Flexible Pavement Maintenance Requirements as Determined by Deflection Measurement

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This paper discusses the results of the use of the deflection method by the California Division of Highways for the evaluation of existing flexible pavements and the recommendation of suitable reconstruction. Since 1960, some 80 projects including state highways, county roads, and city streets, have been subject to deflection investigation by the Materials and Research Department of the California Division of Highways. The primary purpose of these investigations was the recommendation of appropriate corrective treatment. As a result of this intensive program, a large volume of data on the deflection attenuation properties of various roadway materials has been accumulated and is presented in this report, along with the results of individual deflection studies. The test procedure, method of evaluation of deflection data, and design criteria which have evolved are examined in detail. In addition, economical and practical factors involved in making a specific recommendation are discussed. A separate section of the report is devoted to a review of current deflection research, including work now being done on the establishment of maximum deflection criteria which may be adjusted for variations in traffic volume. A brief analysis of radius of curvature data obtained with the Dehlen curvature meter is also included.

•THE CALIFORNIA Division of Highways has used deflection measurement for the evaluation of flexible pavements since 1938. Until 1954, deflection measurements were obtained using General Electric travel gages and a later modification, the linear variable differential transformer gage. During these early years, the limited amount of deflection data available was used to evaluate flexible pavement sections subject to distress investigation. In 1951 a comprehensive deflection research program was initiated by the Materials and Research Department. The principal objective of this study was the establishment of a relationship between the level of pavement deflection and pavement performance or conditions. Secondary objectives included: (a) establishment of the relationship between single-axle load and pavement deflection, (b) determination of the effect on pavement deflection of wheel configuration, and (c) an examination of the relationship between pavement deflection and pavement temperature. Approximately 400 General Electric gage units were installed on 43 projects throughout California.

The test roadways included a wide variety of pavement structural sections because thickness of asphalt-concrete surfacing was a prime variable. Installations were made on both distressed and undistressed sections of the test roads. The rear axle loading for this and all subsequent deflection testing was 15,000 lb. The results and conclusions of this study were published in 1955 (1).

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TABLE 1

MAXIMUM TOLERABLE DEFLECTION LEVELS

Pavement Thickness (in.)	Pavement Type	Max. Deflect. (in.)[a]
8	Portland cement concrete	0.012
6	Cement-treated base[b]	0.012
4	Asphalt concrete	0.017
3	Plant mix on gravel base	0.020
2	Plant mix on gravel base	0.025
1	Road mix on gravel base	0.036
½	Surface treatment	0.050

[a]For design purposes.
[b]Surfaced with bituminous pavement.

Figure 1. Traveling deflectometer.

Examination of the data from this study with respect to level of pavement deflection vs pavement condition permitted the establishment of tolerable deflection criteria for a variety of structural sections. The selected roads were, without exception, "mainline," carrying approximately 10 million or more equivalent 5,000-lb wheel loads (EWL) during their 10-yr design life. The criteria developed as a result of this study (Table 1) are of fundamental importance because they provided the basis for the practical application of pavement deflection data for the determination of the maintenance requirements of a distressed roadway.

These values are applicable primarily to California highways as the methods of mix design, seasonal weather variations, and the characteristics of the construction materials, notably asphalt binder, are peculiar to that state. They are somewhat conservative in comparison to the criteria established by other agencies.

The installation of linear variable differential transformer gages for deflection measurement was a tedious and time-consuming process. Because of this and the relatively high costs involved, only limited coverage was possible.

During the operational phase of the WASHO Road Test (1952-1954), A. C. Benkelman of the U. S. Bureau of Public Roads developed an instrument for measuring pavement deflection with the important advantages of versatility, simplicity, and speed.

With this device, upwards of 300 measurements per normal working day are possible. The development of the Benkelman beam, therefore, greatly augmented pavement deflection research and the use of pavement deflection measurements for overlay design.

Between 1955 and 1960, we developed a semiautomatic deflection device, based on the Benkelman beam principle, known as the traveling deflectometer (Fig. 1). This instrument combines a truck-trailer unit with dual probes for simultaneous deflection measurements under both sets of dual wheels. The device is electro-mechanical and is capable of uniform and consistent measurement of pavement deflections at 12½-ft intervals while traveling steadily at ½ mph. Between 1,500 and 2,000 individual deflection measurements are possible during the average working day. The development of the traveling deflectometer and the results of several of these early deflection studies were described in detail in 1962 at the International Conference on Structural Design of Asphalt Pavements (2).

By 1960, sufficient information on the deflection reduction properties of various roadway materials had been accumulated to permit reasonable estimation of the effectiveness of specific types of reconstruction for roadways evaluated by deflection study. The traveling deflectometer provided the means of obtaining a large volume of deflection test data within a relatively short period of time. Pavement deflection measurement for determination of roadway maintenance requirements, such as overlays, has been used with ever-increasing frequency since that time.

This report describes the evolution of a deflection test method by the California Division of Highways and presents the results of follow-up measurements on projects built in accordance with recommendations resulting from operational deflection studies. Detailed descriptions of five projects of particular interest are included. A portion of the report is devoted to a review of the scope and objectives of the current pavement deflection research program.

DEFLECTION TEST PROCEDURE

Prediction of Deflection Attenuation

Accumulation of deflection attenuation data was accomplished by two methods, the first of which was follow-up measurements over projects constructed according to recommendations resulting from deflection studies. Another very important source was test data from projects selected specifically for peculiarities in structural section, i.e., an unusually thick surfacing or base. From May 1960 to July 1965, some 80 separate deflection studies of an operational nature were conducted for the Division of Highways, counties, and cities involving deflection measurements and recommendations for corrective treatment for 250 individual roadways. As a result of this experience, the Division continues to accumulate a considerable amount of data on deflection attenuation. Figure 2 shows the sum total of experience to date with 17 completed projects. Percent reduction in deflection is plotted against increase in inches of gravel equivalence (the thickness of gravel necessary to produce a load-distributing and soil-restraining effect equal to that produced by the slab action of the thickness of the material being considered—refer to California Test Method No. 301-B). This plot is the basic tool for planning reconstruction of roadways based on deflection measurement. It not only establishes a general trend in the deflection reduction afforded by various thicknesses of base and surfacing, but also indicates the results of specific types of reconstruction on individual projects.

In addition to the general deflection attenuation trends resulting from this program, experience with the deflection method so far has shown the following.

1. In absolute terms, the reduction in deflection afforded by a given thickness of material is to a large extent dependent on the initial deflection level. In other words, the reduction in absolute units of deflection resulting from the placement from an AC layer is substantially greater at high deflection levels than at low deflection levels even though the percentage reduction might be the same in each case. Therefore, it is more realistic to estimate reduction in deflection in terms of percent of initial deflection rather than in terms of 0.001 in. per inch of resurfacing.

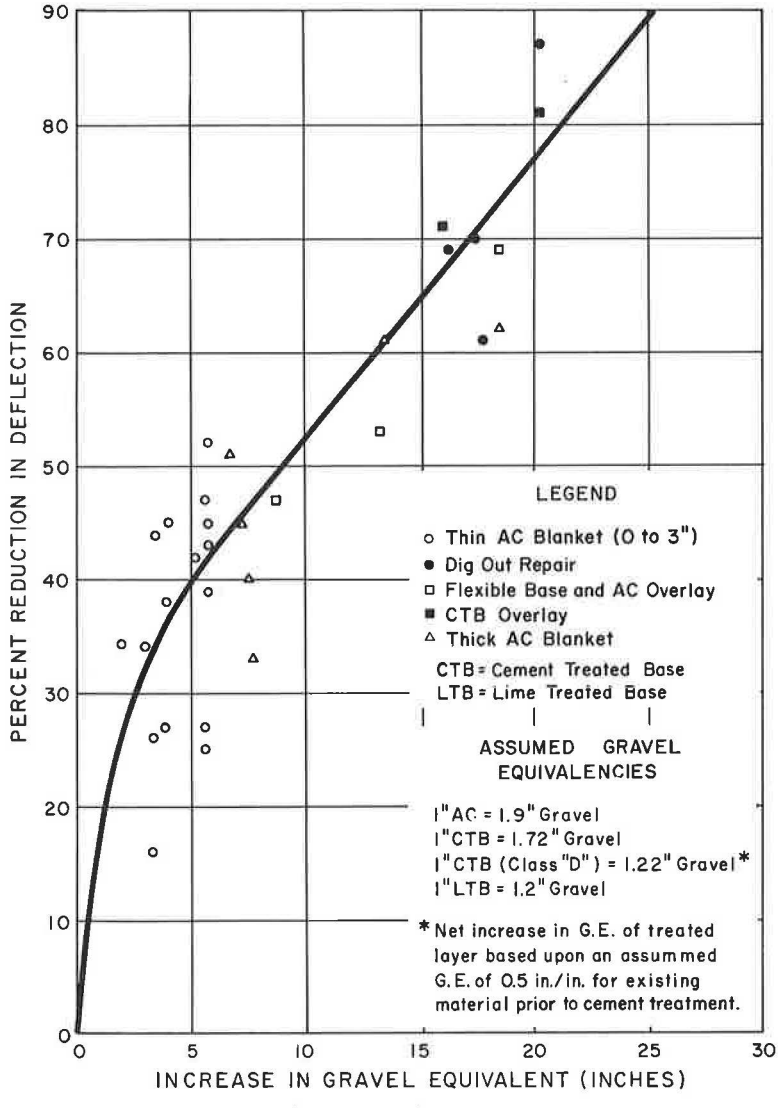

Figure 2. Reduction in deflection resulting from pavement reconstruction.

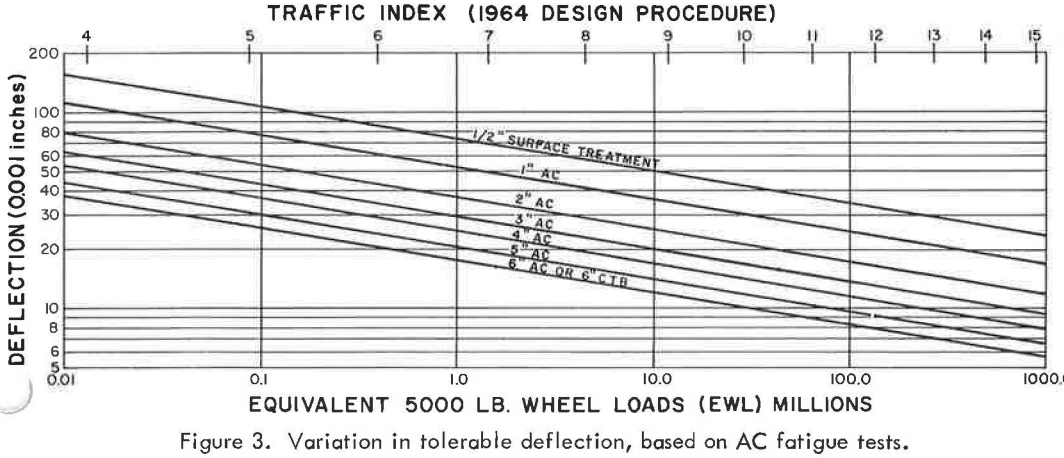

Figure 3. Variation in tolerable deflection, based on AC fatigue tests.

2. A significant reduction in deflection usually occurs during the first year of operation, presumably due to the additional curing of AC surfacing and traffic compaction.

3. The most economical reconstruction involves, insofar as possible, complete utilization of an existing structural section even though the surfacing may be badly cracked and spalled.

4. The highest rate of deflection reduction occurs with relatively thin treatments. This rate of attenuation tends to diminish with an increase in gravel equivalence.

5. The reduction in deflection resulting from the cement treatment of an in-place material is somewhat greater than indicated by existing gravel equivalent factors in California.

Variation in Tolerable Deflection with Traffic

The present limiting deflection criteria were established on the basis of data from heavily trafficked test roadways. It has been long recognized that application of these criteria to secondary state highways, county roads, and city streets would be unrealistic and uneconomical. For this reason, we have developed an interim method for adjustment of tolerable deflection level according to variations in traffic volume. This adjustment is based on AC surfacing fatigue tests made some time ago, which indicated that although the fatigue life of individual AC specimens varied widely (presumably due to variation of mix design, age, and number of previous traffic loadings) the slopes of their load repetition vs deflection lines were relatively uniform when plotted as logarithmic functions. By using an average AC surfacing fatigue line slope and pivoting lines through known deflection criteria at the 9.0 TI (traffic index) level, Figure 3 was developed to make rule-of-thumb adjustments in tolerable deflection for varying traffic volumes. (Traffic index is an exponential function of total EWL anticipated on the highway between the time construction is completed and the end of the design period—Calif. Test Method No. 301-B.) Although these curves are based solely on laboratory surfacing fatigue data and have not yet been correlated with field performance, they appear reasonable within the ranges of 6.0 to 10.0 TI.

Selection of Test Section

Before making deflection measurements on a certain road, the project file is studied for information on variations in structural section, traffic volume, foundation and drainage conditions, and unusual occurrences during construction which may have affected the performance of the roadway. From this and visual examination, test sections considered representative are selected. Approximately 1,000 ft per centerline mi are tested on each project. Deflection test data are separated into categories of fill, cut, cracked, uncracked, travel lane, passing lane, and inner and outer wheel path (OWP). Further breakdowns or divisions are established as warranted by peculiarities of the project. Examination of average deflections for each category can frequently indicate the nature or cause of early pavement distress and the practicability of utilizing more than one type of corrective treatment. In cases where deflection is relatively uniform, an evaluated (deflection value at which 80 percent of the measurements are lower and 20 percent are higher) deflection level (80 percentile) is established by recombining all OWP readings from the test section. This value reflects the deflection characteristics of the section as a whole rather than isolating possible causes of distress or placing undue emphasis on an isolated condition.

Selection of Required Maintenance Treatment

The problem of recommending suitable reconstruction is not simply a matter of establishing a representative deflection level and prescribing a treatment which would reduce this deflection to a tolerable limit. Several other factors are considered to arrive at a satisfactory design; these are (a) existing vertical controls (curbs and gutters); (b) anticipated use of the roadway; (c) extent and nature of cracking; and (d) anticipated traffic volume.

TABLE 2

DEFLECTION DATA FROM TYPICAL CITY STREET IN CALIFORNIA

Test Section	Deflection (in.)			Appearance
	Mean		Evaluated	
	OWP	IWP	(80% level)	
1	0.055	0.028	0.106[a]	Intermittent alligator cracking and shrinkage cracking.
2	0.043	0.031	0.064[b]	Continuous to intermittent alligator cracking in both wheel paths of all lanes.

[a]Based on 35 individual deflection measurements.
[b]Based on 28 individual deflection measurements.

The existence of curbs and gutters or the presence of an excellent passing lane next to a distressed travel lane often makes the use of a travel lane digout feasible. Where no such vertical control exists and a major reconstruction is warranted, a flexible base or cement-treated base (CTB) with an AC blanket is usually recommended so that the residual strength of the old pavement can be incorporated into the new construction.

The anticipated future use of a roadway frequently determines whether we shall "live" with a deflection condition through utilization of a thin blanket or eliminate the problem with major reconstruction.

The extent and nature of cracking is frequently very important in determining whether a blanket will act independently of the old surfacing or become an integral part of the existing surfacing, thereby increasing surface rigidity with a corresponding decrease in the level of tolerable deflection.

The presence of large block or ladder-type cracks indicates that the existing surfacing has a good deal of residual slab strength and could thus be expected to act in conjunction with a new blanket. Thus, the AC surfacing would consist of the original and the repair blanket, acting as a unit. Because of this, the tolerable deflection level would be much lower than that for a new blanket applied to a continuously cracked AC surfacing in which surface distress is in the form of relatively small blocks as is sometimes the case with badly alligator-cracked roads. Here, because the new blanket can be considered independent of the old, the tolerable deflection level can be assumed to be determined by the thickness of the new blanket only.

The deflection method for the design of reconstruction is assumed to be valid when roadway distress is attributable to excessive compression and rebound to the structural section. Evidence of the instability of the structural section as manifested by permanent path rutting or indication of significant permanent deformation on the deflection traces reveals a problem beyond the scope of the deflection method. In these cases, design of corrective treatment is based on the standard California R-value procedure.

To illustrate the method of analysis and procedure for recommendation of corrective treatment based on deflection data, a typical case history of a particular roadway will be examined. The information in Table 2 was acquired during a recent deflection investigation of the streets of a medium-size city in the central valley of California. The roadway had a structural section consisting of 2 in. of AC surfacing over 4 in. of aggregate base over 4 in. of aggregate subbase. The design TI was assumed to be 6.5.

The evaluated deflection levels for the two test sections ranged from 0.064 to 0.106 in. Test section No. 1, however, had a mean OWP deflection level of 0.055 in. The

wide discrepancy between the mean level, 0.055 in., and the evaluated (80 percentile) level, 0.106 in., indicates that the evaluated deflection level was greatly influenced by a few isolated high readings and, thus, is not representative of the test section as a whole. With this in mind, the evaluated deflection level of test section No. 2 (0.064 in.) is selected as the design deflection level. Based on a TI of 6.5 and 3-in. AC surfacing, it is determined from Figure 3 that a deflection level of 0.030 in. can be tolerated. It is, therefore, necessary to effect a reduction in the deflection level of 0.064 in. minus 0.030 in., or 0.034 in. This requires a 0.034 in./0.064 in. = 53 percent reduction in deflection. Figure 2 shows that an increase of 10.5 in. in gravel equivalence is required to reduce the deflection level by 53 percent. For a 3-in. AC surfacing the gravel equivalence is 3.0 × 1.9 in. = 5.7 in. It will, therefore, be necessary to provide 10.5 in. - 5.7 in. = 4.8 in. of additional gravel. A possible reconstruction would, therefore, be the placement of a 3-in. AC surfacing over 5.0 in. of aggregate base directly over the existing roadway.

Another practical approach to the same problem which would cost less takes into consideration the type of distress on the roadway. Here intermittent to continuous alligator cracking occurs in both wheel paths. Because alligator cracks are usually small (2 to 5 in. in diameter) it can be reasonably assumed that the existing pavement will act independently of the new surfacing in much the same manner as an aggregate base. Therefore, consideration should be given to the possibility of placing a thin AC blanket which would permit a higher tolerable deflection level. This approach could be considered "living" with a high deflection condition rather than eliminating it by a major reconstruction. For a 2-in. AC surfacing, Figure 3 shows a tolerable deflection of 0.040 in. It would, therefore, be necessary to reduce the design deflection level of 0.064 to 0.040 in. which requires a 38 percent reduction in deflection. From Figure 2, a 2-in. AC blanket (3.8-in. gravel equivalence) provides a 37 percent reduction in deflection. This is considered close enough to recommend a 2-in. AC surfacing for repair.

In either case, isolated areas of high transient deflection or advanced distress should be subject to substantial digout type repair before the application of the corrective treatments.

RESULTS OF SPECIFIC INVESTIGATIONS

The following are brief histories of five past deflection studies which illustrate unusual problems and conditions. The criteria used in recommending corrective treatment for these projects have been changed somewhat due to a recent revision of gravel equivalences of base and AC surfacing and modification of the deflection attenuation curves which were used at that time.

V-Mon-118-Salinas

In July 1961 District V materials personnel sampled the in-place structural section of this facility at several locations. Within the city of Salinas the asphalt surfacing varied from 3 to 6 in. in thickness and the base material varied from 2½ to 11 in. Average passing and travel lane deflection measurements taken in August 1961 are given in Table 3. Based on the average deflection levels of 0.067 and 0.058 in. for the travel lanes and the deflection design criteria in use at that time, it was determined that an increase in gravel equivalence of 12 in. was required. For the passing lanes, because of their generally good appearance, lower deflection levels and lighter traffic load, an increase of only 4 in. in gravel equivalence was recommended. The existence of curbs, gutters, and buried utility lines near the surface placed severe limitations on the thickness of both an overlay or digout type repair for the travel lanes. As a result, the travel lanes were scarified to a depth of 8 in. On removal of the existing base and surfacing, 8 in. of an untreated Class 2 aggregate base was placed and compacted, bringing the roadway back to original finished grade. Both the passing and the travel lanes were then blanketed with 3 in. of AC surfacing.

The net result of the reconstruction of the travel lanes was the replacement of a cracked AC surfacing with an uncracked 3-in. AC surfacing and the replacement of the existing base with a new lift of aggregate base material. The placement of a 3-in.

TABLE 3

DEFLECTION DATA FROM PROJECT V-MON-118-SALINAS

Location	Lane	Mean OWP Deflect. (in.)
Between Lincoln and Vale St.	Westbound travel	0.067
Between Stone and Capitol St.	Westbound passing	0.034
Between New St. and West City Limits	Westbound travel	0.038
Between Capitol and Stone St.	Eastbound travel	0.058
Between Riker and Capitol St.	Eastbound passing	0.042
Between Clark and New St.	Eastbound travel	0.029

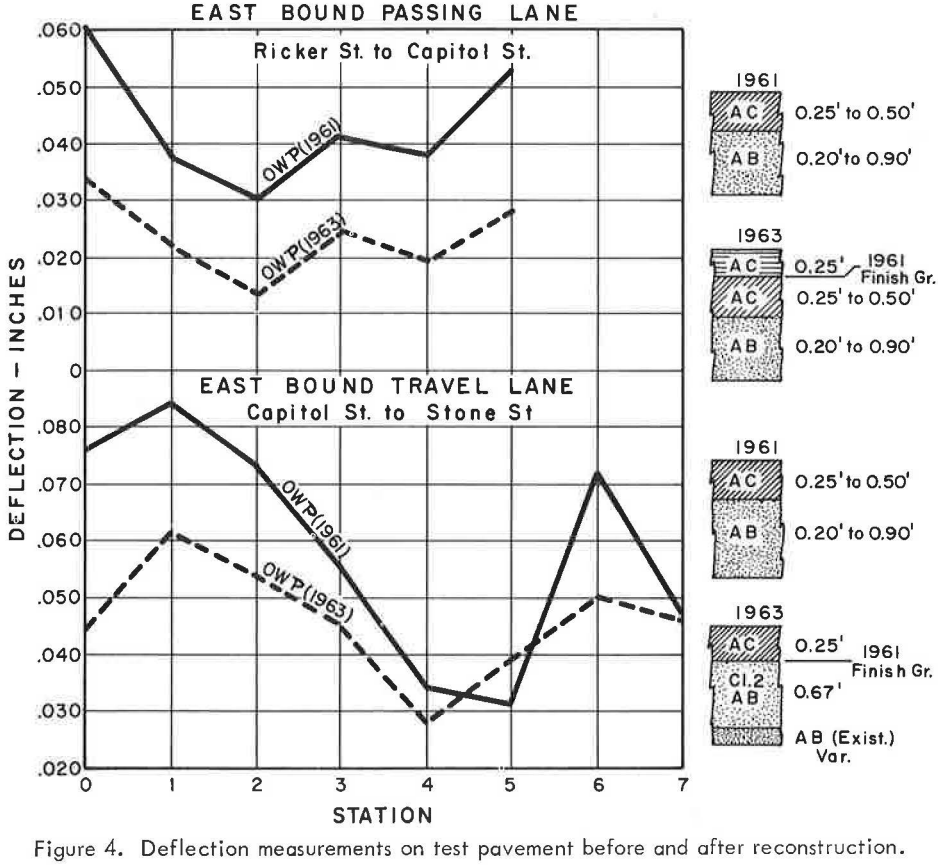

Figure 4. Deflection measurements on test pavement before and after reconstruction.

TABLE 4

PROPERTIES OF ASPHALT BINDER RECOVERED FROM CORES TAKEN ON PROJECT V-SLO-2-PBch, E

Station	Binder	Core	Depth (in.)	Properties	
				Pen., 77F	Duct., 77F (5 cm/min)
"N" 244+64[a]	120-150 Pen.	1954 Surf. course	0-1½	7	8
	200-300 Pen.	1949 Surf. course	3-¾-8	33	100+
"N" 240+50[a]	120-150 Pen.	1954 Surf. course	0-1½	3	0
	200-300 Pen.	1949 Surf. course	3-¾	13	22

[a]Northbound travel lane, OWP.

Figure 5. Road V-SLO-2-PBch, E, northbound travel lane.

contact blanket over the passing lanes, however, resulted in the full utilization of the residual strength of the old surfacing. The results of deflection measurements before and after reconstruction for one test section are shown in Figure 4. The average percent reduction in mean OWP deflection was significantly greater in the passing lane section than in the travel lane digout sections (45% as opposed to 16%). This project illustrates a truism with regard to overlay design, i.e., whenever possible, reconstruction should fully utilize the residual structural strength of an existing roadway which more often than not is considerable even for badly cracked pavements.

V-SLO-2-PBch, E

Originally constructed in 1949, the structural section included 4 in. of AC surfacing over 6 in. of crusher run base covering 12 in. of imported subbase material. Because of the appearance of early surface distress, a portion of the roadway was resurfaced in 1954 with a 3-in. AC blanket. In 1959 District V materials personnel conducted an investigation to determine the cause of surfacing distress which had reappeared since the placement of the 1954 contact blanket. Even though cracking was almost continuous throughout the length of the project, the structural section was entirely adequate in thickness and quality. It was, therefore, suspected that excessive pavement deflection had induced premature fatigue cracking of the surfacing.

In January 1960, materials and research personnel made visual observations, pavement deflection measurements, and cored into the structural section at two locations. Visual inspection of the roadway revealed almost continuous alligator cracking with some spalling in both the IWP (inner wheelpath) and OWP of the outer lane (Fig. 5). Little evidence of rutting or pumping was observed. Deflection measurements were uniformly low, averaging 0.016 in. in the travel lane OWP and 0.012 in. in the passing lane OWP. The results of tests on AC surfacing cores, however, indicated that the asphalt binder in the 1954 surface course had reached a state of hardness such that it could not withstand even the relatively low deflections characteristic of the roadway. This is shown by the results of tests on recovered asphalt from cores taken at two different locations on the roadway (Table 4).

The 1954 surfacing binder reached a critical state of hardness as indicated by recovered penetrations of 7 and 3 and ductilities of 8 and 0. These values show a much greater degree of hardness than that found for the 1949 surface course with recovered penetrations of 33 and 13 and ductilities of 100+ and 22. As a result, the 1954 overlay surfacing was cracked to a much greater extent than even the original 1949 pavement.

In view of the low deflection characteristic of the travel lanes, it was recommended that a 2-in. AC blanket be placed over the entire roadway. Because the 1954 surface course had cracked into relatively small blocks, it was believed that the possibility of reflective cracking into the new blanket would be minimal. A 2-in. AC blanket was placed as recommended, in 1960. To date, after nearly 5½ yr of service, there has been no further manifestation of surface distress. The use of deflection measurements, therefore, resulted in a real savings since, based purely on visual observation, a much greater degree of reconstruction would normally have been recommended.

Greenwood Avenue, Sanger

This roadway is typical of the many county and city streets tested during the past two to three years over which surprisingly low levels of transient deflection were noted in spite of relatively thin structural sections. In this case, the structural section consisted of 2 to 4 in. of oiled earth and rock. Visual appearance of the roadway was generally good with isolated areas of shrinkage and alligator cracking. No wheelpath depressions or other evidence of instability were observed. Deflection measurements made in April 1965 produced relatively low evaluated deflection levels ranging from 0.023 to 0.038 in. which, based on existing criteria for a 3-in. AC surfacing at 6.0 TI (0.035 in.), did not indicate a need for corrective treatment. Consequently, a double screening seal coat was recommended to improve roadway appearance and seal off the section although, based on conventional strength tests, it is likely that a much heavier reconstruction would have been indicated. The good visual appearance and low deflection level of this facility can probably be attributed to age-hardening of the AC

coupled with an increase in load-carrying capacity of the basement soil resulting from successively heavier applications of traffic throughout the years. It is unlikely, therefore, that a similar but newly constructed structural section would prove successful in view of the heavier volume of traffic on the facility immediately after construction.

V-SLO-2-B (Between Atascadero and Paso Robles)

This project was constructed to its present 4-lane divided alignment in 1951. The original structural section consisted of 4 in. of AC surfacing and a variable thickness of base material which had 2 to 3 percent cement added to the upper 8 in. In 1958, as a result of extensive block cracking in the travel lanes, a 1-in. AC blanket was placed over the entire roadway. This was in addition to regular maintenance of a sporadic nature which, by 1960, was estimated to cost nearly $2,000/mi/yr. In June 1961, just before a deflection study, a field review of the road was completed. Visual observations indicated that the travel lanes were badly cracked, with spalling evident in some areas. Only very slight distress was observed in the passing lanes. The nature of the cracking indicated reflection from block cracks in the cement-treated base as the primary cause of surface distress. Mean OWP deflection levels ranged from 0.032 to 0.051 in. and individual measurements in the travel lane varied from 0.012 to 0.084 in. These data confirmed the results of visual observations by indicating that the cement-treated base was providing little or no slab strength. The relatively high mean OWP deflection levels over the uncracked sections (0.018 and 0.025 in.) suggested that even these areas were in a state of incipient distress. This facility (US 101), one of the two major highways between the San Francisco Bay area and Los Angeles, is subject to extremely heavy truck traffic. Because of this and its relatively high level of transient deflection, a major repair was indicated. It was estimated that an AC blanket of sufficient thickness to reduce travel lane deflections to a tolerable level would have required substantial shoulder reconstruction and was not necessary in the passing lane. It was, therefore, recommended that the existing AC surface and cement-treated base be pulverized to a depth of 10 in. below the existing finish profile grade in the travel lanes only and that sufficient cement be added for the construction of new cement-treated base 8 in. in thickness having a minimum 7-day compressive strength of 500 psi. It was further recommended that the travel lane be blanketed with 2 in. of AC over the cement-treated base, returning it to its original grade and that both lanes then be surfaced with a 2-in. AC blanket. With two minor modifications, the roadway was reconstructed as recommended. The thickness of CTB was increased from 8 to 10 in. Also, a ¾-in. open-graded AC surfacing was placed over both lanes in addition to the dense-graded AC blanket originally recommended. The results of deflection measurements over a typical test section are shown in Figure 6. The level of deflection in the OWP was reduced by an average of 87 percent to below 0.005 in.

The results of this and similar projects demonstrate that successful cement treatment of existing base and surfacing materials can greatly strengthen an existing section without significantly raising profile grade. Hence, this technique has proved economical and effective for the reconstruction of roadways subject to the existing vertical control of curbs, gutters, or undistressed interior lanes.

VI-Kin, Tul-135-B, A

Where it is possible to utilize an existing structural section in its entirety, placement of reconstruction directly over existing surfacing permits comparable results with thinner reconstruction. This is demonstrated by the results of the deflection study on road VI-Kin, Tul-135-B, A, which at the time of the investigation had a structural section consisting of 3 in. AC, 6 in. of low strength (Class C, 1 to 2½ percent) CTB, 5 in. of aggregate base, and 11 in. of imported borrow. The results of deflection measurements before reconstruction are given in Table 5.

Based on an average deflection level for the cracked areas of 0.047 in. the design criteria in use at that time indicated a need for an increase in gravel equivalence of 15 in. It was recommended that this be accomplished by scarifying the existing surfacing and base to a depth of 8 in. to be followed with an addition of sufficient cement to form a CTB with a minimum compressive strength of 500 psi in 7 days.

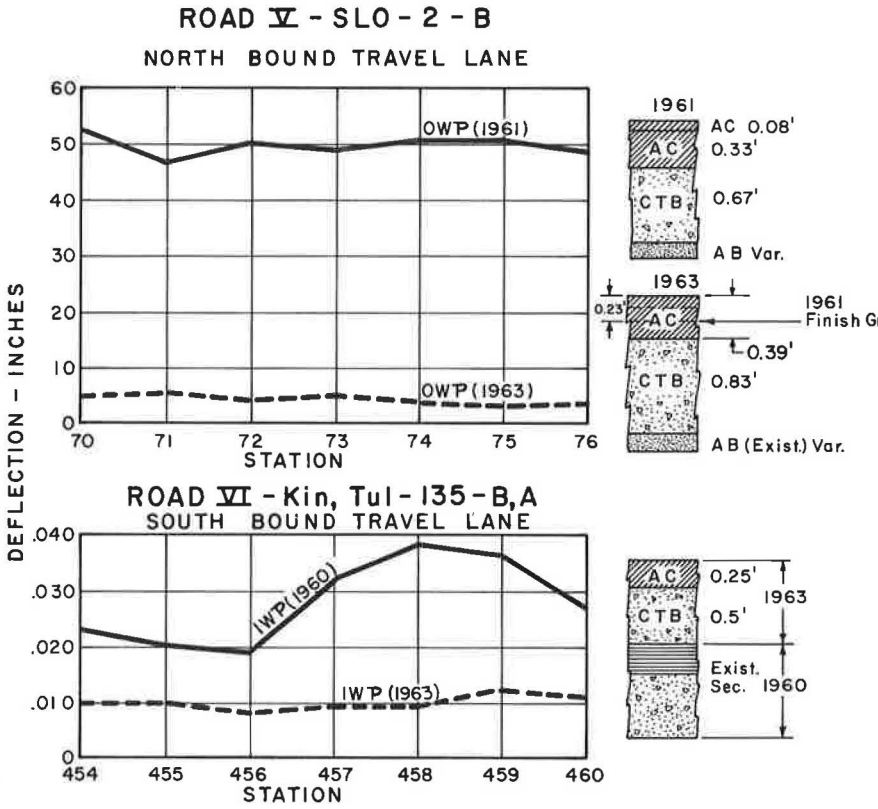

Figure 6. Deflection measurements over test section.

TABLE 5

DEFLECTION DATA FROM PROJECT VI-Kin, Tul-135-B, A

Condition	Mean Deflection (in.)	Evaluated Deflection (in.)
(a) Northbound Lanes		
Uncracked		
OWP	0.036	0.049
IWP	0.028	0.030
Cracked		
OWP	0.057	0.084
IWP	0.047	0.066
(b) Southbound Lanes		
Uncracked		
OWP	0.034	0.042
IWP	0.032	0.038
Cracked		
OWP	0.049	0.068
IWP	0.031	0.038
(c) Summary		
Uncracked	0.032	0.042
Cracked	0.047	0.068

It was further recommended that the entire roadway was to be blanketed with a 3-in. AC surfacing. Because of the absence of vertical controls, the district elected to place a 6-in. layer of cement-treated base and a 3-in. AC blanket directly over the original roadway, which provided for an increase in gravel equivalence of 16 in. Figure 6 shows deflection data before and after reconstruction from one test section. Deflection measurements indicated a reduction in transient deflection level by an average of 71 percent. This project was considered quite successful since the deflection levels after application of corrective treatment were reduced below the critical level.

Full utilization of the deflection test method is of such recent origin that only a portion of the projects subject to deflection study and corrective treatment have been constructed. Even so, the potential of the deflection test method for effecting substantial savings in the maintenance and reconstruction of existing roadways has been convincingly demonstrated on several occasions. Donald Winton (4) stated that large savings were realized by following the recommendations resulting from a pavement deflection study of the Fresno city streets. The Materials and Research Department recommendations, when compared to the cost of the previously anticipated reconstruction, allowed a cost reduction of several hundred thousand dollars.

The costs involved in making the typical deflection study have so far been quite reasonable in consideration of the coverage possible with the traveling deflectometer. Normally ten to twelve 1,000-ft road sections representing approximately 10 mi of roadway are tested during a given working day. The cost of the deflectometer crew and equipment is approximately $275 per day, not including flagmen who are usually supplied by the highway district, city, or country requesting the survey. Most deflection studies have cost between $500 and $1000, including the completed report.

CURRENT DEFLECTION RESEARCH

Pavement deflection research in California is now concentrated in three general problem areas. The first and largest program involves the establishment of a tie be tween tolerable deflection levels, structural section, and traffic volume, or traffic index. As mentioned earlier, the present limiting criteria for maximum allowable deflection were established in 1955 as a result of a comprehensive study throughout the state. It is not unlikely that the values developed as a result of this investigation tend to be conservative when applied to roadways with light and medium traffic volumes, because the initial investigation was conducted over heavily trafficked roads ($9.0 \pm$ TI).

Another important reason why these values may be subject to some alteration is the improvement in asphalt-concrete durability and thus AC surfacing fatigue resistance, which has undoubtedly been brought about by a recent modification of our AC mix design method. The principal objective of this study, therefore, is the establishment of new maximum deflection criteria, which make allowances for a more durable asphalt-concrete and which can be adjusted for variations in predicted traffic volume. This project, in which the U. S. Bureau of Public Roads is cooperating, has been under way for over a year. Twenty-five roadways throughout the state, meeting the following requirements, were selected for a 5-yr comprehensive pretest program:

1. They are AC-surfaced roadways over which reliable traffic data are available.
2. They are newly constructed roadways which have not been in operation for more than 3 yr.
3. They have a reasonably large variation in structural section and deflection level.

The test program, which is being carried out during the spring of each year, consists of deflection measurements obtained with the traveling deflectometer over selected test sections of each roadway. These sections consist of three to five 1,000-ft lengths of the roadway, depending on the size and the nature of the project. In addition to deflection measurements, a precise crack survey and rut depth determination is made over each test section. AC cores 4 and 12 in. in diameter are taken in and between the wheelpaths. These samples are subject to flexural strength, microviscosity, permeability, stability, cohesion, and density tests. The yearly test program outlined previously will be continued until each test section manifests distress to a predetermined level considered to be failure. It is believed that this study is of sufficient

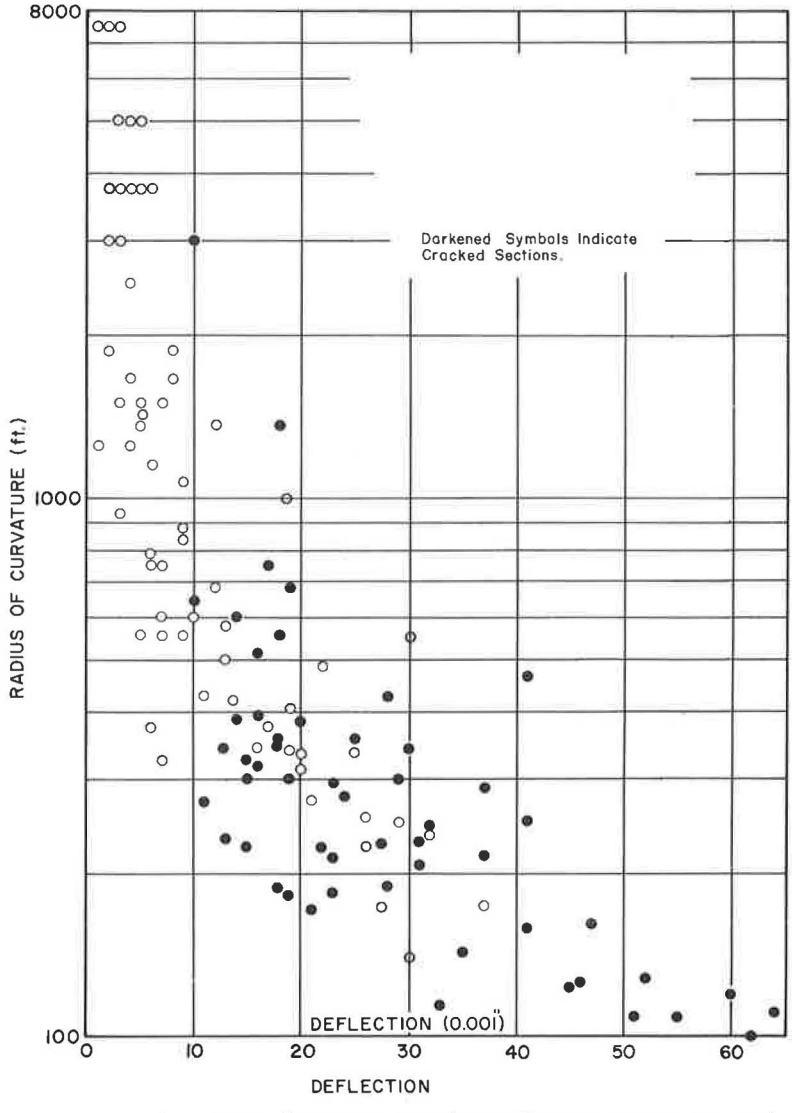

Figure 7. Radius of curvature (curvature meter) vs deflection cement-treated base.

scope to permit a valid appraisal of the effect of transient deflection, fatigue characteristics, asphalt quality, mix design, and traffic volume, on asphalt-concrete performance.

The second area of study involves the determination and analysis of area of influence or radius of curvature of a pavement under load, and the relationship to pavement performance. It would seem entirely reasonable, as many authorities contend, that pavement performance and condition are related more directly to severity of bending or area of influence than to lineal deflection measurement alone. Dehlen (3), proponent of the radius of curvature concept, presented a new device for measurement of radius of curvature, with data resulting from its use. This device, called a curvature meter, is an aluminum bar approximately 1 ft in length with an Ames dial and probe fixed in the center. By placing it between the wheels, it is possible to measure the middle ordinate of a curve 1 ft in length in the deflected basin from which a radius of curvature can be calculated.

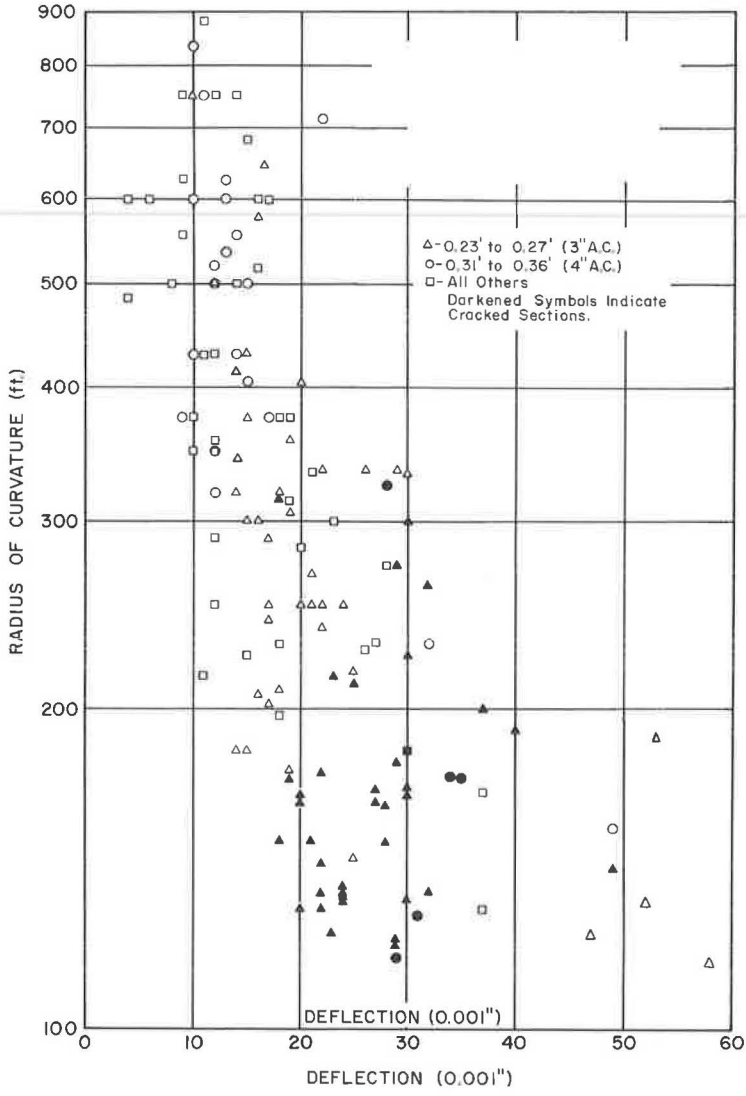

Figure 8. Radius of curvature (curvature meter) vs deflection aggregate base.

This device has been fabricated by us and used on several projects in conjunction with conventional deflection measurements (Figs. 7 and 8). In Figure 7, radius of curvature calculated from curvature meter measurements vs lineal deflection are plotted for cement-treated base construction. The open circles represent unfailed areas, with the closed dots representing cracked sections of the roadway from which the measurements were taken. Although relatively few data are available, it appears that lineal deflection was the best predictor of cement-treated base performance as there is a clear-cut demarcation between cracked and uncracked measurements at the 0.012 in. deflection level. For radius of curvature this demarcation is less clear-cut; however, a critical radius appears to be in the range of from 500 to 700 ft.

Figure 8 shows a similar plot for aggregate base structural sections. In this case, the radius of curvature appears to be the best forecaster of pavement performance, with a critical radius of curvature of approximately 200 ft. The critical zone for lineal deflection occurs at approximately 0.020 in., although there is a considerable overlapping

between 0.020 and 0.030 in. Based on the limited amount of data in Figures 7 and 8, it would be difficult to determine whether lineal deflection or radius of curvature manifests a clear-cut superiority as an indicator of future pavement performance. Because of its simplicity and compactness, in addition to its sensitivity in a very critical zone of the deflected basin, further evaluations of the instrument will be made on projects subject to deflection study.

Attempts made to relate various functions of deflectometer trace shape to pavement condition have so far proved inconclusive. This is possibly because the zone of critical bending is confined to a very small portion of the trace, thus reducing sensitivity.

CONCLUSION

Significance of Pavement Deflection

With a steadily increasing amount of reconstruction of existing roadways, the need for a method to determine the minimum corrective treatment required to restore an existing roadbed to a state in which it may serve present-day traffic and provide maintenance-free service for an extended period has become increasingly important.

The problem encountered in the design of reconstruction is, of course, entirely different from that which occurs with all new construction. In the latter case, samples of basement or embankment soils are tested statically under moisture and density conditions estimated to be the worst that will occur during the lifetime of the pavement. From the results of these tests, subgrade bearing capacity is determined with which the necessary thickness of base or subbase can be calculated to provide the required cover in accordance with the appropriate design formula. The design of reconstruction for an existing roadway presents quite another problem, however, since the most economic reconstruction requires that full benefit be derived from the materials already existing in the structural section. In this case, a laboratory strength value cannot be considered quite valid, since the conditions of moisture and density assumed during preliminary design may not have occurred. Also, it is a well-known fact that many years of successively heavier traffic loadings tend gradually to increase in-place soil strength. Another factor which is difficult to evaluate is the residual strength of an asphalt-concrete surfacing or cement-treated base. Here, the hardening or curing induced by age may lend considerable slab strength to the system even though there is continuous visible distress. The real significance of pavement deflection data, therefore, is that it gives the highway engineer an indication of the total in-place structural strength of an existing roadway and, thus, provides an extremely valuable tool for the determination of the minimum degree of required reconstruction.

ACKNOWLEDGMENTS

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General Discussion

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•THESE PAPERS are concerned with pavement rehabilitation, a problem that is becoming increasingly important. It essentially concerns determination of the additional thickness of overlay material needed to restore the riding qualities of pavements that have deteriorated due to environmental effects or the additional thickness needed to increase the structural capacity of distressed pavements to accommodate existing traffic or an estimated growth in traffic. At one time this was done solely on the basis of judgment and experience of the engineer. These papers demonstrate that an increasing amount of interest is currently being shown in the use of deflection data to arrive at the answers needed. To achieve an appreciable level of success, one must know, within reason, the tolerable deflections for different pavements, and the inherent ability of many different materials to reduce deflection when used as overlay.

The paper by Zube and Forsyth contains considerable information on these two items. By converting the values on the horizontal scale in Figure 2 in the report (Increase in gravel equivalent thickness) to inches of asphalt concrete using the equivalence cited (1 in. AC = 1. 9 in. gravel), it was possible to compute the percent of deflection reduction for each inch of material. The values range from 29 percent per inch of the material per inch of thickness to 14 percent for 3 in. and 9 percent for 6 in. These values, as indicated in the text, show that the degree of reduction or attenuation in deflection depends on the thickness of the AC layer, i. e., as stated, "The highest rate of deflection reduction occurs with relatively thin treatment."

Similar values, developed in Carneiro's paper, indicate that the deflection reduction for 1 in. of a typical grade of asphalt-concrete would amount to about 17 percent per inch for a 1-in. thickness, 14 percent for 3 in., and 10 percent for 6 in.

An attempt was made, without success, to develop a similar set of values from Huculak's paper. However, it is possible to obtain a picture of how Canada views the question by reference to a plot shown in a recent publication of the Canadian Good Roads Association, "A Guide to the Structural Design of Flexible and Rigid Pavements in Canada." According to the plot, the reduction of deflection per inch of thickness is dependent on the tolerable or design deflection. For a tolerable deflection of 0. 030 in. the reduction of deflection is about 6 percent per inch assuming the previously mentioned 1:1. 9 layer equivalency for asphalt-concrete to gravel. The reduction increases with increase in tolerable deflection to 12 percent for a deflection of 0. 050 in. As a greater tolerable deflection would demand less thickness, there again seems to be agreement that the highest rate of deflection occurs with relatively thin treatment. The magnitude of the reduction, however, appears less, according to Canadian experience.

At the AASHO Road Test, studies of 99 overlaid (3-in. -AC) sections of the test pavement showed that the deflection, on the average, was reduced 14 percent per inch of overlay, the same value as that cited previously for California.

From the work done in California, as reported by Zube and Forsyth, tolerable deflection limits have been developed. The values vary over wide limits depending on traffic and the makeup of the pavement. According to Figure 2, for pavement having a 6-in. AC surface and carrying heavy traffic the value amounts to about 0. 017 in., for light traffic about 0. 030 in. In contrast, for a 1-in. AC surface, these values are about 0. 040 in. for heavy and 0. 080 in. for light traffic.

At the AASHO Road Test, analysis of deflection data showed that a pavement having a spring deflection of 0. 020 in. would sustain over 6,000,000 applications of an 18,000-lb axle load before its condition dropped to a serviceability level of 2. 5. In contrast, a pavement having a deflection of 0. 060-in. at this time would support only about 200,000 applications before its serviceability dropped to the same level.

Huculak states: "Higher deflections are usually permissible on a lightly traveled highway as compared to a heavily traveled highway for the same magnitude of load." Also, "Some pavements are still in service with deflections as high as 0. 075 in. but carrying relatively low volume traffic." The influence of the temperature of AC surfaces is discussed in his report as follows: "Since the effect of lower temperatures is to render the bituminous surface more brittle, the pavement is more susceptible to detrimental cracking during the spring period when the surface layer cannot deform as readily without rupturing." On the overall question of permissible deflections, Huculak is of the opinion that those developed at the WASHO Road Test, 0. 035 in. for spring and 0. 050 in. for summer conditions, are realistic values for the environment in his areas (Alberta Province).

The problem is complicated because of the interrelated effects of temperature and thickness. It appears that as the temperature of an asphalt concrete decreases and its thickness increases, there would be an ever-decreasing attenuation in tolerable deflection. To a degree this viewpoint is supported by the California data (Zube and Forsyth), i. e., the tolerable deflection level of flexible pavements decreases as the thickness of the AC surfacing increases.

The report of the Canadian Good Roads Association comments on the subject of permissible deflections as follows:

> The performance and life of flexible pavements with rebound deflection values exceeding 0.05 in. is controlled largely by the wheel loads of the traffic. The life of such pavements which carry more than 1,000 vehicles per lane per day, including wheel loads ranging up to 9,000 lb, is drastically reduced as the rebound values exceed this critical value by relatively small amounts.

So, it is recommended that flexible pavements which will have ADT volumes of 1,000 or more vehicles per lane, including 10 percent or more trucks and buses, within 10 yr after construction be designed for a maximum spring Benkelman beam rebound value of between 0. 030 and 0. 050 in. The choice of design rebound value within this range depends on the relative costs of initial construction and resurfacing.

Carneiro discusses the question of tolerable deflection in considerable detail, mentioning studies conducted by several investigations in Brazil and abroad, including those of the Road Research Laboratory in England; of D. A. Welsh, British Columbia, Canada; and those of Hveem in California before 1960. He cites the following values being used in Brazil at the present time—0. 020 in. for heavy, and 0. 028 in. for light traffic—and he implies that they are subject to revision as data are obtained from the extensive work program planned.

The paper of Schrivner, Swift, and Moore describes a unique device for producing and measuring dynamic deflections of a road surface. Since loads on pavements are essentially dynamic in character, it is more realistic to measure deflections under such loads than under standing or slowly moving loads. Certainly the device described is promising; and after more preliminary testing is done and more data are obtained, it should see considerable use in connection with problems of pavement design, performance, and rehabilitation.

This discussion has served to show that there is wide diversity of opinion existing at the present time on the question of tolerable deflection of flexible pavement and, to a lesser degree, on the ability of overlays to reduce deflection. For example, the Zube and Forsyth paper is the only one presenting evidence of the need for reducing the tolerable level of deflection with increase in thickness of overlay. The factor of temperature of the overlay material and its possible marked effect on tolerable deflection is mentioned only by Huculak.

To say that a pavement of the flexible type has a given level of tolerable deflection has little meaning unless its performance for this level is defined. This is emphasized in the findings of the AASHO Road Test, i.e., at a high level of deflection a given pavement section could sustain only a relatively limited number of repetitions of the deflec-

tion before its condition deteriorates to the extent of needing rehabilitation; at a lower level of deflection a much greater number of repetitions could be sustained. Data reported by Zube and Forsyth agree with this finding.

Without reference to performance, this writer lists some tentative values of tolerable deflection for different intensities of traffic. Obviously, as data are accumulated it may be possible to relate such values to performances; to put the method of pavement rehabilitation on a firm basis by the use of deflection data, this will be necessary.

There is reasonable agreement among investigators regarding the ability of asphalt concrete overlays to reduce deflection. Data in the California and Brazil papers and those of the AASHO Road Test indicate that 3 in. of the material would reduce the deflection about 14 percent per inch; data in the report of the Canadian Good Roads Association suggest a somewhat lesser contribution for this thickness, about 9 percent. More factual data are also needed on this item; the temperature of the material is obviously one of importance.

In light of this discussion, the following values are offered merely as guidelines for those who may be contemplating the use of deflection data in pavement rehabilitation work. For deflections under 18,000-lb axle load, a tolerable value for light traffic would be 0.060 in., for moderate traffic 0.045 in., and for heavy traffic, 0.030 in. deflection reduction afforded by AC overlay: for a thickness of 1 to 2 in., 20 percent per inch; for a thickness of 2 to 4 in., 15 percent per inch; for a thickness of 4 to 6 in., 10 percent per inch.

For those who expect to continue handling the problem of pavement rehabilitation on the basis of judgment and experience, the following material may prove of interest.

Existing Pavement Condition Category	Method of Treatment
Acceptable riding qualities; minor evidence of structural weakness; some perceptible rutting and some surface cracking.	Thin AC overlay
Acceptable riding qualities; marked evidence of structural weakness; excessive rutting and surface cracking.	3 to 5-in. AC overlay
Inferior riding qualities; minor evidence of structural weakness; some perceptible rutting and some surface cracking.	Leveling course, thin AC overlay
Inferior riding qualities; marked evidence of structural weakness; excessive rutting and surface cracking.	Leveling course, 3 to 5-in. AC overlay
Inferior riding qualities; no evidence of structural weakness.	Leveling course plus thin AC overlay

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•ONLY ONE paper mentioned the measurement of radius of curvature of the deflected surface. This may be measured with reasonable accuracy by means of a very simple and inexpensive device known as a curvature meter which originated in South Africa and is described in Highway Research News No. 19.

Measurements of both rebound deflection and curvature were recently made on 57 projects in Virginia. Correlation between the two indicates that rebound deflection could be estimated from curvature measurements with a standard error of approximately 0. 007 in. The uncertainty is greatest on the stiffer pavements of the black-base type where high deflections may be obtained even though curvature values are low. Correlation is much better on the 40 nonblack-base sections where a standard error of only 0. 005 in. was computed.

The paper by Scrivner, Swift, and Moore indicates correlation with a standard deviation of approximately 0. 007 in. between Dynaflect values and deflections on a variety of pavements. Accuracy might be improved by making separate analyses for specific base types such as untreated crushed stone, asphaltic-concrete, cement-treated aggregate. Although the Dynaflect is certainly a much more costly instrument than the curvature meter, it apparently is more rapid and does not require a heavily loaded truck. Its development should be watched with considerable interest by pavement evaluators.