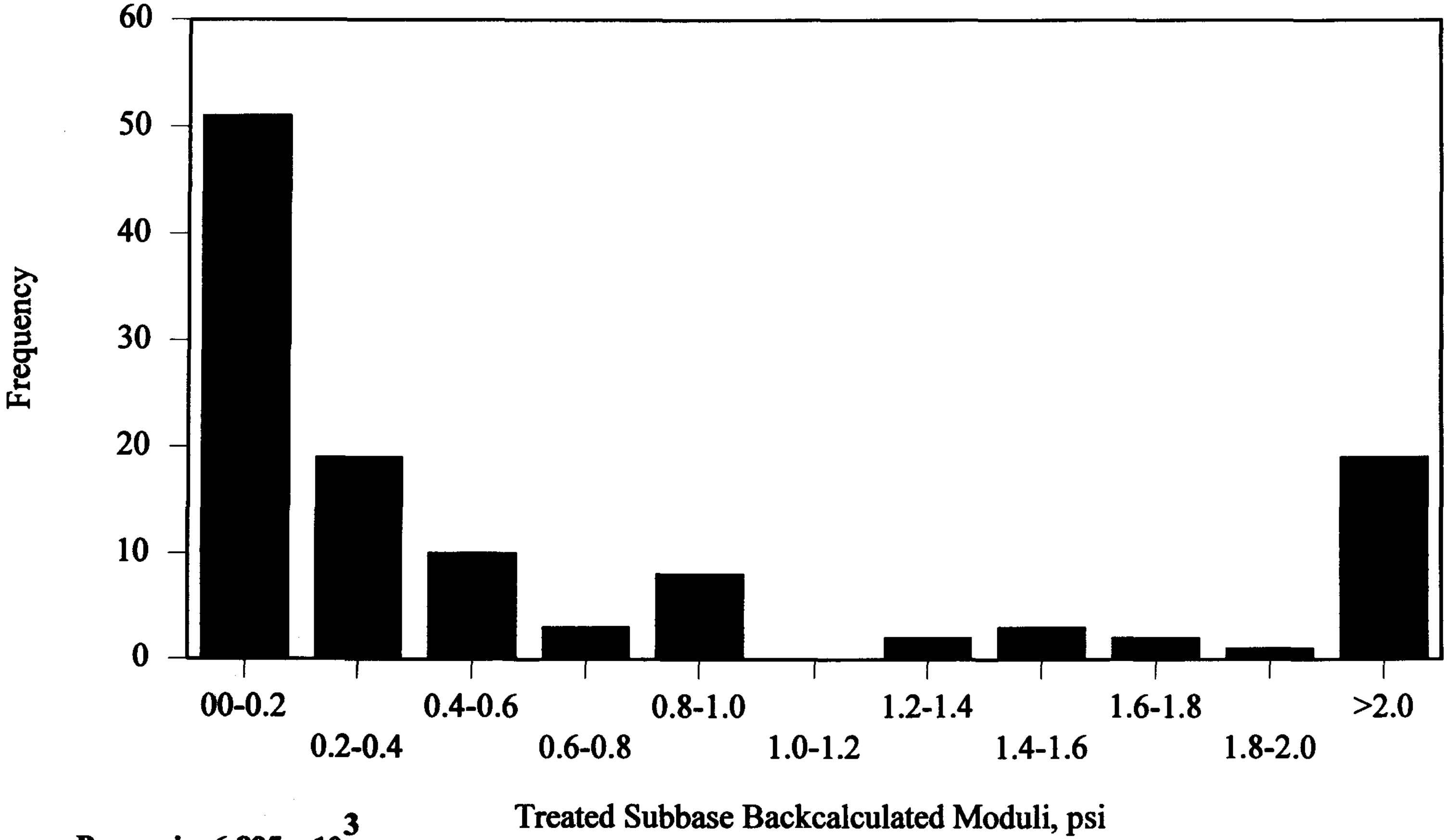
Figure 11. Histogram of backcalculated AC layer moduli for the revised results.



Pa = (psi) x 6.895 x 10^3

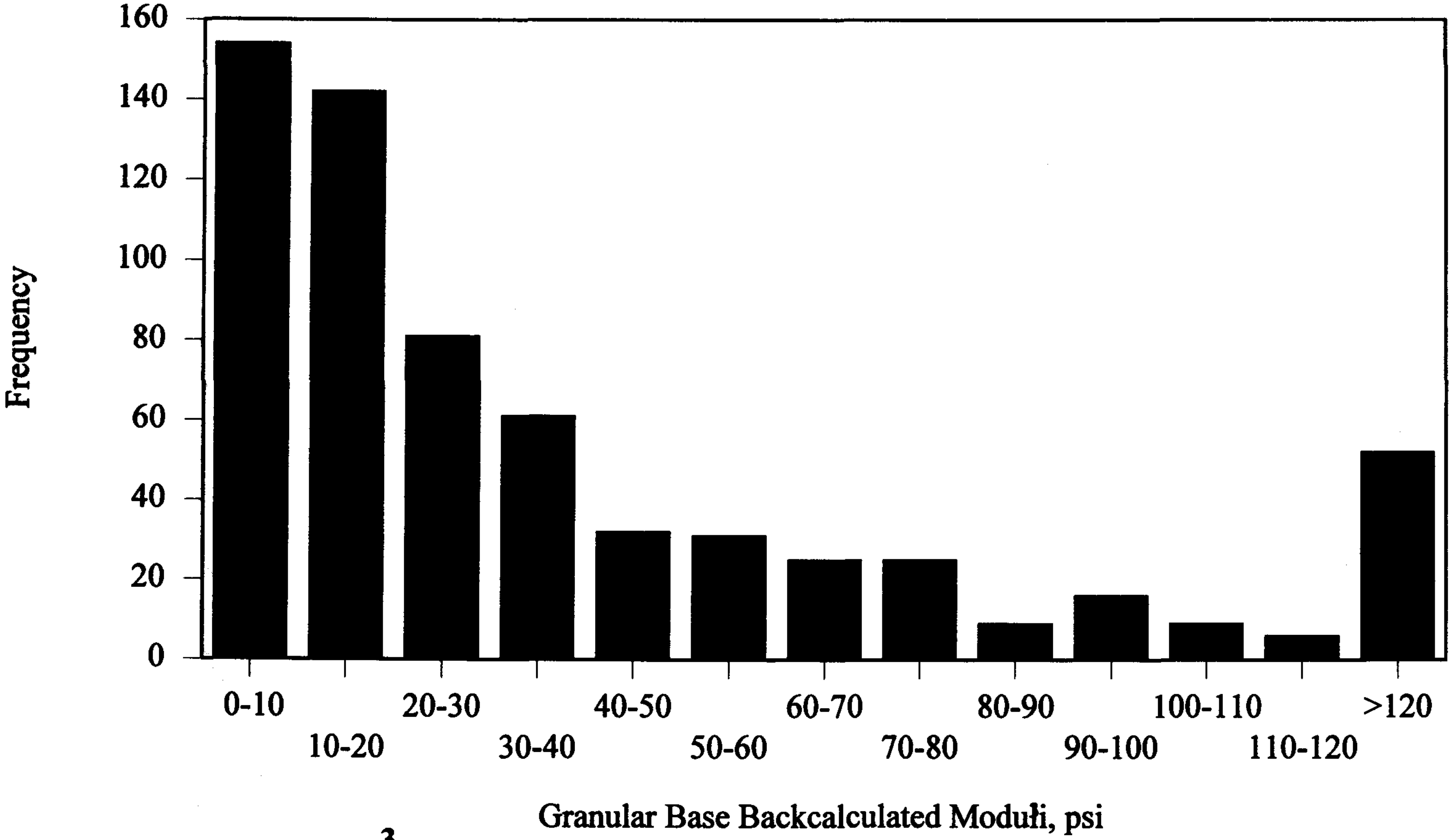
Treated Base Backcalculated Moduli, psi

Figure 12. Histogram of backcalculated treated base layer moduli for the revised results.



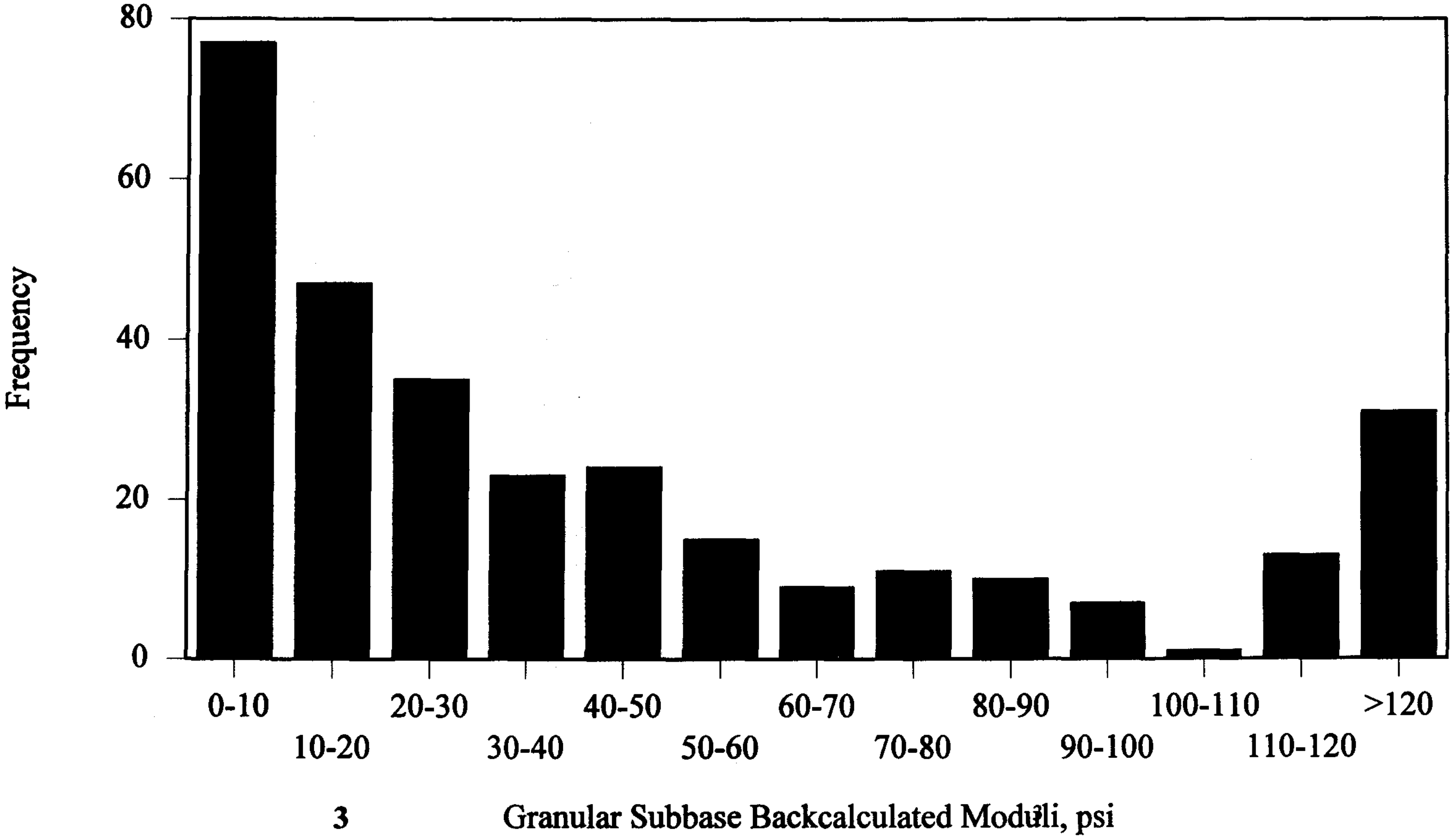
Pa = psi x 6.895 x 10^3

Figure 13. Histogram of backcalculated treated subbase layer moduli for the revised results.



Pa = (psi) x 6.895 x 10^3

Figure 14. Histogram of backcalculated granular base layer moduli for the revised results.



Pa = (psi) x 6.895 x 10^3

Figure 15. Histogram of backcalculated granular subbase layer moduli for the revised results.

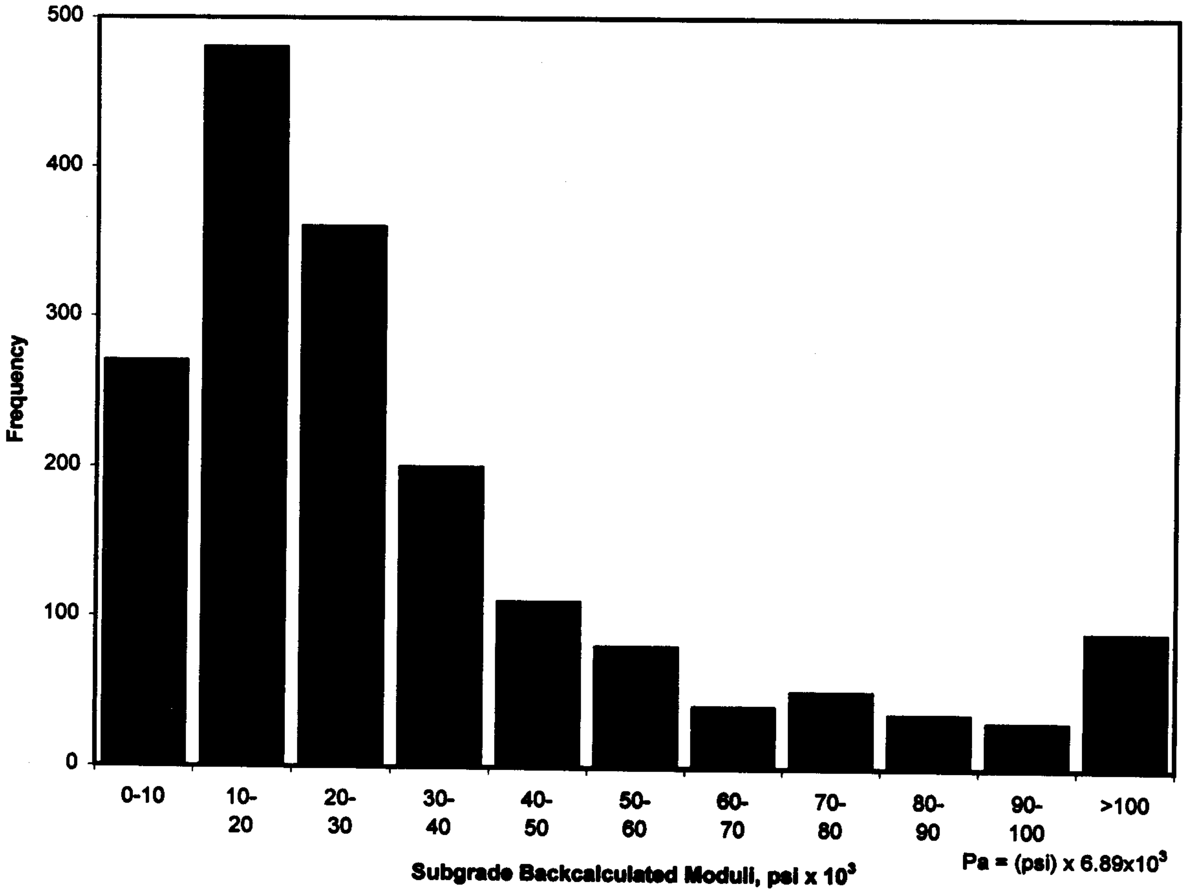


Figure 16. Histogram of backcalculated subgrade layer moduli for the revised results.

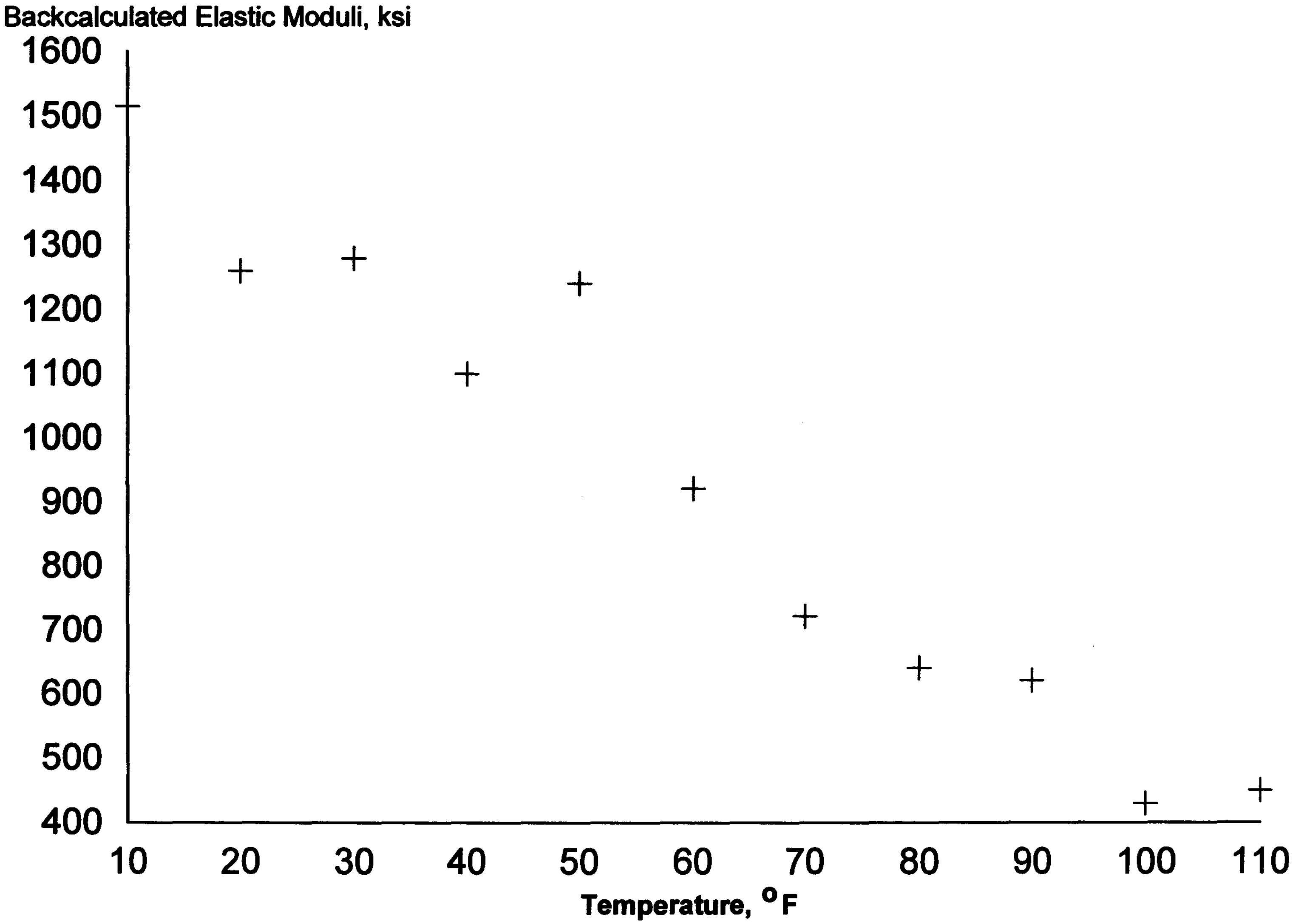


Figure 17. AC backcalculated modulus for successful sections (averaged for temperature range) (10).

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory.

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
I	2,5	3	JPCP	AR	053011	Appr.
I	5	3	JPCP	AR	053011	Leave
I	3,4	2	AC/TB	CA	062053	Appr.
I	3	3	JPCP	CA	063010	Appr.
I	3	3	JPCP	CA	063010	Leave
I	2-6	3	JPCP	CA	063013	Appr.
I	2-6	3	JPCP	CA	063013	Leave
I	3	3	JPCP	CA	063019	Appr.
I	3	3	JPCP	CA	063019	Leave
I	2-5	3	JPCP	CA	063030	Appr.
I	2	3	JPCP	CA	063042	Appr.
I	3-6	3	JPCP	CA	063042	Leave
I	3,4	3	JPCP	CA	067456	Appr.
I	3,4	3	JPCP	CA	067456	Leave
I	2	7A	AC/P.C.	CO	087035	Appr.
I	2,3	9	P.C./P.C.	CO	089019	Leave
I	2,3	3	JPCP	FL	123804	Leave
I	2-7	3	JPCP	FL	124057	Leave
I	2	3	JPCP	FL	124109	Leave
I	2-5	3	JPCP	FL	124138	Appr.
I	1	1	HMAC	FL	129054	Leave
I	2	3	JPCP	GA	133007	Appr.
I	2-5	3	JPCP	GA	133011	Appr.
I	3	1	HMAC	ID	161007	Leave
I	2	1	HMAC	ID	161010	Appr.

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
I	2	5	CRCP	IN	185518	Leave
I	2-5	3	JPCP	IA	193006	Appr.
I	3	3	JPCP	IA	193033	Appr.
I	2,3,4	3	JPCP	KY	213016	Appr.
I	2,3	4	JRCP	LA	224001	Appr.
I	2	4	JRCP	MI	264015	Leave
I	2,3	9	P.C./P.C.	MN	276300	Leave
I	2-6	3	JPCP	MS	283018	Leave
I	2-5	9	P.C./P.C.	MS	289030	Appr.
I	2-6	9	P.C./P.C.	MS	289030	Leave
I	2-6	3	JPCP	NB	313018	Appr.
I	2-6	3	JPCP	NB	313018	Leave
I	2	3	JPCP	NV	323010	Appr.
I	3	3	JCPC	NC	373816	Appr.
I	2	5	CRCP	NC	375826	Leave
I	2	9	P.C./P.C.	OK	404155	Appr.
I	2-4	3	JPCP	OK	404160	Leave
I	2,3	5	CRCP	OK	404166	Leave
I	2,3	5	CRCP	OR	415005	Appr.
I	2,3	5	CRCP	OR	415006	Appr.
I	2	9	P.C./P.C.	PA	421627	Leave
I	2-6	3	JPCP	SD	463013	Appr.
I	3,4	3	JPCP	SD	463053	Appr.
I	2,5	3	JPCP	SD	466600	Appr.
I	5	3	JPCP	TX	483003	Appr.
I	2	3	JPCP	TX	483003	Leave

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
I	2-4	2	AC/TB	TX	483679	Appr.
I	3	5	CRCR	TX	483719	Leave
I	4	9	P.C./P.C.	TX	483845	Leave
I	2,3	4	JRCP	TX	484152	Appr.
I	2,5	5	CRCP	TX	485024	Appr.
I	2	5	CRCP	TX	485284	Appr.
I	5	5	CRCP	TX	485284	Leave
I	2	5	CRCP	TX	485301	Leave
I	2,3	3	JPCP	UT	493011	Appr.
I	2,3	5	CRCP	VA	515010	Appr.
I	2-5	3	JPCP	WA	533011	Appr.
I	2-6	3	JPCP	WA	533011	Leave
I	2	3	JPCP	WA	533014	Appr.
I	3-6	3	JPCP	WA	533019	Appr.
I	3-6	3	JPCP	WA	537409	Appr.
I	2	3	JPCP	WA	537409	Leave
I	2-7	4	JRCP	WV	544004	Appr.
I	2-4	3	JPCP	WI	553016	Leave
I	2-6	3	JPCP	WI	553019	Leave
I	2,3	3	JPCP	QB	893001	Leave
II	3-4	5	CRCP	AL	013998	Appr.
II	3-4-5	1	HMAC	AZ	041002	Appr.
II	3-4-5	1	HMAC	AZ	041002	Leave
II	3-4-5	1	HMAC	AZ	041007	Appr.
II	3-4-5	1	HMAC	AZ	041007	Leave
II	3-4-5	1	HMAC	AZ	041015	Appr.

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
II	3-4-5	1	HMAC	AZ	041015	Leave
II	3-4-5	1	HMAC	AZ	041017	Leave
II	2-3-4	1	HMAC	AZ	041018	Appr.
II	2-3-4	1	HMAC	AZ	041018	Leave
II	3-4-5	1	HMAC	AZ	041021	Appr.
II	3-4-5	1	HMAC	AZ	041021	Leave
II	2-3-4	1	HMAC	AZ	041022	Leave
II	2-3-4	1	HMAC	AZ	041024	Leave
II	2-3-4	1	HMAC	AZ	041025	Appr.
II	2-3-4	1	HMAC	AZ	041025	Leave
II	2-3-4	1	HMAC	AZ	041034	Appr.
II	3-4-5	1	HMAC	AZ	041034	Leave
II	3-4-5	1	HMAC	AZ	041036	Appr.
II	3-4-5	1	HMAC	AZ	041036	Leave
II	3-4-5	1	HMAC	AZ	041037	Appr.
II	3-4-5	1	HMAC	AZ	041037	Leave
II	2-3-4-5	2	AC/TB	AZ	041065	Appr.
II	2-3-4-5	2	AC/TB	AZ	041065	Leave
II	3-4-5	6A	AC/AC	AZ	046053	Appr.
II	3-4-5	6A	AC/AC	AZ	046053	Leave
II	3-4-5	6A	AC/AC	AZ	046054	Appr.
II	3-4-5	6A	AC/AC	AZ	046054	Leave
II	2-3-4-5	6A	AC/AC	AZ	046055	Appr.
II	2-3-4-5	6A	AC/AC	AZ	046055	Leave
II	3-4-5	6A	AC/AC	AZ	046060	Appr.
II	3-4-5	6A	AC/AC	AZ	046060	Leave

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
II	2-3-4	2	AC/TB	AZ	052042	Appr.
II	6-7	4	JRCP	AR	054021	Leave
II	6-7	5	CRCP	AR	055803	Appr.
II	2-3-4	5	CRCP	AR	055805	Appr.
II	2-3-4-5	9	P.C./P.C.	AR	059100	Leave
II	6-7	2	AC/TB	CA	062004	Leave
II	2-3-4	2	AC/TB	CA	062038	Appr.
II	2-3-4	2	AC/TB	CA	062051	Appr.
II	2-3-4	2	AC/TB	CA	062051	Leave
II	6-7	3	JPCP	CA	063005	Appr.
II	2-3	3	JPCP	CA	063021	Leave
II	3-4-5	2	AC/TB	CA	067452	Leave
II	2-3-4	2	AC/TB	CA	067491	Appr.
II	2-3-4	2	AC/TB	CA	068150	Leave
II	2-3-4	1	HMAC	CA	068153	Leave
II	1-2-3	1	HMAC	CA	068534	Leave
II	3-4-5	1	HMAC	CO	081029	Appr.
II	3-4-5	1	HMAC	CO	081029	Leave
II	3-4-5	1	HMAC	CO	081047	Appr.
II	3-4-5	1	HMAC	CO	081047	Leave
II	3-4-5	1	HMAC	CO	081053	Appr.
II	3-4-5	1	HMAC	CO	081053	Leave
II	3-4-5	1	HMAC	CO	081057	Appr.
II	3-4-5	1	HMAC	CO	081057	Leave
II	3-4-5	2	AC/TB	CO	082008	Appr.
II	3-4-5	2	AC/TB	CO	082008	Leave

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
II	3-4-5	3	JPCP	CO	083032	Leave
II	3-4-5-6	6A	AC/AC	CO	086002	Appr.
II	3-4-5	6A	AC/AC	CO	086002	Leave
II	3-4-5	6A	AC/AC	CO	086013	Appr.
II	3-4-5	6A	AC/AC	CO	086013	Leave
II	2-3-4-5	7A	AC/P.C.	CO	087036	Leave
II	3-4-5	3	JPCP	CO	087776	Appr.
II	3-4-5	3	JPCP	CO	087776	Leave
II	3-4-5	1	HMAC	CO	087780	Appr.
II	3-4-5	1	HMAC	CO	087780	Leave
II	3-4-5	2	AC/TB	CO	087781	Appr.
II	3-4-5	2	AC/TB	Co	087781	Leave
II	2-3-4-5	6A	AC/AC	CO	087783	Appr.
II	3-4-5	6A	AC/AC	CO	087783	Leave
II	5-6-7	3	JPCP	FL	124109	Appr.
II	2-3-4	1	HMAC	FL	124154	Appr.
II	2-3-4	1	HMAC	FL	124154	Leave
II	5-6-7	3	JPCP	GA	133017	Leave
II	5-6-7	2	AC/TB	GA	134092	Appr.
II	1-2-3	7A	AC/P.C.	GA	137028	Leave
II	3-4-5	1	HMAC	ID	161001	Appr.
II	3-4-5	1	HMAC	ID	161001	Leave
II	3-4-5	1	HMAC	ID	161005	Appr.
II	3-4-5	1	HMAC	ID	161005	Leave
II	1-2-3-4	1	HMAC	ID	161007	Appr.
II	1-2-3-4	1	HMAC	ID	161007	Leave

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
II	3-4-5	1	HMAC	ID	161010	Leave
II	3-4-5	1	HMAC	ID	161020	Appr.
II	3-4-5	1	HMAC	ID	161020	Leave
II	3-4-5	1	HMAC	ID	161021	Appr.
II	3-4-5	1	HMAC	ID	161021	Leave
II	3-4-5	3	JPCP	ID	163017	Leave
II	3-4-5	5	CRCP	ID	165025	Appr.
II	3-4-5	6A	AC/AC	ID	166027	Leave
II	3-4-5	1	HMAC	ID	169032	Appr.
II	3-4-5	1	HMAC	ID	169032	Leave
II	3-4-5	1	HMAC	ID	169034	Appr.
II	3-4-5	1	HMAC	ID	169034	Leave
II	2-3-4-5	4	JRCP	IN	184021	Appr.
II	2-3-4-5	9	P.C./P.C.	IN	189020	Leave
II	2-3-4-5	5	CRCP	IA	199116	Leave
II	2-3-4-5	7B	AC/P.C.	IA	199126	Appr.
II	3-4-5	3	JPCP	KS	203013	Appr.
II	3-4-5	3	JPCP	KS	203013	Leave
II	4-5-6	4	JPCP	KS	204053	Appr.
II	6-7	4	JRCP	KS	204053	Leave
II	3-4-5	4	JRCP	KS	204054	Appr.
II	4-5-6	4	JRCP	KS	204063	Leave
II	6-7	4	JRCP	KS	204067	Appr.
II	3-4-5-6	1	HMAC	KY	211010	Appr.
II	5-6-7	1	HMAC	MI	261010	Appr.
II	5-6-7	1	HMAC	MI	261010	Leave

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
II	4-5-6	2	AC/TB	MS	283085	Appr.
II	3-4-5	2	AC/TB	MS	283085	Leave
II	2-3-4	4	JRCP	MO	294031	Appr.
II	5-6-7	4	JRCP	MO	294069	Appr.
II	5-6-7	4	JRCP	MO	294069	Leave
II	3-4-5-6	6A	AC/AC	MT	306004	Appr.
II	3-4-5-6	6A	AC/AC	MT	306004	Appr.
II	3-4-5	6A	AC/AC	MT	306004	Leave
II	3-4-5	2	AC/TB	MT	307076	Appr.
II	3-4-5	2	AC/TB	MT	307076	Leave
II	3-4-5	1	HMAC	MT	307088	Appr.
II	3-4-5	1	HMAC	MT	307088	Leave
II	3-4-5	1	HMAC	MT	308129	Appr.
II	3-4-5	1	HMAC	MT	308129	Leave
II	3-4-5-6	1	HMAC	NB	311030	Appr.
II	3-4-5-6	1	HMAC	NB	311030	Leave
II	2-3-4-5	6B	AC/AC	NB	316700	Leave
II	3-4-5	9	P.C./P.C.	NB	316701	Appr.
II	3-4-5	2	AC/TB	NV	321030	Leave
II	3-4-5	2	AC/TB	NV	322027	Appr.
II	3-4-5	2	AC/TB	NV	322027	Leave
II	5-6-7	1	HMAC	NC	371817	Leave
II	3-4-5	3	JPCP	NC	373807	Appr.
II	3-4-5	3	JPCP	NC	373807	Leave
II	3-4-5-6	5	CRCP	NC	375827	Leave
II	6-7	3	JPCP	ND	383005	Appr.

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
II	3-4-5	7A	AC/P.C.	OH	397021	Appr.
II	4-5-6	6B	AC/AC	OK	404086	Leave
II	3-4-5-6	2	AC/TB	OK	404088	Appr.
II	3-4-5	2	AC/TB	OK	404164	Leave
II	3-4-5	5	CRCP	OR	415008	Leave
II	3-4-5	7A	AC/P.C.	PA	427025	Leave
II	2-7	3	JPCP	SD	463010	Appr.
II	3-4-5-6	1	HMAC	TX	481122	Leave
II	4-5-6	2	AC/TB	TX	482133	Appr.
II	4-5-6	2	AC/TB	TX	482133	Leave
II	3-4-5-6	1	HMAC	TX	483579	Appr.
II	6-7	2	AC/TB	TX	483689	Appr.
II	3-4-5-6	1	HMAC	UT	491001	Appr.
II	3-4-5	6A	AC/AC	UT	491004	Appr.
II	3-4-5	1	HMAC	UT	491008	Appr.
II	3-4-5	1	HMAC	UT	491008	Leave
II	3-4-5-6	3	JPCP	UT	493010	Appr.
II	6-7	2	AC/TB	VA	511423	Appr.
II	3-4-5	1	HMAC	WA	531002	Appr.
II	3-4-5	1	HMAC	WS	531002	Leave
II	3-4-5	6B	AC/AC	WA	531005	Appr.
II	3-4-5	6B	AC/AC	WA	531005	Leave
II	3-4-5	1	HMAC	WA	531008	Appr.
II	3-4-5	1	HMAC	WA	531008	Leave
II	3-4-5-6	3	JPCP	WA	533812	Appr.
II	3-4-5	6A	AC/AC	WA	536056	Appr.

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
II	3-4-5	6A	AC/AC	WA	536056	Leave
II	3-4-5	6A	AC/AC	WA	537322	Appr.
II	3-4-5	6A	AC/AC	WA	537322	Leave
II	3-4-5	2	AC/TB	WY	562015	Leave
II	3-4-5	1	HMAC	WY	566029	Appr.
II	3-4-5	1	HMAC	WY	566029	Leave
II	3-4-5	1	HMAC	WY	567775	Appr.
II	3-4-5	1	HMAC	WY	567775	Leave
III	2	5	CRCP	AL	013998	Leave
III	2	4	JRCP	AL	014007	Leave
III	4	4	JRCP	AR	053059	Leave
III	2	4	JRCP	AR	054021	Leave
III	2	4	JRCP	AR	054023	Leave
III	2,3	3	JPCP	CA	063024	Appr.
III	2	3	JPCP	CO	083032	Appr.
III	2,3	3	JPCP	ID	163017	Leave
III	2	3	JPCP	ID	163023	Appr.
III	2	4	JRCP	IL	174074	Leave
III	2	5	CRCP	IL	175843	Appr.
III	2	5	CRCP	IL	175843	Leave
III	2	3	JPCP	IN	183031	Appr.
III	2	4	JRCP	IN	184021	Leave
III	2	5	CRCP	IN	185043	Appr.
III	2,3	9	P.C./P.C.	IN	189020	Appr.
III	2	3	JPCP	IA	193009	Leave
III	2	3	JPCP	IA	193055	Appr.

Table 5. Listing of sections with problem deflection basins that are not compatible with elastic layer theory (continued).

Type of Deflection Basin	Sensors Where Problem Characteristics Were Measured	GPS Experiment No.	Pavement Surface Type	State	Section ID No.	Section End
III	3,4	3	JPCP	KS	203060	Appr.
III	2	3	JPCP	MN	273013	Appr.
III	2,3	7A	AC/P.C.	MS	283097	Leave
III	2	5	CRCP	MS	285025	Appr.
III	2	5	CRCP	MS	285805	Leave
III	4,5	4	JRCP	MO	295473	Appr.
III	2	4	JRCP	MO	295483	Appr.
III	2,3	2	AC/TB	NV	321030	Appr.
III	2,3	3	AC/TB	NV	323013	Leave
III	2	5	CRCP	OK	404158	Leave
III	2,3,4	5	CRCP	OR	415021	Leave
III	2	5	CRCP	OR	415022	Appr.
III	2,3	6A	AC/AC	OR	416011	Leave
III	2,3	5	CRCP	OR	417081	Leave
III	2	3	JRCP	PA	423044	Appr.
III	2,3	5	CRCP	PA	425020	Appr.
III	2,3	9	P.C./P.C.	PA	429027	Leave
III	2	5	CRCP	SC	455034	Leave
III	2,3	3	JPCP	TX	483010	Appr.
III	3,4	3	JPCP	TX	483010	Leave
III	2,3	9	P.C./P.C.	TX	483569	Appr.
III	2	4	JRCP	TX	484143	Leave
III	2,3	5	CRCP	TX	485026	Leave
III	2,3	3	JPCP	PR	724121	Appr.

is interesting to note the percentage of irregularly shaped deflection basins between PCC and AC surfaced pavements. A total of 5.3 percent of the basins were found to have increasing deflections further from the load between successive sensors. Of these, 92 percent were PCC pavements and only 8 percent were AC sections. This suggests the possibility of voids beneath the PCC surface or that extreme temperature gradients could exist which resulted in a loss of support due to curling and/or warping of the PCC slabs.

Several sections were noted that had varying pavement structures between the two ends of the test section. This did not necessarily affect the backcalculation results; however, it should be noted that one end or the other may or may not represent the actual 500-ft (152-m) pavement test section, or in fact, there may be a homogeneity problem throughout the test section.

A further investigation of a few of the sections with problematic deflection bowls was conducted for the Southern region. For those sites studied, the problems with the deflections appear to be caused by a variety of problems. An example would be a site that is an AC surface over a lime treated base where the lime treated base set up, to the extent that it is now very hard and the AC surface layer has exhibited cracking similar to an AC overlay of a PCC pavement. Hence, when testing this section, the deflections were very small and were noted at the time to be problematic. Similarly, other sections studied in the southern and western regions were found to have sand subbase layers with extremely high moduli, indicative of a cement treated material.

Another section studied was a PCC section and again the deflections were very small. It was noted that the FWD operator tried moving to different areas to determine if the problem was only at a particular location; however, this was not the case because all of the deflections were very small. It has also been noted that other sections in the GPS 7 experiment are known to be difficult for FWD testing. Based on an initial review in the Southern region, it is believed that most of the problems occurring are indicative of some type of material problem rather than a problem in the FWD software or FWD operations.

Problem sections have been noted in the backcalculation data base (12) with a comment and are not recommended for use in any further data analyses.

7.0 DATA BASE GENERATION

A data base has been generated with results from both the WESDEF analysis and the original LTPP backcalculation analysis. These data represent a combination of the most reliable data available between the two analyses. The following items are included in the data base:

1) GPS Section Number
2) Testing Location
3) Description of Layers
4) Thickness of Layers
5) Poisson's Ratio of Layers
6) Moduli of Layers
7) Percent Error per Sensor
8) Bowl Identifier (i.e., which bowls used to determine moduli values)
9) Pavement Testing Temperatures
10) Load Level
11) Backcalculation Program Used for Reported Results
12) Non-Decreasing Deflections Identifier

The results housed in this data base were used for other analyses and are expected to be a valuable research tool for other researchers evaluating pavement related issues on other research activities. A summary of this data base is included in reference 12.

8.0 CONCLUSIONS

Backcalculation of pavement layer moduli from deflection measurements has and will continue to be an important part of pavement diagnostic studies. This study has focused on improving the backcalculation of layer moduli resulting from the SHRP-LTPP study. Many of the larger error terms were reduced to an "acceptable" value. However, there are still many GPS end sections with error terms significantly exceeding a value of 2.5 percent per sensor. The following lists those observations noted from this study and effort, which have been noted and documented by other reports.

1) There is <u>no</u> unique solution for a particular deflection basin; engineering judgement must be used in determining reasonable solutions.

2) Most programs based on elastic layer theory can be used to find a combination of layer moduli with an error term less than 2.0 percent per sensor. However, these

layer moduli can be consistently and significantly different between these programs, which prevents the combination and random use of different programs.

3) An extremely large number of GPS section ends in the Western States or region have solutions that did not converge to an error term less than 2.5 percent per sensor. A reason for these large error terms was not identified.

4) There are slightly more than 10 percent of the GPS section ends which have measured deflection basins with uncommon characteristics that cannot be analyzed with elastic layer theory. Many of these GPS sites are those that have a portland cement concrete surface, which may indicate possible voids beneath the surface or curling and/or warping of the PCC surface during the time of testing.

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