Nondestructive Pavement Evaluation: The Deflection Beam

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The prediction of the effects of vehicle motion on pavements is time dependent. Current design procedures, however, account for this motion as a sequence of equivalent static conditions reduced to passes or coverages. A solution to this problem was obtained by verifying the following hypothesis. A pavement system operated on by a vehicular input produces an output response. Relating the two is a time-dependent transfer function that contains within it the properties of the system. This function is obtained, in a mathematical sense, by using Laplace transformations without the need to simulate respective material performance or to determine values for preselected descriptors. The time-dependent transfer functions can be used to predict the response and the performance of a pavement system when it is subjected to an imposed load. The investigation was carried out by extending transfer function theory in connection with a finite convolution procedure to define the time-dependent transfer functions of a pavement. Moving trucks and aircraft were used in full-scale dynamic tests in service environments (six highway and two runway cross sections). It was shown that the time-dependent transfer functions obtained represent the characteristics of flexible pavements. Changes in parameters of the functions reflect changes in the performance and the condition of the pavement.

The major problem that faces the highway engineer today is not how to design and construct new pavements but how to evaluate, maintain, and upgrade existing pavement systems to meet today's demand for higher magnitudes of traffic loading and frequency.

The closing of a highway to permit the use of conventional destructive evaluation methods (such as test pits and plate load tests) may have catastrophic consequences. The need for rapid, nondestructive methods of pavement evaluation has been recognized in recent years (28,29), and different methods of nondestructive pavement evaluation have been developed (12,30,31). These methods, however, do not simulate actual traffic loading or take into account the complexity of the mechanism of pavement-subgrade interaction.

This paper introduces equipment for the rapid, nondestructive evaluation of pavement and a test procedure that was used at nine highway and airfield sites to measure flexible pavement deflections caused by the passage of a conventional vehicle.

DEVELOPMENT OF TESTING METHOD

The need for remedial measures to upgrade pavements so that they meet today's traffic demands has led many investigators to agree that a closer look must be taken at the materials that make up the pavement structure. Researchers concerned with fatigue failures have long recognized the need for a testing method that would simulate the action of traffic (8):

> Irrespective of the theoretical method of evaluation of load tests, there remains the important question as to what extent individual static load tests reflect the results of thousands of dynamic load repetitions under actual traffic. Tests have already indicated that various types of soils react differently and that the results of static load tests by no means bear a simple relation to pavement behavior.

In 1947, Campen and Smith (7), Hittle and Goetz (17), McLeod (20), and Phillipe (23) had all begun investigations of repeated-load tests on model pavement sections in which the number of load repetitions was on the order of 10. But these tests were destructive, time consuming, and costly, and experimentation with repeated-load testing in the conventional triaxial cell was soon recognized as a better method (32). Cyclic (repeated) plate load tests could only evaluate soil parameters under one set of conditions—those that existed at the time of testing—whereas critical soil conditions could be reproduced in the triaxial cell. Consequently, the effects of many different parameters (such as density, water content, degree of saturation, confining pressure, and deviatoric stresses) were soon being investigated (1,4,5,9,10,11,14,15,16,18,19,21,22,24,25,26,27).

Terrel and Awad (25) stressed the continuation of research to develop a newer theoretical technique and refine existing test procedures so that adequate material parameters could be obtained. Recently, investigators recognized that pavement deflection was one such technique, and a search was begun for a method of accurately predicting pavement deflection.

In 1970, Harr introduced the transfer function concept as a method of determining pavement parameters. Ali (33) applied transfer function theory to the study of flexible pavement under controlled laboratory conditions. Boyer and Harr, extending transfer function theory to in-service pavement systems, conducted field tests at Kirtland Air Force Base, New Mexico, and concluded that the characteristics of flexible pavements could be represented by a time-dependent transfer function (6). They were successful in their prediction of pavement deflections, but their method of testing was destructive.

In response to ambient conditions, volume changes cause pavement surfaces to curl and warp with time and location (13). Portions of the surface may therefore not be in contact with underlying materials when the pavement is subjected to vehicle loadings. Thus, any apparatus used to evaluate a pavement system must not alter the conditions that prevail before loading. All devices in use today—such as the Benkelman beam and vibrators—suffer from this shortcoming. In the Benkelman beam test procedure, the beam is set up next to a stationary load vehicle and the rebound of the pavement is measured as the vehicle moves away. Vibrators must seat the pavement before introducing steady-state vibrations. It should be noted that the nature of loading (the magnitude and frequency) of steady-state vibrators bears little resemblance to the transient input of an actual vehicle. Although Benkelman beams treat vehicle loads, they monitor only residual deflections after the pavement surface has been seated by vehicles at creep speeds.

If developed hardware is to gain widespread acceptance and use, it must (a) be inexpensive; (b) be operable with minimal or no training on the part of the user; (c) be lightweight, self-contained, and mobile; and (d) be able to accommodate available vehicles at the test site.

FIELD INVESTIGATION

The field phase of this study had as its objective the development, design, and use of rapid, nondestructive techniques for obtaining the data needed to determine

1. A time-dependent deflection response function for pavement,
2. An equivalent forcing function for the vehicle, and
3. The attenuation of energy in the pavement section.

Boyer's work at Kirtland Air Force Base, New Mexico (6), provided the technical guidance for the early phases of these investigations. Boyer reported that accurate deflection measurements could be obtained by using linear variable differential transformer (LVDT) gauges embedded in the pavement system. He also noted that accelerometer gauges are inadequate for the task because of their slow response and electrical drift. Based on Boyer's tests, it was decided to use LVDTs with an accuracy of 0.0025 mm (0.0001 in).

The initial LVDT installations were made on a line perpendicular to the wheel path at a gravel pit road near the West Lafayette, Indiana, campus of Purdue University. The objectives of these installations were (a) to determine the width of the dynamic deflection basin of the pavement section for a wide variety of trucks that enter the gravel pit plant and (b) to help in designing and checking the nondestructive measurement system. Results of this test program indicated that the width of the deflection basin extends less than 1.5 m (5 ft) laterally from the outside edge of the wheel for highway pavements.

The time-dependent deflection response functions of the pavement were recorded under varying ambient conditions for a wide variety of truck gear configurations by using the installed LVDT gauges at the gravel pit road. Analyses of these results led to the construction of a lightweight aluminum beam that carried six LVDTs (so that there would be no need to install gauges in subsequent tests). Figure 1 shows a schematic representation of the LVDT beam. It should be emphasized that measurements made with the LVDT beam are nondestructive.

The LVDT beam was first placed over the installed gauges, and pavement deflections were recorded by both systems. Figure 2 shows a plot of pavement deflections recorded by the LVDT beam versus those recorded by the installed LVDT gauges at the same lateral distances from the edge of the tire. Deflection measurements made by the beam were also checked against data from two other sets of installed LVDT gauges at Eglin Air Force Base, Florida. In those tests, an F-4 aircraft with a 111.2-kN (25 000-lb) wheel load was used as a loading vehicle, and tests were performed on a parking area as well as on an active taxiway. Pavement deflections at the same lateral distances from the wheel path showed the same relative equivalence as those shown in Figure 2.

Scope

The field investigations were conducted at seven sites. Locations of four of those sites are given below (1 m = 3.3 ft):

Site	Road	Indiana Location
1	Gravel Pit Road	West Lafayette, entrance to gravel plant after railroad bridge (installed LVDT gauges 45 m inside the gate)
2	Happy Hollow Road	West Lafayette, 182 m north of Happy Hollow Park entrance
3	North 9th Street	Lafayette, at exit of a small road leading to an old bridge
4	County Road 200 North	West Lafayette

Cross-sectional characteristics of these four sites are shown in Figure 3. Information about the other three

Figure 1. LVDT beam.

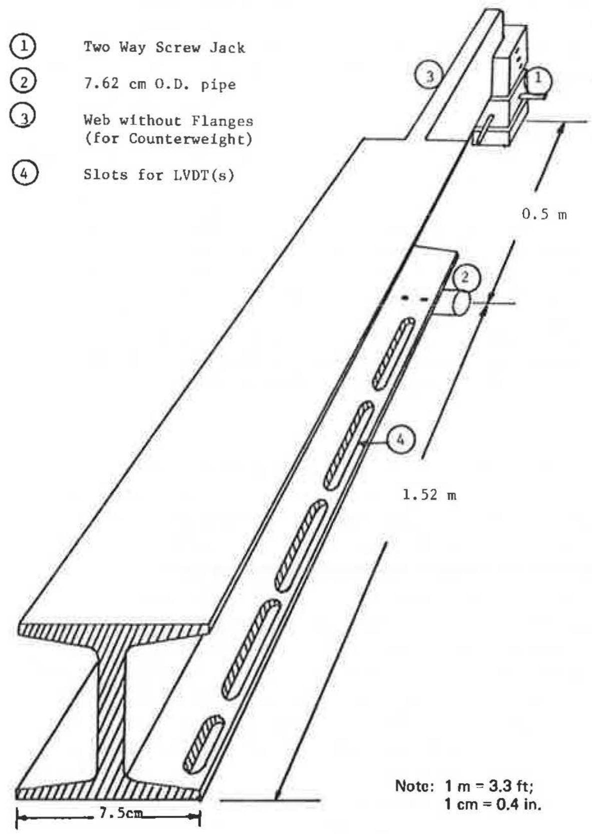


Figure 2. Pavement deflection responses of LVDT beam and LVDT gauges.

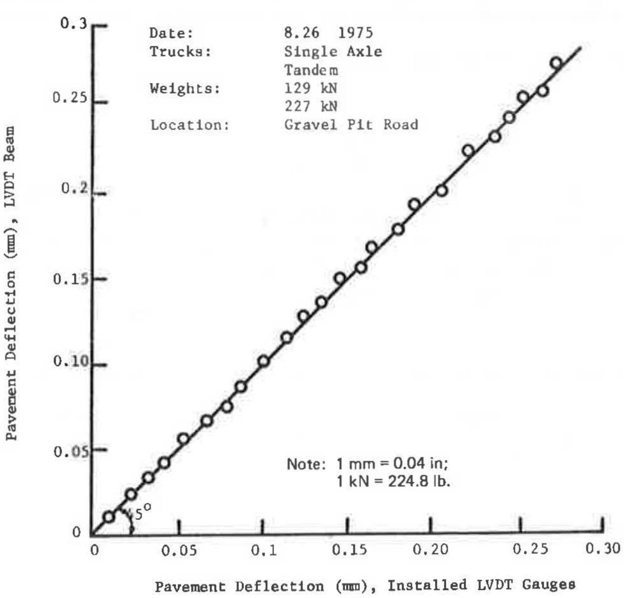
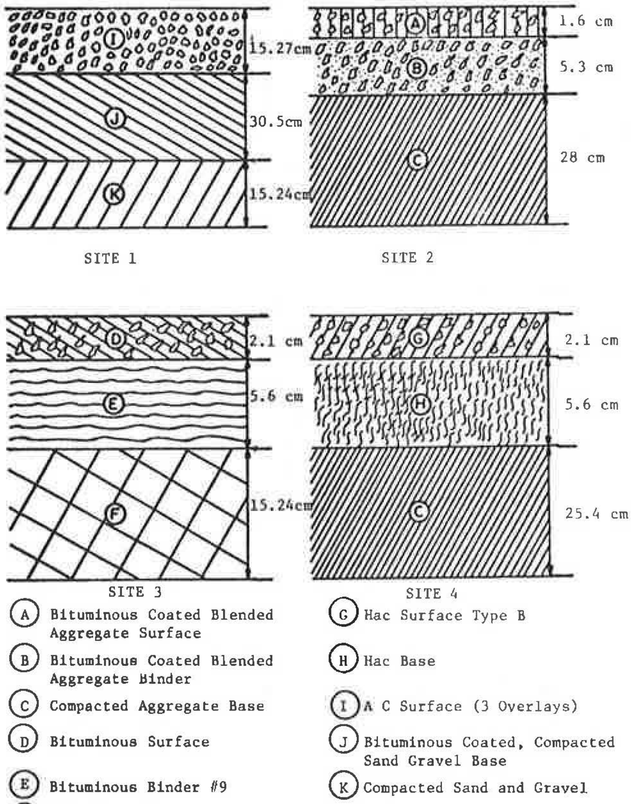


Figure 3. Cross sections of sites 1, 2, 3, and 4.



Note: 1 cm = 0.4 in.

sites may be obtained elsewhere (3). Investigations were designed and tests were performed to account for various factors that were thought to influence the performance and response of pavement. These factors include (a) ambient conditions (Table 1), (b) gear configuration (Table 2), (c) load variation (Table 2), (d) tire pressure (Table 2), and (e) load repetitions (Table 3).

Signature

The signature of a vehicle is defined here as the pavement's time-dependent deflection response function that is measured or calculated at the edge of the tires of the loading vehicle. The symbol for the signature is y(0,t).

The overhang of the LVDT beam and the bulge of the side of the tire prevented the direct measurement of vehicle signature. However, pavement deflections were measured at different lateral distances from the edge of the tire. A study of the deflection basin at the embedded LVDT gauges determined that the deflection would follow the expression

$$y(x,t) = y(0,t)\exp[-(1/B)x^N] \quad (1)$$

where

y(x,t) = measured deflection at lateral distance x from the tire edge at time t,
y(0,t) = calculated deflections [signature at the tire edge (x = 0) and at time t],
x = lateral distance from the tire edge to the LVDT gauge at which y(x,t) was measured, and
B and N = parameters of the equation.

The LVDT beam was placed at the side of the embedded LVDT gauges at site 1 (gravel pit road). The loading vehicle was then driven so that the intermediate and rear tires passed over one of the embedded gauges. Pavement deflections were recorded under the tire and at various gauge positions on the LVDT beam. The vehicle signature was calculated by using Equation 1.

Table 1. Ambient test conditions.

Date	Time	Temperature (°C)	Wind (km/h)	Sky	Precipitation
3/12/75	9:00 a.m.-1:00 p.m.	2.8	North at 16	Cloudy	1 d after rain
3/13/75	9:00 a.m.-1:00 p.m.	-3.9	North at 11	Cloudy	Snowing
4/10/75	9:00 a.m.-2:00 p.m.	-2.2	Southwest at 16	Cloudy	Snowing
4/12/75	9:00 a.m.-2:00 p.m.	4.4	South at 16	Cloudy	2 d after snow
8/26/75	9:00 a.m.-3:00 p.m.	23.9	Southwest at 16	Partly cloudy	1 d after rain
10/10/75	10:00 a.m.-3:00 p.m.	7.2	North at 13	Clear	3 d after rain
1/5/76	9:00 a.m.-1:00 p.m.	-24.4	North at 16	Clear	1 d after snow
1/10/76	9:00 a.m.-11:00 a.m.	-23.3	North at 13	Clear	1 d after snow
3/17/76	9:00 a.m.-2:00 p.m.	-5.6	Southeast at 8	Clear	2 d after snow
5/13/76	9:00 a.m.-1:00 p.m.	17.8	Northwest at 16	Partly cloudy	5 d after rain
7/30/7	9:00 a.m.-1:00 p.m.	25.6	Southwest at 13	Partly cloudy	Hours after rain
8/12/76	9:00 a.m.-4:00 p.m.	26.7	South at 13	Partly cloudy	5 d after rain
9/13/76	12:00 n.-1:00 p.m.	26.7	Southwest at 16	Clear	10 d after rain

Note: 1°C = (1°F - 32)/1.8; 1 km = 0.62 mile.

Table 2. Data for truck types at site 1.

Gear Configuration	Gross Load (kN)		Speed Range (km/h)	Tire Pressure Range (kPa)
	Empty	Loaded		
Double tandem	111	325	18-40	483-621
Tandem	89	222	10-40	517-689
Single axle	36	89	16-48	517-621
Automobile	18	19	6-16	138-172
Pickup	27	40	16-24	172-241
Concrete truck	133	289	16-32	552-689
Tandem	93	231	16-48	483-695

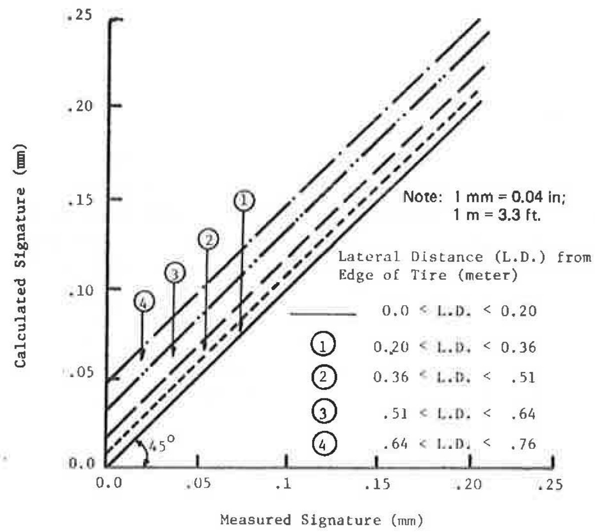
Note: 1 kN = 225 lb; 1 km = 0.62 mile; and 1 kPa = 0.145 lbf/in^2.

Table 3. Average count of load repetitions at sites 1, 2, 3, and 4.

Site	Average Load Repetition[a]	Vehicle Type	Counting Days
1	200 000	90 percent trucks[b] 10 percent automobiles	Monday, Wednesday, Friday[c]
2	250 000	5 percent trucks 95 percent automobiles	Monday, Wednesday, Saturday
3	300 000	10 percent trucks 20 percent pickups 70 percent automobiles	Monday, Wednesday, Saturday
4	200 000	5 percent trucks 15 percent pickups 80 percent automobiles	Monday, Wednesday, Saturday

[a] Number of wheels that passed over one point in the pavement.
[b] Checked at the scale with the bookkeeper of the gravel road plant.
[c] Plant closes over weekends.

Figure 4. Calculated versus measured signature at site 1.



The region between the straight lines shown in Figure 4 designates the locus of the pairs of calculated and measured signatures for various lateral positions of loading vehicles. The solid line represents the correspondence between the measured and calculated signatures within the accuracy of the measurements. This last condition was found to hold for all tests when the intermediate and rear tires of the loading vehicles passed within 20 cm (8 in) of the front of the LVDT beam. Discrepancies between calculated and measured values were noted for vehicle paths at greater lateral distances.

Figure 5 shows typical measured deflections and calculated signature as a function of time at different lateral distances from the wheel path. Figure 6 shows measured and calculated deflections as a function of lateral distances.

The values of the parameters N and B of Equation 1 were calculated for sites 1 through 7 and are given in Table 4. Figure 7 shows plots of the values of N (to an arithmetic scale) against the corresponding values of B (to a logarithmic scale) for sites 1, 2, 3, and 4. The

Figure 5. Typical measured deflection and calculated signature (G_o) versus time for standard highway truck at site 2.

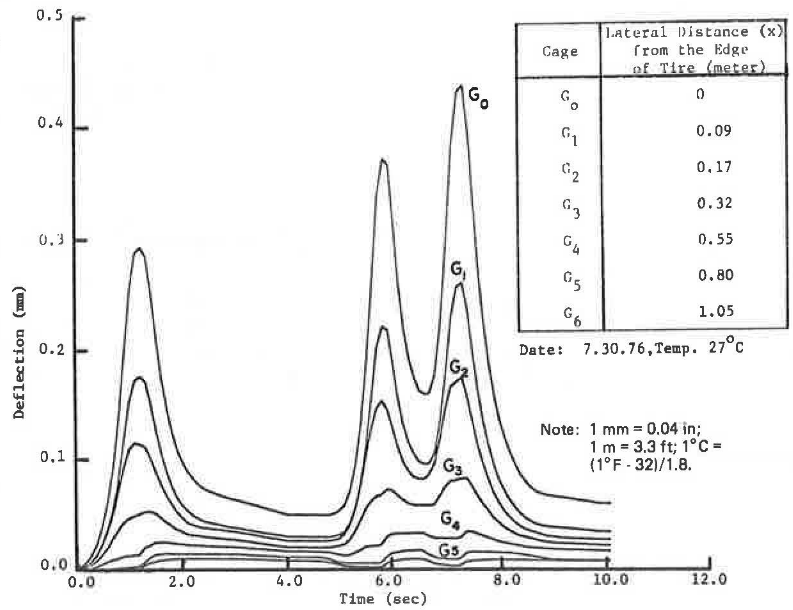


Figure 6. Measured and calculated peak deflection versus lateral distance for standard highway truck at site 2.

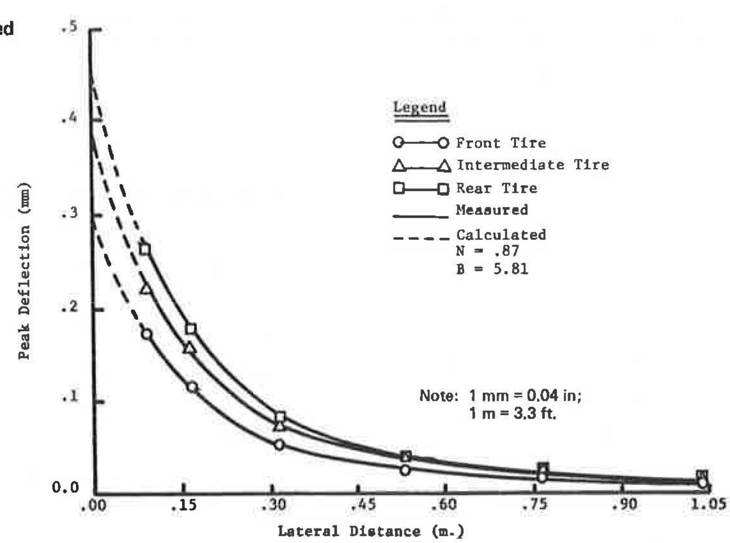


Figure 7. N versus log B for sites 1, 2, 3, and 4.

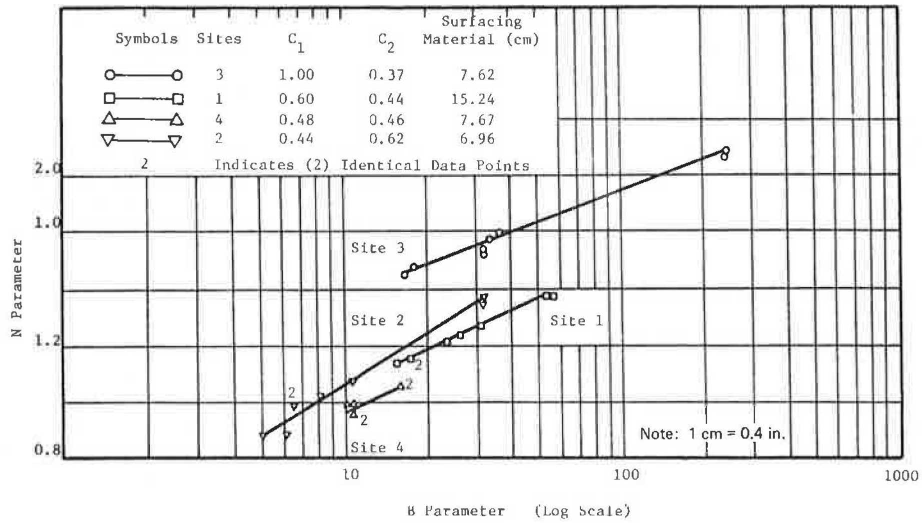


Table 4. Data for standard highway truck at all seven sites.

Site	Date	Air Temperature (°C)	Wheel Load (kN)			Peak Deflection (mm)			Vehicle Velocity (m/s)	Deflection Basin Parameters	
			Front	Intermediate	Rear	Front	Intermediate	Rear		N	B
1	8/26/75	24	29	30	30	0.17	0.17	0.17	0.81	1.26	31.64
		24	29	30	30	0.17	0.17	0.17	0.86	1.26	31.82
	1/05/76	-24	29	30	30	0.00	0.00	0.00	0.82	-	-
		-24	29	30	30	0.00	0.00	0.00	0.88	-	-
	3/17/76	-5.6	28	39	42	0.13	0.18	0.19	1.08	1.38	53.30
		-5.6	28	38	42	0.13	0.18	0.19	0.99	1.38	52.28
	5/13/76	17.8	29	37	39	0.14	0.19	0.19	0.77	1.22	26.28
		17.8	29	37	39	0.14	0.19	0.19	0.72	1.22	23.62
	7/30/76	25.6	30	38	39	0.17	0.21	0.21	1.09	1.14	17.25
		25.6	30	36	41	0.17	0.20	0.22	1.27	1.15	17.04
	9/13/76	26.7	20[a]	12	16	0.14	0.08	0.11	0.67	1.128	15.62
		26.7	4[b]	-	4	0.03	-	0.02		1.13	15.60
2	8/25/75	27.8	28	32	31	0.26	0.29	0.28	0.95	1.01	8.46
		27.8	29	33	30	0.34	0.39	0.35	1.10	1.07	10.70
	1/05/76	-24	28	31	30	0.00	0.00	0.00	0.80	-	-
		-24	28	32	29	0.00	0.00	0.00	0.89	-	-
	3/17/76	-5.6	31	35	36	0.30	0.34	0.35	0.91	1.37	31.95
		-5.6	31	37	37	0.29	0.34	0.35	0.80	1.34	32.24
	5/13/76	20	31	36	35	0.40	0.46	0.43	0.77	0.99	6.54
		20	31	36	35	0.40	0.46	0.43	0.91	0.99	6.54
	7/30/76	26.7	28	36	36	0.25	0.49	0.50	0.91	0.87	5.81
		26.7	28	35	37	0.25	0.46	0.51	0.77	0.88	6.75
3	8/26/75	24	27	33	34	0.83	1.02	1.05	1.01	1.60	37.29
		24	27	34	37	0.68	0.92	0.92	0.34	1.57	34.67
	1/5/76	-24	29	35	36	0.00	0.00	0.00	1.10	-	-
		-24	29	35	36	0.00	0.00	0.00	0.58	-	-
	3/17/76	-5	29	39	44	0.26	0.34	0.39	0.63	1.86	241.39
		-5	29	39	44	0.26	0.34	0.39	0.63	1.88	252.09
	5/13/76	20	29	39	39	0.59	0.78	0.78	0.78	1.52	32.01
		20	29	40	38	0.62	0.84	0.80	0.74	1.53	32.39
	7/30/76	27	31	35	43	0.96	1.13	1.37	1.03	1.45	16.77
		27	31	35	44	0.86	0.99	0.67	1.27	1.48	18.28
4	8/25/75	28	25	36	32	0.82	0.98	0.87	0.89	1.05	16.15
		28	25	36	36	0.82	0.97	0.87	0.95	1.05	16.16
	1/5/76	-24	29	36	36	0.00	0.00	0.00	0.28	-	-
		-24	29	35	36	0.00	0.00	0.00	1.26	-	-
	5/13/76	20	29	40	41	0.96	1.30	1.30	0.84	0.99	10.11
		20	29	39	39	0.98	1.32	1.33	0.83	0.99	10.64
	7/30/76	27	31	36	44	1.01	1.15	1.41	0.86	0.93	10.81
		27	31	36	44	1.01	1.16	1.41	0.80	0.93	10.80
5	8/12/76	27	31	38	42	0.44	0.53	0.58	0.45	1.15	20.17
6	8/12/76	27	28	39	41	0.21	0.28	0.29	0.38	0.87	6.87
7	8/12/76	27	28	39	41	0.58	0.80	0.84	0.40	0.50	2.08

Note: 1°C = (1°F - 32)/1.8; 1 kN = 225 lb; 1 mm = 0.04 in; and 1 m = 3.3 ft.

[a]Standard (empty) highway truck.

[b]Ford automobile.

figure suggests that N and B may be related functionally as

$$N = C_1 + C_2 \log B \quad (2)$$

where C_1 and C_2 are constants that depend on the characteristics of the pavement section at each site. Analyses of the data have indicated the constants to be independent of temperature, number of load repetitions, and loading vehicle. Corresponding values of the constants calculated for each of the four sites are shown in Figure 7.

The N and B parameters of Equation 1 may be thought of as descriptors of the distribution of deflections from the edge of a loading tire. For example, if N = 2, Equation 1 resembles the normal (Gaussian) distribution with B proportional to the variance. Thus, changes in values of N and B for a pavement section reflect changes in the distribution of deflections and structural characteristics of that section.

Figure 8 represents four typical, normalized peak deflection curves as a function of lateral distance for sites 1, 2, 3, and 4. The corresponding values of N and B parameters and the values of $(B^{1/N})$ are indicated in the figure. It can be seen that the higher the value of $(B^{1/N})$ is, the greater is the lateral spread of the deflection. Again, the analogy to the normal distribution should be noted for N = 2. For this state, $(B^{1/N})$ is seen to be proportional to the standard deviation. Most tests were conducted by using the same loading vehicle traveling at creep speed; the input energy was thus fairly constant and the amount of lateral spread may be thought of as a measure of the lateral attenuation of energy in the pavement. These observations gave rise to the use of the N and B parameters as indicators of pavement performance.

Plots of the B parameter as a function of the number of load repetitions for sites 1, 2, 3, and 4 are shown in Figure 9, and corresponding data are given in Table 5. The solid symbols in the figure designate conditions at a temperature of -5.5°C (22°F). Open symbols indicate the temperature range of 18° to 27°C (64° to 80°F). The straight lines between the data points were obtained from a least squares analysis. The coefficients of correlation (R^2), the y-intercepts, and the slopes of the lines are given in Table 5. The table also gives the numbers of trucks, pickups, and automobiles that traveled over each of the road sites (as a percentage of the total traffic at the site). Figure 9 and Table 5 indicate that in all cases the B parameter decreases with increasing load repetitions during the period of

Figure 8. Normalized peak deflection versus lateral distance for sites 1, 2, 3, and 4.

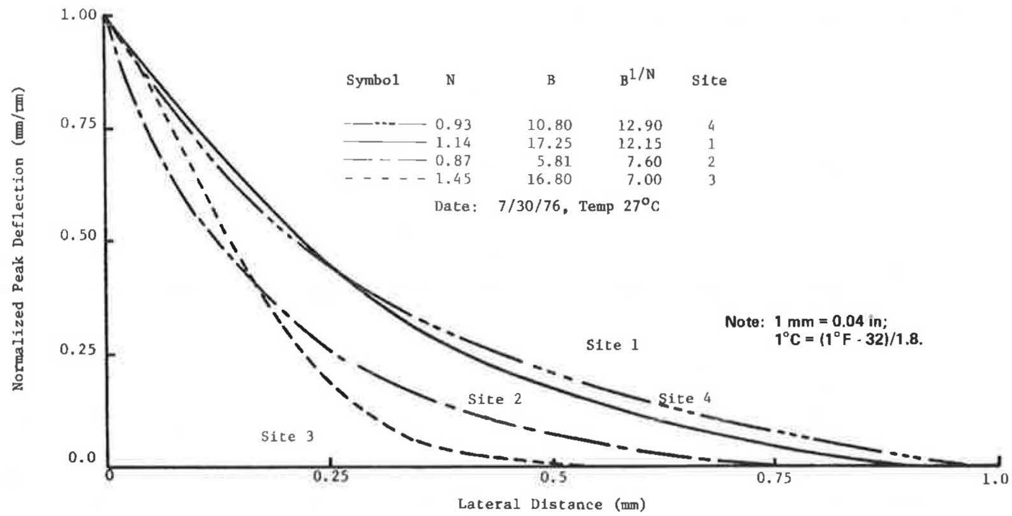


Figure 9. B versus load repetition for sites 1, 2, 3, and 4.

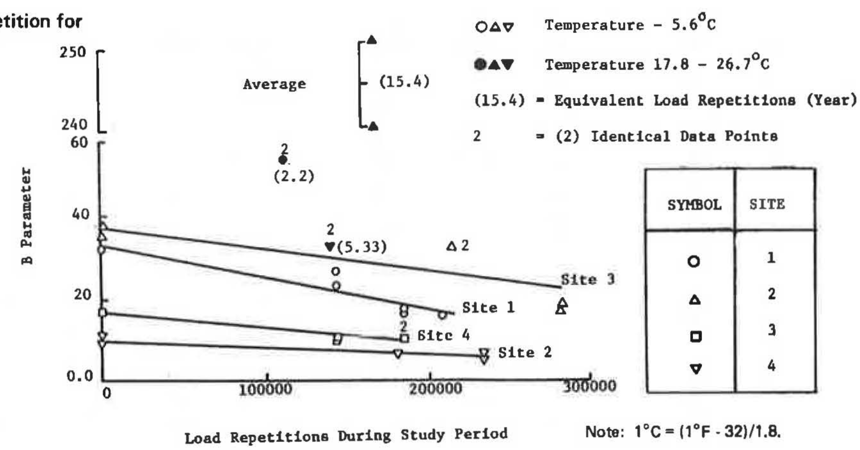


Table 5. Data for B versus load repetition (Figure 9).

Symbol	Site	Slope $\times 10^{-8}$	Y-Intercept	R^2 (%)	Percentage of Total Traffic: Truck	Pickup	Automobile
○	1	-7.4	32.51	94.6	90	0	10
△	2	-5.4	37.45	80.4	10	20	70
□	3	-3.2	15.93	95.8	5	15	80
▽	4	-1.5	9.51	89.6	5	0	95

study. In addition, the steeper the slope of the line is, the higher is the percentage of trucks traveling over the site.

Plots of the N parameter with load repetitions are shown in Figure 10. The N parameter also decreases with increasing load repetitions, but the slopes of the lines—obtained from a least squares analysis—show much less variation than did those for the B parameter.

Figure 11 shows a schematic representation of the typical deflection basin with corresponding relative values of the N and B parameters at one site. The figure show that, the smaller the value of the parameters is, the more rapid is the lateral attenuation of energy and the deeper it penetrates under the wheel. As noted above, implicit in this is that, as N and B decrease, more work is done to the pavement section in the vicinity of the wheel load. As a result, greater distress might be expected to occur with fewer passes.

Table 5 indicates that, at an air temperature of -5.5°C (22°F), the values of N and B parameters are larger than those listed at higher temperatures. This is a consequence of the more uniform deflection for the colder pavement. Conditions for this temperature are designated in Figures 9 and 10 by the solid symbols. The number shown in brackets next to each of these symbols indicates the equivalent number of years of traffic that must travel over the road site so that the data point will fall back on the straight line representing the site. These numbers were calculated by using the noted slopes of the lines and relating observed load repetitions and time.

SUMMARY AND CONCLUSIONS

Equipment for rapid, nondestructive pavement evaluation was designed and used on nine different highway and airfield sites. Time-dependent deflection response functions were measured, and deflections under the edge of the loading wheel were calculated by using Equation 1. Analyses of the data indicated the following conclusions:

1. The results obtained from the LVDT beam (nondestructive system) were found to be in extremely close agreement with those obtained by the embedded LVDT gauges.
2. The lateral extent of the deflection basin was found in all cases to be less than 1.5 m (5 ft) from the edge of the loading tire.
3. The deflection basin extending laterally from the edge of a tire of a loading vehicle was found to follow an exponentially decaying function (Equation 1).
4. The parameters of Equation 1 were found to be independent of gear configuration, tire pressure, and wheel load. They did depend on the number of load repetitions and temperature.

Figure 10. N versus load repetition for sites 1, 2, 3, and 4.

Symbol	Site	Slope x10^{7}	y Intercept	R^2(%)
○	1	-5.8	1.27	90.6
▽	2	-6.0	1.05	83.5
△	3	-3.9	1.59	92.5
□	4	-5.9	1.05	95.4

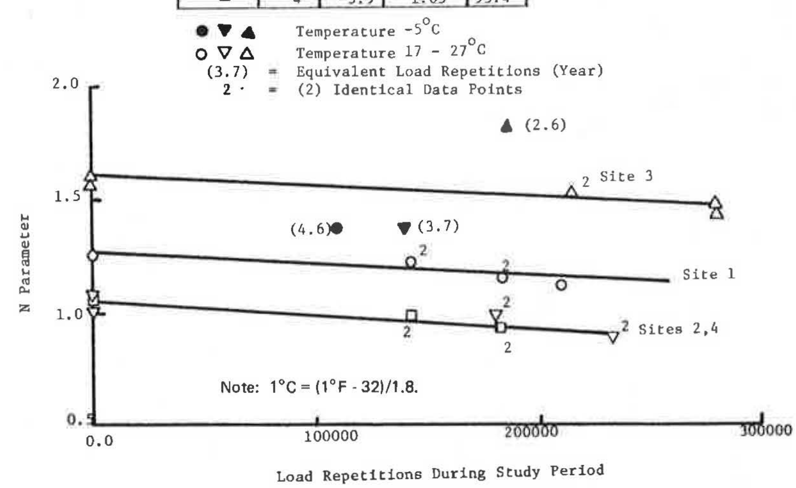
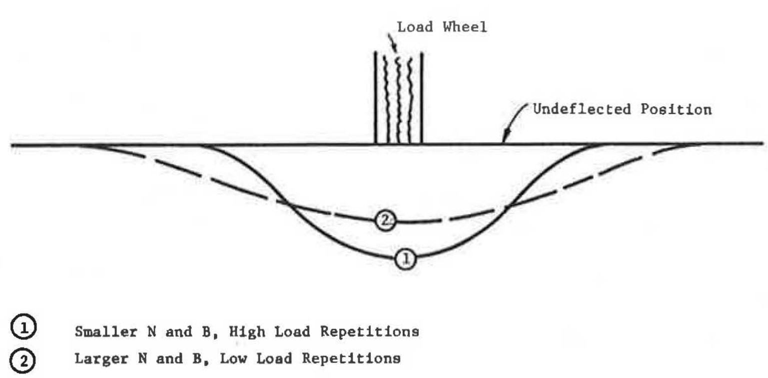


Figure 11. Typical deflection basin.



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