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Comparison of Falling Weight Deflectometer with Other Deflection Testing Devices

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ABSTRACT

Pavement modeling has always been a complex and difficult problem for the highway engineer. Currently, there are complex and precise computer programs that provide the engineer with a means of computing theoretical behavior. However, full-scale field testing has not kept pace, and new testing devices are just now becoming readily available. For many years the Benkelman beam was the standard, and later developments tended to be compared with this method for acceptance. However, it became apparent that better methods were required for adequate representation of pavement behavior under moving wheel loads. In this paper a summary of comparison tests conducted in Scandinavia is presented. The comparison included two designs of falling weight deflectometers (FWDs), Dynaflect, plate bearing, traveling deflectograph, vibrators, and Benkelman beam. These devices were used to test a variety of pavement structures. The results have revealed a wide range of deflections depending on the pavement section. These differences are caused by the magnitude and nature of applied load, time of loading, pavement thickness, and other factors. It appears that the FWD is well suited to a wide range of pavements and provides uniformly accurate results that are consistent with actual pavement loading and behavior.

Modeling of highway and airport pavements has been a difficult task since the beginning of road building. A pavement has many variables, such as thickness and type of materials, environment, traffic, and others. To account for many of these variables simultaneously, full-scale testing, such as deflection measurements, has proved to be beneficial.

The basic assumption in the behavior of pavements is that a pavement can withstand a number of repetitions of a given load before it fails. Failure can mean many forms of distress under some form of loading. If this loading is representative of traffic, then the strain or deformation could be related to performance by a failure model.

During the past several decades a large volume of data from Benkelman beam testing has been compiled and in various ways compared with pavement performance. This large bank of knowledge has become the principal reason for continued reliance on the Benkelman beam. Therefore the correlation between

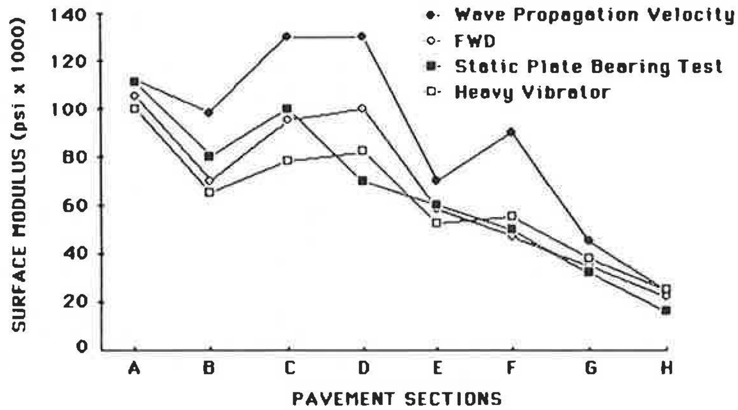

FIGURE 1 Comparison of different bearing capacity measurement methods on different road structures.

the Benkelman beam and other devices has become the apparent test of acceptability. Some engineers have reasoned that the understanding of pavements and their behavior is applicable only if the Benkelman beam or some similar device is used. That sort of reasoning may lead to the conclusion that a new testing device with increased capability (accuracy) may be desired, but that it should still give results closely correlated to the Benkelman beam. This prerequisite may be required by many engineers, in spite of the fact that the method does not relate to strain at traffic loading.

In this paper an attempt is made to demonstrate the factors involved and the range of results that might be expected from several of the pavement testing methods that are available to the engineer.

COMPARISON OF DIFFERENT METHODS

The comparison of various pavement devices has been an ongoing process, and many of these comparisons were made in Scandinavia, where much of the early work on falling weight deflectometers (FWDs) was done (1-11). The goal of most of these studies was

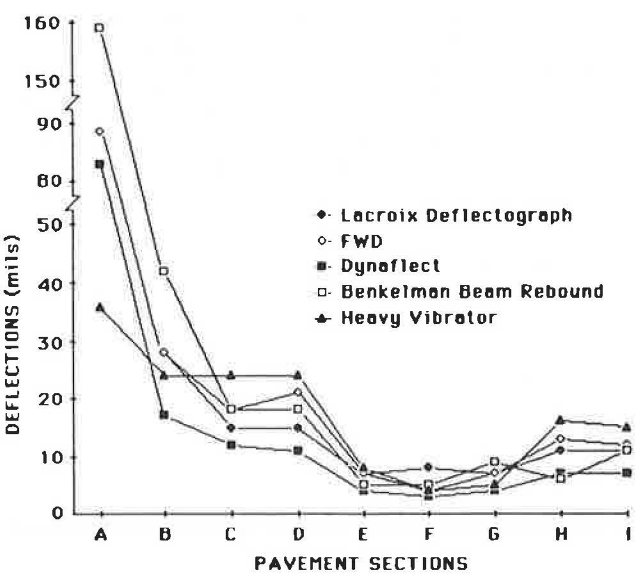

FIGURE 2 Comparison of different bearing capacity measurement methods on different road structures, with deflections normalized to 11,250-lb load.

to determine the behavior of pavements under different types of loading rather than to make a direct comparison of testing devices.

Two particular studies are of note and have been well documented. The first study (5) by the Swedish Road and Traffic Research Institute included eight different pavement structures that were tested on eight occasions over a time period of slightly more than a year. Also, four testing methods were used: static plate bearing tests, FWDs, heavy vibrators (15 Hz), and a wave propagation test. Figure 1 shows the surface moduli of the eight different pavement sections; these have been averaged with time for each pavement structure.

The second study (6) included the evaluation of 12 testing methods used in the Nordic countries on 12 different pavement sections. Figure 2 shows the surface deflection for five of the testing methods for a range of pavements. The values plotted in Figure 2 are normalized to 11,250 lb. The data in Table 1 give an explanation of the various pavement types included in this study, and Table 2 gives a list of the deflection testing devices used.

Examination of Figures 1 and 2 indicates that the use of the various testing methods results in the same general trends over the range of pavement structures. When both static and dynamic testing methods are used on the same pavement, the FWD seldom results in extreme values, as compared with some of the other methods.

Tables 3 (5) and 4 (6) are correlation matrices from the two research projects. It is apparent that most of the correlation coefficients are rather high. However, it must be kept in mind that the

TABLE 1 Description of Pavement Sections

		Base Course		Subbase		
Section	Wearing Course[a]	Type	Depth (in.)	Type	Depth (in.)	Subgrade
A	Gravel	Gravel		Sand		Peat on clay
B	Asphalt	Gravel	12	Bark	40	Peat and mud on clay
C	Asphalt	Cement slab	6	Gravel	12	Till and clay
D	Asphalt	Gravel	28	–		Till and clay
E	Asphalt	Crushed rock	51	–		Soil embankment
F	Asphalt	Asphalt Gravel	12 2	Sand	12	Clay
G	Asphalt	Asphalt Gravel	8 2	Sand	16	Clay
H	Asphalt	Gravel	10	Sand	16	Clay
I	Asphalt	Gravel	10	Sand	28	Clay

[a]All pavement sections with an asphalt wearing course are about 2 in. thick or less.

TABLE 2 Identification of Testing Devices

Symbol	Testing Device
I	Danish traveling deflectograph
II	La Croix deflectograph
III	Benkelman beam
IV	FWD (one-mass system)
V	FWD (two-mass system)
VI	Heavy vibrator (39 kN, 17 Hz)
VII	Dynaflect (5 kN, 8 Hz)
VIII	Static plate bearing test method 1
IX	Static plate bearing test method 2
X	Dynamic plate bearing test

TABLE 3 Correlation Coefficients (r) from Comparison of Surface Moduli Measured by Different Methods (5)

	Static Plate Bearing	Heavy Vibrator	Wave Propagation Velocity
FWD	0.84	0.90	0.86
Static plate bearing test		0.75	0.77
Heavy vibrator			0.78

coefficients are not universal values that represent the two methods being compared; they also depend on the choice of tested structures. In fact, it would be relatively easy to find populations with correlation coefficients near zero.

Further evaluation indicates that a high correlation coefficient does not prove that the two methods are accurately measuring the parameter desired. For example, in Table 4 the coefficient for the two static plate bearing tests (VIII and IX) is 0.98. When the regression line was examined, the two tests on one pavement indicated the same static surface modulus, whereas on the other structure there was a difference of a factor of two.

The correlation coefficients in these studies were consistently high, which indicates that the translation between different test methods may be reasonable, but only within a certain narrow range of pavement structures. Therefore, within these boundaries, a reasonable correlation could be developed.

It can be noted that the FWDs, particularly the two-mass FWDs, show high correlation coefficients when compared with the other most important families of testing devices--the vibrator and the Benkelman beam--along with their relatives. The correlation between the heavy vibrator and members of the Benkelman beam family is poor.

The fact that most test methods result in about the same measure of bearing capacity is not too surprising. It is not likely that a method would be used if it gave poor results. With some experience a pavement engineer can estimate the strength or bearing capacity without testing. However, when more accurate and useful information is required, accurate testing becomes more desirable. Therefore, an approximate agreement between methods may make the method useful for approximate surveys, but the choice of testing method for more precise evaluations is important.

When a more detailed comparison of testing methods is made, greater differences begin to appear. A complete analysis might be interesting, but would also be too lengthy. The following sections give examples of how the FWD compares with other methods.

FWD Versus Wheel Load

It is generally known that the deflection that occurs under a moving wheel load is dependent on vehicle speed. There may be a considerable difference between the deflection at normal traffic speed and at creep speed, which is used when testing with the Benkelman beam and the traveling deflectograph (2,12-15). Among other factors, the temperature of asphalt pavements plays a significant role, and uniform results are more easily attainable at normal traffic speed. The goal in developing the FWD was to obtain the same deflection as that measured under traffic loads at normal speed.

On one Danish test road with an asphalt pavement, deflections at traffic loads, FWD tests, and Benkelman beam tests were compared by means of accelerometers buried in the pavement (2). The results conclusively demonstrated that the FWD deflections were similar to those caused by traffic loads, whereas the Benkelman beam deflections were considerably larger.

It was further noted in the tests shown in Figure 2 that time of loading was a factor in pavements with thick asphalt layers and a peat subgrade. On pavements without these layers, the wheel load tests indicated smaller deflections than the FWD tests. This difference was most likely because the deflections of the wheel load tests were not measured in the loaded area and because the reference beam may have had its feet within the deflection bowl. Typical values of the deflection ratio between FWD and wheel loading at creep speed on these pavements ranged from 1.05 to 1.35. In another comparison, the difference between the two traveling deflectograph deflections was greater than the difference between deflections measured by FWD and traveling deflectographs.

TABLE 4 Correlation Coefficients (r) and Number of Test Points in Comparison Between Different Testing Devices (6)

Testing Device	Testing Device I	II	V	VII	IV	III	VIII	X	IX	VI
I		0.89	0.85	0.89	0.78	0.96				0.66
II	55		0.96	0.95	0.95	0.94				0.75
V	55	77		0.96	0.95	0.88		0.91	0.67	0.95
VII	55	76	128		0.93	0.91				0.84
IV	41	58	109	111		0.92		0.86	0.73	0.87
III	42	59	99	100	99				0.85	0.76
VIII								0.50	0.98	
X			32		32		32			0.98
IX			33		33	33	33			0.49
VI	42	58	64	65	64	65		31	32	

Note: Correlation coefficients are given in the upper half of the table and the number of test points is given in the lower half of the table. A description of the testing devices is given in Table 2.

Two-Mass Versus One-Mass FWD

Commercially available FWDs operate on similar principles, but have three important differences:

1. The force generating unit,
2. The method of distributing load on the pavement, and
3. The method of measuring deflection.

Force Generation

Typical force pulses from the one-mass system are shown in Figure 3 (16). The sharp rise of the force pulses does not accurately simulate moving wheel loads. Further, one-mass force pulses often exhibit high frequency distortions, as noted at the top of the second and third pulses in Figure 3. If this distortion occurs before the main peak, then the peak force measured is not compatible with deflections measured by sensors farther away from the load plate. This phenomena could then be a source of greater variation, which results in nonreproducible values of bearing capacity.

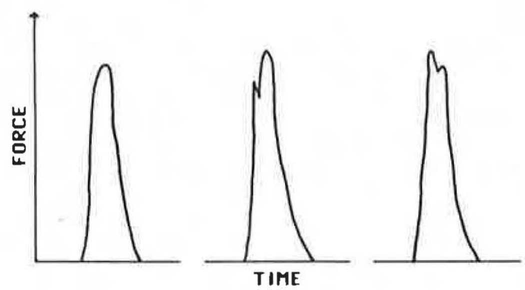

FIGURE 3 Examples of force pulses by measurement with one-mass FWD at different normal conditions (*16*).

To improve on this system the two-mass system was developed for the KUAB FWD. Typical examples of force pulses produced by this system are shown in Figure 4. The more gradual rise in the force pulses and the shape of the pulses are the same as those produced by moving wheel loads. The shape of the force pulses are always smooth for a wide range of pavement sections, and they are reproducible.

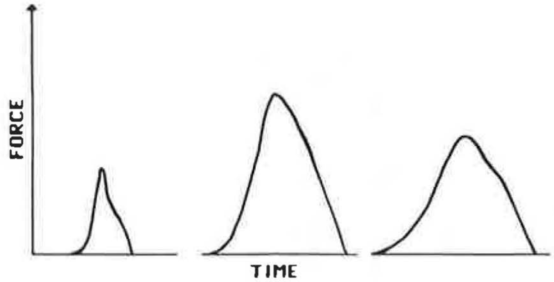

FIGURE 4 Representative examples of different force pulses from two-mass FWD system with rubber buffers.

Load Distribution

Deflection tests are generally conducted on pavements in need of rehabilitation; the surface is often uneven because of wheel ruts, cracks, and so forth. Several tests were conducted (1,16) on uneven roads, and it was found that deflection errors ranged from 10 to 20 percent. To improve accuracy, the KUAB FWD was designed with a segmented circular loading plate as shown in Figure 5. Each of the four segments can move independently; thus a uniform load is applied to each even though the vertical position may be different. This is achieved by loading each plate with a plunger that is connected to a common oil chamber. The spherical bearings are designed such that the center of rotation is low, thus permitting controlled lateral movement of the plates when they are tilted.

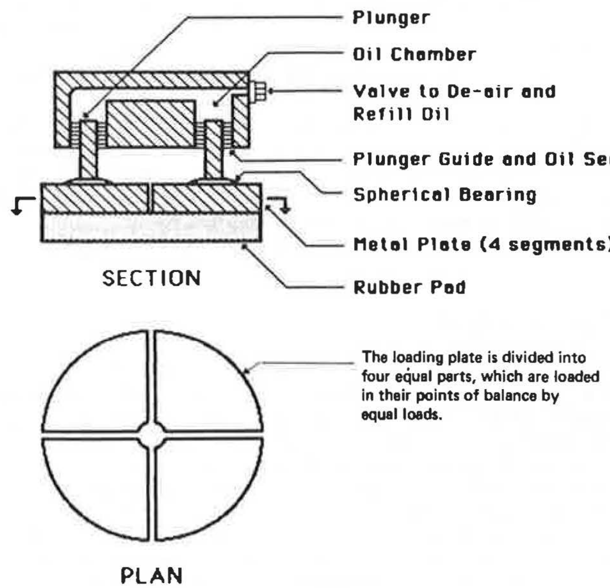

FIGURE 5 Principle of hydraulic load distribution plate.

Deflection Sensors

Deflection measurement has frequently been a difficult task in dynamic loading situations. Most FWDs use velocity transducers or geophones, and by integration of the measured velocity the deflection is obtained. However, a problem with this method is the difficulty with field calibration. Relative calibration is possible by placing all geophones next to or on top of each other and noting the similarity in deflection. This may be considered a reasonable method to check the device, but to give full proof of correct operation the comparison would have to be made on one pavement with a deflection rise time in the low range and on one pavement with a deflection rise time in the high range thus requiring an analogue recording of the deflection or some other means of measuring rise time and pulse shape. In addition, the comparison could be made on both small and large deflections, and finally some variables may be expected to influence all geophones in a similar manner.

The primary disadvantage of the relative calibration method is that when a calibration change is discovered, the test does not supply any data for correcting the change. In other words, the relative calibration does not indicate what has changed (i.e., frequency of the geophone, the damping ratio of the geophone, or some part of the electronics).

To improve field calibrations, special seismometers were designed for the KUAB FWD. The seismometers use a mass-spring system as a reference and the sensing element is a differential transformer (LVDT). This system permits direct measurement of deflections, and because the mass and LVDT core are suspended with springs, there is no problem of reference. Calibration is accomplished with a micrometer provided with each seismometer. Thus each seismometer can be accurately calibrated in the field to measure deflections in the range of 0 to 5 mm (0 to 200 mils).

FWD Versus Static Plate Bearing Test

Many comparisons of FWD and static plate bearing test methods have been made (1,5,6,8,10,11), and the general conclusion is that there is no unique ratio between the deflections measured with each device. The static tests result in higher deflections on bituminous materials and on softer subgrades such as peat. Typical ratios of deflections for these situations range from about 1.5 to 3.

On stiffer materials, such as glacial till and gravels, the deflection ratios appear to approximate unity. On such materials there was no evidence that the scatter or difference between FWD and static plate bearing tests was any greater than the difference between various plate bearing test procedures.

FWD Versus Vibrators

Testing with the FWD and heavy vibrators often results in similar deflections. In one study (5) the overall ratio of the two deflections was unity. However, there was a range in values: the FWD indicated 10 to 20 percent higher modulus on thick asphalt pavements, but the reverse was true for unbound rock surfaces. During most of these tests only one frequency was used with the vibrator, thus interpretation of the results was difficult. It was noted that a 10- to 30-percent difference in modulus resulted by altering the frequency; most likely this was the result of the time dependence of the asphalt layer, but phenomena related to resonance also could have been involved.

Some testing agencies (17-19) believe that a single testing frequency with vibrators is insufficient to obtain reliable data. Also, resonance may be an important influence on results. FWDs appear to be somewhat less affected by this phenomena, however (17). Some data (6) have clearly revealed this independence, as noted in Figure 6. In this figure the ratio of deflections is shown for several pairs of testing devices. The testing devices and pavement structures shown in this figure are noted in Tables 1 and 2. There is a reasonably wide range of force and frequency represented by the vibrator and Dynaflect. There is also a difference in impact time between the two FWDs. Deflections shown in Figure 6 are mean values that have been normalized to 11,250 lb. Pavement structures A and B are on peat subgrade and have low resonant frequency.

Although there is a wide range of parameters among the various testing procedures, the difference between the vibrators is rather large. The validity of vibrators can certainly be questioned over a range of pavement types. Also noted in Figure 6 is the reasonable agreement between the two FWDs, in which the ratio of deflection values is approximately unity.

PRECISION OF TESTING DEVICES

Variation in most testing is to be expected when a pavement is tested at several locations on the surface. The variation (or coefficient of variation) is caused by true variation in the quantity measured as well as lack of precision in the test. A small coefficient of variation means either that the variation in bearing capacity (or deflection) is small, or that the test method is incapable of detecting the variation. If the bearing capacity variation within the pavement section is small, then the precision of the test method may be determined on the pavement.

From the data in the Nordic study (6), those sections in which the coefficient of variation was less than 10 percent for at least one of the test methods were selected for further analysis (see Table 5). These values are given under the "Measured" columns. In this table the coefficient of variation of the bearing capacity within one pavement section is less than the lowest of the coefficients by the different methods. It could be assumed that a portion of the variation of each pavement is caused by bearing capacity variation and the remainder is caused by lack of precision of the test methods. The difference in precision among methods can be estimated by assuming that the lowest coefficient of variation of each section is equal to the sum of the portions, as noted previously. The numbers under the "Adjusted

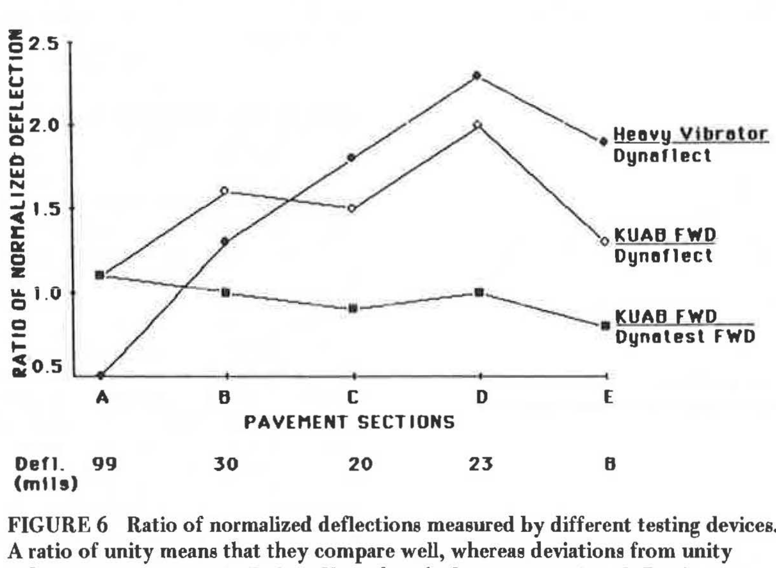

FIGURE 6 Ratio of normalized deflections measured by different testing devices. A ratio of unity means that they compare well, whereas deviations from unity indicate relatively less similarity. Note that the bottom line gives deflections at which comparisons are made for each pavement section.

TABLE 5 Coefficients of Variation of Different Bearing Capacity Tests on Homogeneous Road Sections (*16*)

	Coefficient of Variation (%) of Different Pavement Sections									
	C		C		D		D		E	
Test Device	Measured	Adjusted from Analysis	Measured	Adjusted from Analysis	Measured	Adjusted from Analysis	Measured	Adjusted from Analysis	Measured	Adjusted from Analysis
I	8	7	17	16	7	6	9	8	26	25
II	10	9	16	15	7	6	12	12	18	17
III	10	9	19	17	15	15	12	12	22	22
IV	13	12	19	17	6	5	12	12	16	15
V	6	4	10	8	4	3	5	4	6	4
VI	12	11	–	–	5	4	–	–	12	11
VII	10	9	9	6	4	3	12	12	16	15

Note: The numbers in the Adjusted from Analysis columns are estimates of the coefficient on a completely homogeneous section. The number of test points on each section and test method was 10.

from Analysis" columns in Table 5 are estimates of the coefficients for a completely homogeneous pavement section.

Another measure of quality of testing is to look at the width of 95 percent confidence intervals of the bearing capacity values at a test point. The data in Table 6 give these values for several of the test methods evaluated. The two-mass FWD revealed very good precision and very good repeatability--much better than the other devices evaluated.

TABLE 6 Relative Repeatability of Various Test Devices at a Given Test Point

Test Method	Width of 95 Percent Confidence Interval at Test Point (%)
FWD (two-mass system)	20
Dynaflect heavy vibrator and Danish traveling deflectograph	40
La Croix deflectograph and FWD (one-mass system)	50
Benkelman beam	60

CONCLUSIONS

The pavement studies conducted in the Nordic countries have provided an excellent opportunity for comparing a variety of testing devices. The devices have all been used by various agencies and have become a part of design and analysis procedures. Although most new methods have been traditionally compared with the Benkelman beam, there is no evidence that indicates that this method is any better than any other. Thus there is no particular reason to attempt correlations to gain acceptance of a method.

Pavement modeling that uses such approaches as elastic layer theory requires feedback from field tests that represent the actual behavior as closely as possible. Recent work in Europe and in the United States has demonstrated that load response using the FWD is very close to real-world conditions, and hence the FWD is being promoted as the best testing system.

The study reported herein has provided an opportunity to evaluate the relative merits of two FWD systems as well as compare them to other methods. Based on the study, the following conclusions appear warranted:

1. FWDs provide a force pulse shape that tends to simulate moving wheel loads better than the other devices compared in this study.
2. In a comparison of the two FWDs, the two-mass system appeared to have better precision and better repeatability qualities (Tables 5 and 6).
3. The Dynaflect compared well with other devices, both in precision and repeatability; however, it does a relatively poor job of simulating full-scale moving wheel loads.
4. Pavement vibrators compared favorably with other devices, except in pavements with soft subgrades, such as peat.

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Asphalt Concrete Overlay Design Procedure for Portland Cement Concrete Pavements

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ABSTRACT

The development and practical application of a reflection cracking analysis and overlay design procedure, which was developed for the Arkansas State Highway and Transportation Department, are described. The procedure is mechanistically based, but it is calibrated to the performance of experimental overlay sites in Arkansas and Texas. The procedure is incorporated into a computer program (ARKRC-2) for both existing pavement evaluation and overlay design. It considers asphalt concrete overlays and several techniques of reflection cracking control that may accompany overlay placement. These measures include bond breakers, stress-relieving interlayers, undersealing, and increased overlay thickness. The design procedure calls for a program of field measurements of vertical and horizontal slab movements to establish the potential for slab movement after overlay. Differential vertical slab movements are measured at joints (or cracks) by using a light-load deflection device (such as the Dynaflect). Measurements of horizontal slab movement are made over 2 or 3 daily temperature cycles at several existing joints (or cracks) by using a mechanical strain gauge. In the analysis procedure differential vertical slab movements are used to characterize load transfer and predict shear strains that will occur in the overlay under a simulated 18-kip axle load. Horizontal slab movements, on the other hand, are used to predict the maximum daily tensile strains that will be generated in the overlay during different seasons of the year. For both strain criteria, a fatigue-type approach is used to predict how long the overlay will last. A probabilistic distribution is then applied to the horizontal tensile (environmental) strain criteria, such that the overlay design can be based on a minimum tolerable level of reflection cracking over the design life. For joints (or cracked areas) that have problems with poor load transfer and would thus generate excessive overlay shear strains, it is recommended that some type of slab repair or undersealing operation be performed. (The findings of the original study for Arkansas indicated that other control measures such as increased overlay thickness and stress-relieving interlayers are not cost-effective compared with remedying the cause of the poor load transfer problem.) Besides providing a general description of the analytical models and the ARKRC-2 program (which can be adapted to almost any environment in the United States), examples of the overlay design nomographs developed for the specific construction materials and environmental regions found in Arkansas are also presented.