Comparison of Backcalculated Moduli from Falling Weight Deflectometer and Truck Loading

PETER E. SEBAALY, NADER TABATABAEE, AND TOM SCULLION

Historically, the in situ resilient moduli of pavement layers have been evaluated from nondestructive deflection testing (NDT) devices such as the Dynaflect, Road Rater, or falling weight deflectometer (FWD). Even though the FWD is the best NDT device available, it still does not fully represent the loading conditions generated by a moving truck. Therefore, the moduli values, backcalculated from FWD deflections, may be different from those that are backcalculated from truck loading data. The in situ resilient moduli of the pavement layers were backcalculated from FWD, multidepth deflectometers (MDD), and strain gauge data. In the case of the FWD loading, the backcalculated moduli from the FWD deflection basins are compared with the ones backcalculated from the MDD deflections. In the truck loading case, the backcalculated moduli from the MDD deflections are compared with the ones backcalculated from the strain gauge data.

A large number of the nation's highways are approaching the end of their service lives. Consequently, there is an urgent need to upgrade and maintain these highways. By applying a well-designed overlay to a deteriorated pavement section, its functional and structural performances can be greatly improved.

The key word in the preceding discussion is the well-designed overlay: What does this mean? On the basis of the classical pavement design approach, a well-designed overlay is one that is designed using the most representative (a) material properties of the existing pavement structure and (b) traffic load distributions throughout the expected design life. The evaluation of materials properties has been a great concern for the pavement design community for a long time. Very often, the engineer asks, What is the most appropriate way of evaluating material properties that is consistent with current design procedures?

BACKGROUND

Historically, the in situ resilient moduli of pavement layers have been evaluated from various nondestructive deflection testing devices. Currently, the falling weight deflectometer (FWD) is considered the best NDT device available to simulate actual traffic loading conditions. Even though the FWD is the best NDT device available, it still does not fully represent the loading conditions generated by a moving truck. The major discrepancies exist in the differences between the frequency content of the FWD signal (2 to 100 Hz) and the signal imparted from a truck moving at 50 to 60 mph (1 to 20 Hz). It is well known that the resilient modulus of the asphalt concrete material is highly dependent on the frequency of the loading (*1*). Therefore, the moduli values, backcalculated from FWD deflections, may be different from those that are backcalculated from truck loading data.

In recent years, several backcalculation automated search routines have been developed that minimize the error between the measured and calculated surface deflection bowls (*2–5*). Christison and Shields developed an iterative procedure by which layer moduli can be evaluated from pavement instrumentation for a two-layer pavement system (*6*). They used surface deflections and the strains at the bottom of the asphalt concrete layer to backcalculate the modulus of the asphalt and the subgrade under truck and nondestructive testing equipment. The study presented in this paper will focus on backcalculating layer moduli for four-layer pavement systems from measurements collected by strain gauges, multidepth deflectometers (MDD), and surface deflection sensors.

DESCRIPTION OF TEST SECTIONS

As a part of the research project, In Situ Instrumentation for Resilient Moduli Measurements, various types of pavement instrumentation were selected for field evaluation under actual truck loading (*7*). Three different types of strain gauges were selected to measure the longitudinal strain at the bottom of the asphalt concrete layer, including the Kyowa H gauge, the Dynatest H gauge, and instrumented core gauges. The multidepth deflectometer device was selected to measure the vertical deflection throughout the depth of the pavement structure (*8*).

The gauges were installed at the test track at Pennsylvania State University in two newly constructed sections (*7*). The structures of the constructed sections consisted of a thin section (6 in. of asphalt concrete over 8 in. of crushed aggregate base and 12 in. of subbase) and a thick section (10 in. of asphalt concrete over 10 in. of crushed aggregate base and 12 in. of subbase). The loading of the test sections was conducted with a single-axle tractor and tandem-axle trailer combination. The experimental plan for field testing is shown in Table 1. The test sections were also tested by the FWD.

P. E. Sebaaly, Department of Civil Engineering, University of Nevada, Reno, Nev. 89557. N. Tabatabaee, Pennsylvania Transportation Institute, Research Building B, University Park, Pa. 16802. T. Scullion, Texas Transportation Institute, Texas A&M University, College Station, Tex. 77843.

TABLE 1 Experimental Plan for Field Testing

Variable	Levels
Pavement section	Thin and thick
Load	Empty, intermediate, fully loaded
Tire pressure	100, 125 psi
Speed	20, 35, 50 mph
Replicate measurements	4

DESCRIPTION OF GENERALIZED MODULUS BACKCALCULATION PROCEDURE

A key requirement of this study was to be able to convert the output of pavement instrumentation under known loadings to appropriate layout moduli. The instrumentation to be used includes strain gauges and multidepth deflectometers. The conversion will be made using calculations made with linear elastic theory. A search routine is used to minimize error between the measured readings (strains or deflections) and the computed values. In the search routine, the solution is the set of layer moduli that produces the best fit between measured and calculated values. The scope of the system developed by Uzan et al. (*9*) was expanded to permit strain bowl and depth deflections, in addition to surface deflection, to be used in the backcalculation process.

The procedure is designed to find the set of parameters that correspond to the best fit of the measured pavement response (i.e., strain or deflection). The best fit is achieved by minimizing the error between the measured and the calculated pavement response curves. The objective function can, therefore, be written as

Minimize

$$\sum_{i=1}^{n} \varepsilon^2 = \sum_{i=1}^{n} \left[\frac{W_i^m - W_i^c}{W_i^m} \right] W_{ei}$$

where

ε^2 = squared error,
W_i^m = measured pavement response (i.e., deflection or strain) at distance i away from load,
W_i^c = calculated pavement response (i.e., deflection or strain) at distance i away from load,
n = number of distances away from load, and
W_{ei} = user-supplied weighing factor for distance i.

INPUTS TO GENERALIZED BACKCALCULATION PROCEDURE

The generalized backcalculation procedure permits flexible input of measured pavement responses. Measured values can be taken from various sensors, which is the case with surface or depth deflection sensors, or from multiple loading positions on a single sensor.

Strain Gauge

Strain gauges are typically installed at the bottom of the asphalt layer. Therefore, to analyze strain gauge data, it is necessary to calculate the strains induced as the wheel approaches the single gauge. An example of this can be seen in Figure 1; the tensile strains at offsets of 0, 6, 12, 18, 24, and 30 in. are extracted from the strain pulse. Using these offsets and the relevant gauge depth (6 in.), a data base of strain values will be generated for the user-supplied range of acceptable moduli. The measured tensile strains, as shown in Figure 1, are then compared with the calculated strains in the data base.

Multidepth Deflectometer

Multidepth deflectometers can be located at various depths within each layer of the pavement. However, these devices present an added complication because they measure the relative movement between the sensor location and an anchor buried at some depth (in this project, 73 in.) below the surface. The anchor movement must be taken into consideration. This is done within the generalized backcalculation procedure by calculating the theoretical anchor movement for each combination of layer moduli within the data base. Then, on entering the pattern search, the theoretical relative deflection (theoretical deflection at depth minus theoretical anchor movement) can be compared with the MDD readings.

BACKCALCULATION OF LAYER MODULI

To evaluate the layer moduli for the test sections, pavement responses were measured using FWD and truck loading. Multiple backcalculation analyses were conducted under each loading condition.

Backcalculation of Layer Moduli from FWD Data

The FWD was positioned directly over the multidepth deflectometer, and drops were made at three different load levels. Deflections were simultaneously measured on the surface and at MDD locations; the results are shown in Tables 2 and 3.

Offset Distance (ins)	0	6	12	18	24	30
Tensile Strain (microstrain)	95	82	40	-10	-40	-40

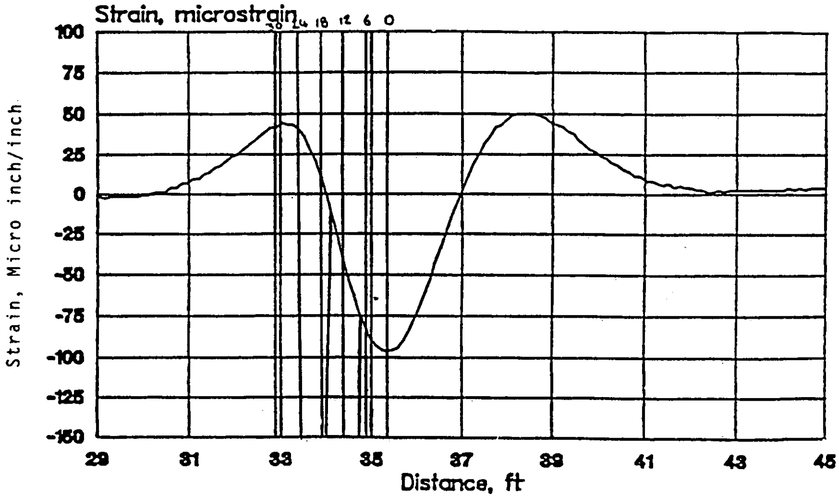

FIGURE 1 Typical strain response from strain gauge at bottom of asphalt concrete layer: thin section, Dynatest, Station 9, 50 mph.

TABLE 2 FWD and MDD Test Results From Thin Pavement Section

Drop #	Load (lbs)	FWD Deflections (mils)						MDD (mils)		
		0	12	24	32.5	48	-12	6.5	14.5	26.5
1	7,310	12.68	8.46	4.74	3.03	1.26	8.54	11.19	7.64	2.57
2	8,606	15.47	10.51	5.94	3.74	1.52	10.59	13.68	9.78	3.18
3	10,271	18.54	12.64	7.21	4.53	1.85	12.79	16.67	12.04	3.81

TABLE 3 FWD and MDD Test Results From Thick Pavement Section

Drop #	Load (lbs)	FWD Deflections (mils)						MDD (mils)			
		0	12	24	32.5	48	-12	3	10	20	32
1	7,495	5.51	3.15	1.97	1.34	1.26	3.38	4.74	3.71	2.05	1.09
2	8,698	6.85	3.98	2.44	1.65	1.52	4.33	5.81	4.58	2.56	1.36
3	10,271	8.07	4.84	2.95	2.01	1.10	5.24	6.91	5.54	3.02	1.59

Backcalculation of In Situ Moduli from Surface Deflections

Backcalculation of in situ moduli from surface deflections consisted of the traditional backcalculation of layer moduli from surface deflections. The results of this analysis are shown in Table 4. These results indicated extremely low values for the subbase and subgrade layers of the thin sections. The large difference between the subbase and subgrade moduli of the two sections is unusual because both sections are within 100 ft of the test track.

Backcalculation of In Situ Moduli from MDD Deflections

Backcalculation of in situ moduli from MDD deflections consisted of backcalculating the layer moduli from the MDD deflections. Table 5 summarizes the layer moduli values obtained from this analysis.

The data in Tables 4 and 5 show that there are major disagreements between the backcalculated moduli from surface deflections and those calculated from MDD deflections. However, both analyses agree that the subbase on the thin section is very weak.

Modulus Backcalculation Using Sensor Data Collected Under Truck Loading

The generalized backcalculation procedure was used to process the strain basins and MDD deflections under truck loading to backcalculate the in situ resilient moduli. All of the backcalculation analyses are conducted on the basis of measurements under the single drive axle.

Backcalculation of In Situ Moduli from Measured Strain Basins

Table 6 summarizes the values of the backcalculated moduli as a function of the truck speed and axle load for the thick section. The data show good agreement between the two types of gauges (i.e., Kyowa and core gauges). The effect of speed on the moduli of the asphalt concrete layer (E_1) is very noticeable under all load levels. The effect of load magnitude on the backcalculated moduli is insignificant, which indicates that the nonlinearity of the base and subgrade materials is insignificant.

Table 7 summarizes the backcalculation results of the thin section on the basis of measurements from all three types of gauges. In this case, there is less agreement among the results of the various gauges compared with the thick section data. The effect of truck speed on the backcalculated moduli of the asphalt concrete layer is very significant, whereas the effect of load level is insignificant.

Backcalculation of In Situ Moduli from Measured MDD Deflections

As discussed earlier in the paper, one MDD was installed in each test section (thick and thin). The MDD in the thick section had four modules at depths of 3, 10, 20, and 32 in.;

TABLE 4 Layer Moduli Backcalculated Using Surface Deflections

Pavement	AC Modulus (ksi)	Base Modulus (ksi)	Subbase Modulus (ksi)	Subgrade Modulus (ksi)
Thin	301	67	7	6
Thick	271	81	76	22

TABLE 5 Layer Moduli Backcalculated Using MDD Deflections

Pavement	AC Modulus (ksi)	Base Modulus (ksi)	Subbase Modulus (ksi)	Subgrade Modulus (ksi)
Thin	455	25	6	25
Thick	402	29	34	46

TABLE 6 Backcalculated Moduli for Thick Section Under Single-Drive Axle, on Basis of Strain Measurements

Speed (mph)	Load (k)	Station (Strain gauge)	E_1 (ksi)	E_2 (ksi)	E_3 (ksi)	E_4 (ksi)
50	20	6 (k)	545	10	7	60
		12 (c)	461	10	5	60
	12	6 (k)	556	10	7	60
		12 (c)	640	10	13	60
	8	6 (k)	534	10	7	60
		12 (c)	641	10	13	60
35	20	6 (k)	350	10	5	44
		12 (c)	366	10	5	60
	12	6 (k)	347	10	5	39
		12 (c)	349	10	5	41
	8	6 (k)	393	10	11	60
		12 (c)	361	10	5	60
20	20	6 (k)	258	10	16	60
		12 (c)	230	10	11	60
	12	6 (k)	214	18	40	60
		12 (c)	200	22	40	60
	8	6 (k)	200	21	40	60

k = Kyowa gauge

c = core gauge

and the MDD in the thin section had three modules at depths of 6.5, 14.5, and 26.5 in. In the case of the MDD, the peak deflections at each level were used to backcalculate the in situ moduli. Tables 8 and 9 summarize the in situ moduli for the thick and thin sections, respectively.

Backcalculation of In Situ Moduli from Combination of Measured Strain Basins and MDD Deflections

The data set chosen for evaluation is shown in Table 10. These data were measured on the thick pavement section using a fully loaded truck with a single-drive axle and 125 lb/in.^{2} tire pressure. The data represent the peak depth deflections and strain bowls (Kyowa gauge) under single axle (19.6 kips per axle).

A four-layer structure was assumed, as shown in Figure 2. The procedure consists of using the generalized backcalculation method as follows:

1. Fix the E_1 value calculated from the strain bowl; use the MDD data to calculate E_2, E_3, and E_4 values.
2. Fix the E_2, E_3, and E_4 values calculated in Step 1; use the strain data to calculate an E_1 value.

Steps 1 and 2 are repeated until the error between measured and computed deflection and strain values are reduced to an acceptable level. The results of this analysis are shown in Table 11. At each speed, two iterations were used. The surfacing modulus showed some distinct speed effects; the base and subbase were weak, and the subgrade was relatively strong.

IMPACT OF VARIOUS MODULI VALUES

Analysis of the pavement response data indicates that the backcalculated layer moduli are affected by various factors, including

1. Type of loading—FWD or truck,
2. Measured pavement response—surface deflection, MDD, and strain gauges, and
3. Analysis approach—single response or multiple responses.

TABLE 7 Backcalculated Moduli for Thin Section Under Single-Drive Axle, on Basis of Strain Measurements

Speed (mph)	Load (k)	Station (Strain gauge)	E_1 (ksi)	E_2 (ksi)	E_3 (ksi)	E_4 (ksi)
50	20	30 (d)	758	10	5	10
		29 (k)	675	10	5	10
		12 (c)	1170	10	5	18
	12	30 (d)	900	12	5	10
		29 (k)	896	10	5	10
		12 (c)	1500	44	5	35
	8	30 (d)	900	15	5	10
		29 (k)	764	10	5	10
		12 (c)	1500	23	5	38
35	20	30 (d)	511	10	5	10
		29 (k)	425	10	5	10
		12 (c)	828	10	5	10
	12	30 (d)	700	10	5	10
		29 (k)	568	10	5	10
		12 (c)	1368	10	8	60
	8	30 (d)	855	10	5	10
		29 (k)	703	10	5	10
		12 (c)	1339	10	6	60
20	20	30 (d)	329	10	10	60
		29 (k)	298	10	8	60
		12 (c)	368	10	12	60
	12	30 (d)	329	14	40	60
		29 (k)	302	10	10	60
		12 (c)	420	20	40	60
	8	30 (d)	---	--	--	--
		29 (k)	233	19	15	10
		12 (c)	431	10	15	50

d = Dynatest gauge
k = Kyowa gauge
c = core gauge

TABLE 8 Backcalculated Moduli for Thick Section Under Single-Drive Axle, on Basis of MDD Measurements

Speed (mph)	Load (k)	E_1 (ksi)	E_2 (ksi)	E_3 (ksi)	E_4 (ksi)
50	20	363	10	24	50
35	20	340	10	23	50
20	20	200	12	23	50

TABLE 9 Backcalculated Moduli for Thin Section Under Single-Drive Axle, on Basis of MDD Measurements

Speed (mph)	Load (k)	E_1 (ksi)	E_2 (ksi)	E_3 (ksi)	E_4 (ksi)
50	20	200	12	9	47
	12	900	10	13	41
	8	900	25	25	50
35	20	551	10	9	50
	12	900	12	19	41
	8	900	11	18	50
20	20	201	11	9	44
	12	900	10	11	41
	8	900	13	22	50

TABLE 10 Strain and Deflection Data Used in Analysis

MPH	MDD DEPTHS (in.) 3	20	32	STRAIN OFFSET (in.) 0	6	12	24
20	8.46	3.36	1.56	155.4	100.7	10.7	-45.4
35	7.50	2.81	1.34	120.8	99.6	38.7	-41.5
50	6.98	2.74	1.37	79.9	69.1	40.9	-23.5

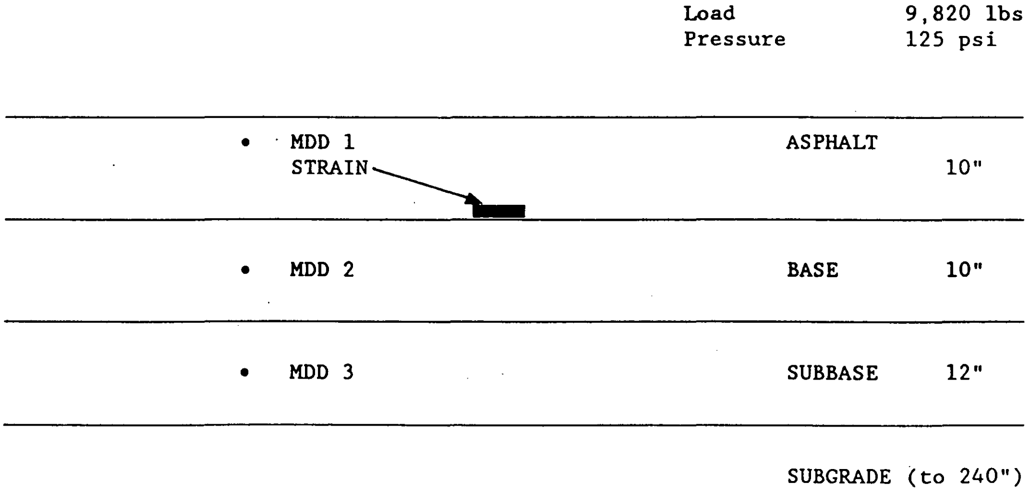

FIGURE 2 Setup of MDD and strain gauge for moduli evaluation of pavement layers.

TABLE 11 Layer Moduli Values Backcalculated Using Deflection and Strain Data

Speed (mph)	Description	MDD (mils) Depths			Max. Strain	Moduli (ksi)				No. Iteration
		3"	20"	32"	(microstrain)	E_1	E_2	E_3	E_4	
20	Measured	8.46	3.36	1.56	155.4	291	9	19	44	2
	Calculated	8.46	3.36	1.56	171.0					
	% Error	0.0	0.0	0.0	-10.0					
35	Measured	7.50	2.81	1.34	120.8	414	8	21	48	2
	Calculated	7.31	2.74	1.34	132.5					
	% Error	2.6	2.4	0.0	-9.7					
50	Measured	6.98	2.74	1.37	79.9	751	5	14	36	2
	Calculated	6.79	2.69	1.36	88.8					
	% Error	2.7	1.7	0.6	-11.2					

One fundamental way to evaluate the significance of the differences between the moduli values from the various analyses is to study their influence on the end product, i.e., equivalent single axle loads (ESALs). It is very common that the backcalculated moduli will be used in either of the following two analyses:

1. To evaluate the capacity of the existing pavement section using the AASHTO design guide (*10*), or
2. To evaluate the capacity of the existing pavement section using a mechanistic-empirical approach (*11*).

The end product of the two analyses is the number of ESALs that the pavement section can handle before the ultimate failure of the pavement.

The AASHTO design guide procedure consists of evaluating the structural number (SN) of the existing pavement section and determining the ESALs for specific values of re-

TABLE 12 Impact of Various Backcalculated Moduli for Thin Sections

Method of Backcalculation Analysis	Standard Number (SN)	AASHTO ESAL's (millions)	Critical Strains (Micro)	Cracking ESAL's (millions)
1. FWD Load & Surface Deflection	4.5	2.4	168	3.2
2. FWD Load & MDD Deflections	4.3	30.0	208	1.1
3. Truck Load & Strain Gauge, 50 mph	3.6	2.0	198	0.9
4. Truck Load & Strain Gauge, 35 mph	3.4	1.7	277	0.5
5. Truck Load & Strain Gauge, 20 mph	3.3	31.0	325	0.4
6. Truck Load & MDD, 50 mph	4.4	50.0	139	2.4
7. Truck Load & MDD, 35 mph	5.0	50.0	132	2.8
8. Truck Load & MDD, 20 mph	4.3	50.0	141	2.2
Mean		27.1		1.7
Standard Deviation		20.9		1.0
Coefficient of Variation (%)		77		59

liability, standard deviation, loss of pounds per square inch, and subgrade moduli. In this analysis, the following values were used:

- Reliability, 95 percent;
- Standard deviation, 0.35; and
- Loss of pounds per square inch, 1.5.

On the basis of the thickness of the pavement section and the backcalculated moduli, the SN value was evaluated for each combination of pavement type (i.e., thin or thick) and for each method of backcalculation analysis. When using the AASHTO nomograph, a maximum value for the effective roadbed soil resilient modulus of 40,000 lb/in.^{2} and a maximum value of 50 million ESALs were used.

The second analysis consisted of evaluating the capacity of the existing pavement section using a mechanistic-empirical approach. The following fatigue performance equation, developed by Finn et al., was selected for this analysis (*11*):

$$\log N_f = 15.947 - 3.291 \log\left(\frac{\varepsilon}{10^{-6}}\right) - 0.854 \log\left(\frac{E}{10^3}\right)$$

where

N_f = number of load applications required to cause 10 percent Class 2 cracking of wheel tracks;
ε = tensile strain at bottom of asphalt concrete layer; and
E = resilient modulus of asphalt concrete layer.

The tensile strains at the bottom of the asphalt concrete layer were evaluated from the multilayer elastic solution, and the resilient modulus value was obtained from the backcalculated moduli.

The data shown in Tables 12 and 13 indicate that there are significant differences among the predicted ESALs from various methods of backcalculation analyses. Figures 3 and 4 show the distribution of AASHTO and cracking ESALs for the thin and thick sections, respectively.

TABLE 13 Impact of Various Backcalculated Moduli for Thick Sections

Method of Backcalculation Analysis	Standard Number (SN)	AASHTO ESAL's (millions)	Critical Strains (Micro)	Cracking ESAL's (millions)
1. FWD Load & Surface Deflection	6.1	50	72	57.1
2. FWD Load & MDD Deflections	8.0	50	93	17.6
3. Truck Load & Strain Gauge, 50 mph	5.7	50	101	10.3
4. Truck Load & Strain Gauge, 35 mph	4.7	50	146	4.5
5. Truck Load & Strain Gauge, 20 mph	5.1	50	166	3.8
6. Truck Load & MDD, 50 mph	6.1	50	127	6.9
7. Truck Load & MDD, 35 mph	5.9	50	134	6.1
8. Truck Load & MDD, 20 mph	5.1	50	188	3.2
9. Truck Load, MDD, & Strain Gauge, 50 mph	6.5	50	82	15.6
10. Truck Load, MDD, & Strain Gauge, 35 mph	6.4	50	120	7.4
11. Truck Load, MDD, & Strain Gauge, 20 mph	5.5	50	155	4.3
Mean		50		12.4
Standard Deviation		0		14.8
Coefficient of Variation (%)		0		119
Excluding the FWD Load & Surface Deflection Analysis				
Mean				8.0
Standard Deviation				4.8
Coefficient of Variation				60

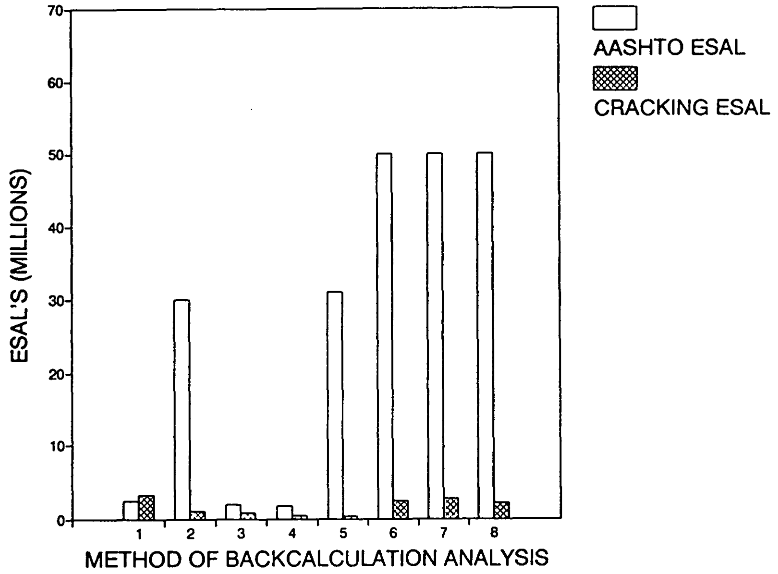

FIGURE 3 Distribution of predicted ESALs from various analyses, thin section (see Table 12 for method).

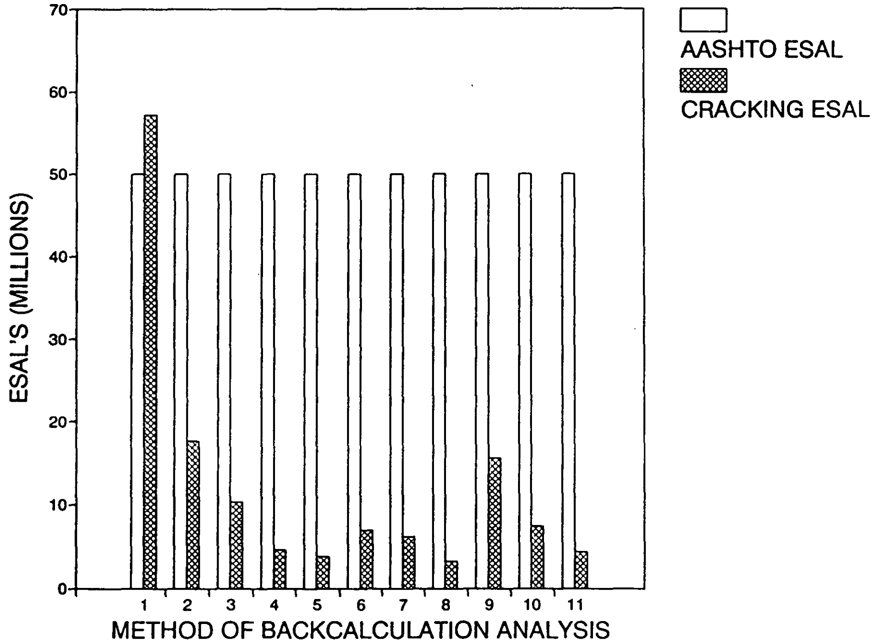

FIGURE 4 Distribution of predicted ESALs from various analyses, thick section (see Table 13 for method).

CONCLUSIONS AND RECOMMENDATIONS

On the basis of an appraisal of the backcalculated moduli from the various analyses, the following conclusions and recommendations can be made.

- The backcalculated moduli of all the pavement layers are significantly affected by the mode of loading (i.e., FWD or truck). The modulus of the asphalt concrete layer was reduced by 50 percent as a function of reducing the speed from 50 to 20 mph. The effect of truck speed on the granular and subgrade layers was insignificant.
- The effect of the magnitude of the axle load on the backcalculated moduli of all the pavement layers was insignificant. This observation indicates that for the data collected in this experiment and the methods of analyses used, the effect of the material's nonlinearity is very small.
- The combined analysis of strain and MDD data show that the speed has a significant effect on the modulus of the asphalt concrete layer. The backcalculated moduli from these com-

bined analyses have high merit because they satisfy two independently measured pavement response parameters (strains and depth deflections).

- The effect of the various backcalculation analysis on the predicted ESALs was very significant. The coefficients of variations of the predicted ESALs were 77, 59, and 119 percent for the AASHTO and cracking ESALs of the thin and thick sections, respectively. The coefficient of variation of the cracking ESALs on the thick section was dramatically improved by the removal of FWD load and surface deflection analysis.
- The FWD load and surface deflection backcalculation analysis has shown the closest agreement between the AASHTO ESALs and the cracking ESALs. However, the set of moduli generated from this analysis did not satisfy the independently measured depth deflections (Table 4).

On the basis of the findings of the research presented in this paper, it is almost impossible to produce one set of layer moduli that satisfies all of the pavement response parameters. The combined analysis of MDD deflections and strain gauge measurements represents a major step forward toward the appropriate solution. However, it does not represent the complete solution because it did not satisfy the FWD load and surface deflection case. In the meantime, it seems appropriate to use the FWD load and surface deflection analysis while the research for the perfect solution continues because it is the only analysis that provided a close agreement between the AASHTO and the cracking ESALs.

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